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Aspects of Cellular Planning in Mobile Broadband Systems

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To my Family

and to my Students

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Abstract

Mobile Broadband Systems (MBS) will introduce high data rates (up to 155 Mb/s) into the cellular communications market for high mobility outdoor scenarios. These systems will use millimetre wavebands, and will be deployed mainly in urban centres by using a micro-cellular structure. This thesis starts by proposing a complete classification of MBS services and applications, their characterisation parameters, and deployment scenarios. From a comparison of cellular coverage and frequency re-use between the 40 and 60 GHz bands in different geometries, one concludes that a lower reuse pattern is achieved for the latter (but only in the lower part of the band). The Markov-Modulated Poisson Process is used to model multi-service traffic, assuming the use of a MAC protocol that extends ATM to the air interface. One concludes that there are limitations in scenarios with higher maximum load per user, and that the consideration of terminal mobility imposes important restrictions in high mobility scenarios, namely main roads and highways. Finally, a simple approach to cost/revenue performance is explored, assuming that costs are of the order of magnitude of today's micro-cellular systems, and that the price of a call per minute will be proportional to the user load (in kb/s). Although optimum values cannot be achieved for the coverage distance, one has obtained feasible upper bounds within the range of 80-175 m, depending on the scenario.

Keywords: Mobile Broadband Systems, Millimetre wavebands, Characterisation of services and applications, Multi-service traffic, Microcellular planning.

Resumo

Os Sistemas de Comunicações Móveis de Banda Larga (MBS – *Mobile Broadband Systems*) permitirão estender os elevados ritmos de transmissão (até 155 Mb/s) ao sector das comunicações móveis, suportando comunicações de alto débito em cenários de elevada mobilidade. Estes sistemas utilizarão a banda das ondas milimétricas e serão desenvolvidos em cenários urbanos, utilizando micro-células. Nesta tese, começa-se por propor uma classificação completa para os serviços e aplicações previstos para o MBS, e identificam-se os seus parâmetros de caracterização e os cenários de desenvolvimento associados. Comparando as bandas dos 40 e 60 GHz, concluiu-se que o padrão de reutilização é inferior na última (mas apenas na parte inferior da banda). Utiliza-se o modelo *Markov-Modulated Poisson Process* para analisar o tráfego multi-serviço, assumindo-se a utilização de um protocolo MAC (*Medium Access and Control*) que estende o ATM até à interface ar. Conclui-se que existem limitações em cenários com elevada carga máxima por utilizador, e que a consideração da mobilidade impõe limitações para cenários de elevada mobilidade, nomeadamente estradas e auto-estradas. Finalmente, explora-se uma análise simples para os custos e proveitos, assumindo que os custos serão da ordem de grandeza dos associados aos actuais sistemas micro-celulares e que o preço de uma ligação por minuto será proporcional à carga por utilizador (em kb/s). Embora não se atinjam valores óptimos para a distância de cobertura das células, obtiveram-se valores realizáveis no intervalo 80-175 m, dependendo do cenário.

Palavras chave: Sistemas de Comunicações Móveis de Banda Larga, ondas milimétricas, reutilização de frequências, tráfego multi-serviço, planeamento micro-celular.

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Acronyms and Abbreviations

16-OQAM	16ary Offset Quadrature Amplitude Modulation
AAL	ATM Adaptation Layer
ABR	Available Bit Rate
ACTS-SAMBA	Advanced Communications Technologies and Services – System for Advanced Mobile Broadband Applications
ADPCM	Adaptative Differential PCM
AGC	Automatic Gain Control
AMOS	ACTS Mobile Communications Summit
AR	Auto-regressive models
ARIMA	Auto-regressive Integrated Moving Average
ARMA	Auto-regressive Moving Average
Asy	Asymmetric
ATM	Asynchronous Transfer Mode
ATR	Assistance in Travel
B-ISDN	Broadband Integrated Services Digital Network
BAS	Basic Service Component
BCC	Business City Centre (deployment scenario)
BER	Bit Error Rate
BHCA	Busy Hour Call Attempt
BHR	Busy Hour Rate
Bid	Bi-directional
BPP	Bernoulli-Poisson-Pascal
BRAN	Broadband Radio Access Networks
BS	Base Station
BSC	Base Station Controller
BUS	Business
CAD/CAM/CAE	Computer Added Design/Manufacturing/Engineering
CBD	City Business District

CBR	Constant Bit Rate
CDV	Cell Delay Variation
CLR	Cell Loss Ratio
COM	Commercial Zones (deployment scenario)
CPN	Customer Premise Network
CPU	Central Processing Unit
DCA	Dynamic Channel Allocation
DECT	Digital Enhanced Cordless Telecommunications
DL	Downlink
DMAP	Discrete-time MAP
DMM	Desktop Multimedia
DOWN	Downlink
DSA++	Dynamic Slot Allocation ++
DSI	Digital Speech Interpolation
ECO	E-commerce
EDGE	Enhanced Data Rates for GSM Evolution
EIRP	Effective Isotropic Radiated Power
EMB	Electronic Mailbox Service for Multimedia
ENP	E-newspaper
ETSI	European Telecommunications Standard Institute
ETSI-RES	ETSI / Radio Equipment and Systems
FAM	Familiar
FCA	Fixed Channel Allocation
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFM	Freight & Fleet Management
FTP	File Transfer Protocol
GBR	Gross Bit Rate
GMDP	Geometrically Modulated Deterministic Process
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
GT	Guard time
HD	High Definition
HDTV	High Definition Television
HDTV-OB	High Definition Television Outside Broadcast
HDV	High Definition Video
HG	High Gross Bit Rate

HID	High Data Rate Data
HIF	Hifi
HIPERLAN	High Performance Radio Local Area Network
HIPERLAN-2	High Performance Radio Local Area Network-type2
HOB	HDTV Outside Broadcast
HOM	Home (deployment scenario)
HSCSD	High Speed Circuit Switched Data
HVT	HD Video-telephony
HW	Highways (deployment scenario)
HYP.	Hypothesis
i.i.d.	Independent and identically distributed
IBCN	Integrated Broadband Communications Networks
IC	Integrated Circuit
Ind	Indoors
IND	Industry (deployment scenario)
IPP	Interrupted Poisson Process
ISDN	Integrated Services Digital Network
ISO	Isochronous
ITU	International Telecommunications Union
IV1	Interactive Video at 384 kb/s
IV2	Interactive Video at 1 920 kb/s
IVC	ISDN-Videoconference
IVI	Interactive Video
JPEG	Joint Photographic Experts Group
LAN	Local Area Network
LG	Low Gross Bit Rate
LOD	Low Data Rate Data
LoS	Line-of-Sight
MAC	Medium Access and Control
MAP	Markovian Arrival Process
MBS	Mobile Broadband Systems
MD1	Medium Bit Rate Data at 1152 kb/s
MD2	Medium Bit Rate Data 1 536 kb/s
MD3	Medium Bit Rate Data 1 920 kb/s
MED	Medium Data Rate Data
MES	Mobile Emergency Services
MG	Medium Gross Bit Rate
MIPS	Millions of Instructions Per Second

MM	Multimedia
MMIC	Monolithic millimetre wave Integrated Circuit
MML	Multimedia Library
MMPP	Markov Modulated Poisson Process
MODAL	Microwave Optical Duplex Antenna Link
MPEG	Moving Pictures Expert Group
MR	Main Roads (mobility scenario)
MRA	Mobile Repair Assistance
MRI-CAT	Magnetic Resonance Imaging - Computerised Axial Tomography
MS	Mobile Station
MTW	Mobile Tele-working
MVS	Mobile Video Surveillance
N-ISDN	Narrowband Integrated Services Digital Network
NISO	Non-isochronous
NRT	Non-Real Time
NTB	Non Time Based
NTSC	National Television System Committee
OFDM	Orthogonal Frequency Division Multiplexing
OFF	Offices (deployment scenario)
OQPSK	Offset Quadrature Phase Shift Keying
Outd	Outdoors
PABX	Public Access Branch Exchange
PAL	Phase Alternate Line
PASTA	Poisson Arrivals See Time Averages
PCM	Pulse Code Modulation
PD	Pedestrian (mobility scenario)
PDH	Plesiochronous Digital Hierarchy
PIM	Professional Images
pmf	Probability marginal function
POTS	Plain Old Telephone System
PRIV	Private
PUB	Public
QoS	Quality of Service
RACE	Research and Development on Advanced Communications Technologies in Europe
RACE-MBS	RACE Mobile Broadband System
ROA	Primary Roads (deployment scenario)
RPC	Remote Procedure Call
RT	Real Time

SAD	Speech Activity Detector
SBBP	Switched Batch Bernoulli Process
SDH	Synchronous Digital Hierarchy
SDU	Service Data Unit
SECAM	SEquentiel Couleur Avec Memoire
SIM	Subscriber Identity Module
SONET	Synchronous Optical NETwork
SPP	Switched Poisson Process
ST	Static (mobility scenario)
STM	Synchronous Transport Module
STM-1	Synchronous Transport Mode-level 1
STS	Synchronous Transport Signal
Sym	Symmetric
TB	Time Based
TBg	Tail at the Begining
TCP/IP	Transmission Control Protocol / Internet Protocol
TDD	Time Division Duplexing
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TE	Tail at the End
TES	Transform-expand-sample
TIN	Tourist Information
TITAN	Tool for Introduction Scenarios and Techno-Economic Evaluation of the Access Network
TM	Tail at the Middle
TOT	Total
TRA	Trains (deployment scenario)
TS*i*	Training Sequence *i*
TVD	TV Programme Distribution
TW	Tele-working
UB	Urban (mobility scenario)
UBR	Unspecified Bit Rate
UGD	Urban Guidance
UHF	Ultra High Frequency
UL	Uplink
UMTS	Universal Mobile Telecommunications System
Und	Unidirectional
UP	Uplink

URB	Urban Residential Areas
VBR	Variable Bit Rate
VOI	Voice
WAG	Wireless ATM Group
WATM	Wireless ATM
W-CDMA	Wideband Code Division Multiple Access
WDM	Wavelength Division Multiplex
WLI	Wireless LAN Interconnection
WWW	World Wide Web
ZMNL	Zero Memory Non-linearity

List of Symbols

α	mean duration of the ON state in an ON-OFF process
$\alpha(f)$	α parameter from the rain attenuation model
$\alpha_{3\mathrm{dB}}$	half power antenna beam width
α_c	ratio between the minimum carrier-to-interference ratio and the minimum carrier-to-noise ratio
α_j	arrival rate
α_j^{norm}	normalised α_j
β	mean duration of the OFF state in an ON-OFF process
$(-\beta_j)$	service component j activation rate
$\beta_{j\,max}$	maximum activation rate
β_j^{norm}	normalized β_j
χ_n	variation of the new connections traffic linear density
Δ	velocity deviation
ε_{Pb}	error associated with the blocking probability
ε_{Phf}	error associated with the handover failure probability
ϕ	angle between antenna sectors
γ	handover rate
γ_o	oxygen absorption coefficient
γ_r	rain absorption coefficient
γ_t	total attenuation
η	cross-over rate
η^*	average cross-over velocity
$\eta_{i,J+1}(\boldsymbol{n})$	departure rate (from the system) at cell i
$\eta_{ij}(\boldsymbol{n})$	transition rate between a cell i and a cell j
$\eta_{ij}(n_i)$	transition rate between a cell i and a cell j in the linear and circular geometries
η_j	service component j cross-over rate
$\eta_{J+1,j}(\boldsymbol{n})$	arrival rate (at the system) at cell i
η_k	application k cross-over rate

$\mathrm{H}_i(\boldsymbol{n})$	total service rate at cell i multiplied by n_i
H_j	service component j total service rate
$\mathrm{H}_{j\|k}$	total service rate of service component j given application k
H_k	application k total service rate
ϑ	set of resource components
λ	rate parameter of the Poisson process (and that characterizes the inter-arrival times of the exponential distribution)
λ_1, λ_2	arrival intensities for an SPP
λ_{dk}	rate of the Poisson process when the system is in state k (for data)
λ_h	handover connection generation rate
λ_i	new connection generation rate at cell i
$\lambda_j(n_j)$	rate parameter of the exponential distributed customer / arrival process
λ_k	rate of the Poisson process when the system is in state k (for voice)
Λ_i	composite (internal or external) arrival rate (departure rate) at cell i
$\Lambda_{j\|k}$	rate of activation of service component j given application k
Λ_k	application k total generation rate
Λ_k^*	normalized generation rate
μ	service rate
μ_j	service component j service rate
μ_k	application k service rate
ρ	overall traffic (under the condition of homogeneous traffic)
ρ_h	handover traffic (under the condition of homogeneous traffic)
ρ_j	overall traffic at cell j (or mean offered traffic)
ρ_k	traffic generated by application k
ρ_m	supported traffic with m channels by cell and no guard channels for handover
$\rho_{m,g}$	supported traffic with m channels by cell and from which g are guard channels for handover
ρ_n	new connection traffic (under the condition of homogeneous traffic)
$\rho_{P_b}(R)$	supported traffic resulting from blocking probability constraints
$\rho_{P_{hf}}(R)$	supported traffic resulting from handover failure probability constraints
τ	duration of a connection without any restriction on the cell it occurs (it can be completed while traversing several cells)
$\bar{\tau}$	average duration of a connection (call)
τ_c	channel occupancy time
$\overline{\tau_c}$	average channel occupancy time
τ_h	cell dwell (or residing) time
τ_i	duration of a call session in cell I
$\overline{\tau_j}$	mean holding time

$\overline{\tau_{j\|k}}$	average duration of service component *j* given application *k*
$\overline{\tau_k}$	average duration of application *k*
$\{\tau_n\}$	jump (transition) times associated with the Markov chain $\{M_n\}$
ξ_n	new connections traffic linear density

A	capacity vector
a	edge of the square that defines the 'Manhattan grid' blocks of buildings
A	total area
A_{cell}	cell area
A_f	asymmetry factor
a_j	service component *j* capacity demand
A_k	k^{th} *inter-arrival time*
A_n	n^{th} inter-arrival time
A_{nc}	net cell area
$\{A_n\}$	random sequence of inter-arrival times
b	distance between base station of neighbour cells in the Manhattan grid geometry
B	system bit rate per kilometre
b_1	maximum load per user
B_c	bandwidth per cell
BER_{max}	maximum bit error rate
$BHCA_j$	busy hour connection attempt for application *j*
BHR_j	busy hour rate for application *j*
B_j	set of blocking states
b_k	data rate associated with application *k*
B_{sj}	service component *j* data rate
B_t	total bandwidth assigned to the system
C	average power of the carrier
c	number of channels both available for new and handover connections
C^*	normalized cost per kilometre (or km^2)
$C/(N+\alpha_c.I)$	carrier-to-noise-plus-interference ratio
C/I	carrier-to-interference ratio
$(C/I)_0$	minimum carrier-to-interference ratio
C/N	carrier-to-noise ratio
$(C/N)_0$	minimum carrier-to-noise ratio
C_0	overall cost per kilometre
C_{1920}	cost (per minute) of each 1920 kb/s (corresponding to 5 basic channels)

C_{384}	cost (per minute) of a basic resource of 384 kb/s
C_{BS}	annual cost associated with a base station
$C_{BS\text{-}tower}$	cost of a base station
C_{fb}	annual base station fixed cost per kilometre
C_{fi}	annual fixed cost per kilometre
C_{ft}	annual transceiver cost per kilometre
$Changed\_M_{max\_load}$	changed number of potential users corresponding to the maximum load
$C_{mnt\&op}$	cost of maintenance and operation
C_n	net cost per kilometer (or per km^2 in 2D geometries)
$(C_n)_{lin}$	linearised net cost
c_r	r^{th} element of the resource capacity vector
C_{tot}	total annual cost per kilometre
$\mathbf{c}_\mathbf{v}=\{c_1, c_2, \ldots, c_{Re}\}$	resource capacity vector
d	distance
D	re-use distance
D_f	density factor
f	frequency
Δf	carrier spacing
$f(v)$	velocity density probability function
f_a	fraction of active users
$f_{a\text{-}BCC}$	fraction of active users in the BCC scenario
$f_{a\text{-}DOWN}$	downlink fraction of active users
$f_{a\text{-}ROA}$	fraction of active users in the ROA scenario
$f_{a\text{-}UP}$	uplink fraction of active users
$f_{a\text{-}URB}$	fraction of active users in the URB scenario
g	number of guard channels for handover
GBR	gross bit rate
G_r	gain of the receiving antenna
G_t	gain of the transmitting antenna
I	average interference power
i	cell i
I_r	rain intensity
J	number of different service components (or customer classes)
K	reuse pattern
$k(f)$	k parameter from the rain attenuation model
K_{app}	total number of applications
K_i	normalisation constant for the state probabilities
L_c	cell length

l	street length
L	system average load
L_{max}	maximum load
L_u	load from each user
m	number of channels available in a cell
M'	Markov process defining the Markov-modulated process
$M=I/N$	interference-to-noise ratio
ΔM	difference of the values of M between 40 and 60 GHz bands frequencies
M_{ENV}	number of potential users in a given environment
M_j	application j subscribers during the busy hour
$m_j(y)$	auxiliary variable for the recursive algorithm
M_{max_load}	number of potential users corresponding to the maximum load
$\{M_n\}$	Markov chain
M_T	total number of potential users
n	average power decay exponent
$\mathcal{N}$	set of possible states in terms of occupied channels
N	thermal noise power
$\boldsymbol{n} = (n_1, n_2, ..., n_J)$	state of the system (defining the number of each component active requests)
$\boldsymbol{n} = (n_1, n_2, ..., n_{Nc})$	state of the number of users in cells 1, 2, …, N_c.
$N(t)$	counting process
$\boldsymbol{N}(t)$	vector that defines the temporal evolution of the state of the system
N_c	number of cells in the system
$N_{c/km}$	number of cells per kilometre
$N_{c/km2}$	number of cells per km^2
$(N_{conns})_j$	total number of active connections from application j
n_i	number of active users at cell i (it corresponds to the number of occupied channels in the single-service approach)
$n_i(t_i)$	number of users at cell i at instant t
n_j	actual number of active users accessing to component j
N_j	actual number of users accessing to service component j
$N_j(t)$	random variable of the number of class l customers
$n_{j\|k}$	number of times service component j is activated during application k
N_k	number of users for slot k
n_l	actual number of class l customers in the system
N_{op}	number of operators
N_s	dimension of the state space
N_{SU}	number of supported users
$\mathcal{N}_y$	set of values of the state variable $\boldsymbol{n}$ corresponding to a given occupancy

p	probability parameter of the geometric distribution
$p(\boldsymbol{n})$	equilibrium *pmf* of the state $\boldsymbol{n}$
P_b	customer or connection blocking probability
P_{Bi}	blocking probability at cell I
$(P_b)_{max}$	blocking probability threshold
P_c	price (in Euros)
P_d	connection dropping probability
$(P_d)_{max}$	connection dropping probability threshold
P_{ft}	profit in percentage
P_h	probability of handover
P_{hf}	handover failure probability
P_{hfki}	handover failure probability from cell i to cell k
$(P_{hf})_j$	service component j handover failure probability
$(P_{hf})_{max}$	maximum (or threshold) handover failure probability
$(P_{hf})_{maxj}$	maximum handover failure probability for service component j
$p_i(n_i)$	probability of n_i channels being occupied at cell i
p_{ij}	transition probability from cell i to cell j (the state j = N_c+1 defines the 'outside world')
P_j	application j penetration
p_k	probability of an user having application k active
P_r	average received power
$prop_k$	proportion of application k usage
P_t	average transmitted power
P_{tb}	time blocking probability
Q	transition matrix
$q(y)$	equilibrium *pmf* of the occupancy
$Q(y)$	probability distribution function of the occupancy
Q_{ij}	elements of the transition matrix
R	maximum coverage distance of a cell
R_{384}	revenue (per minute) of a basic resource of 384 kb/s
r_c	cluster revenue-to-cost ratio
r_{cc}	reuse factor
R_e	number of different resource facilities
$(R_{ev})_{BS}$	annual revenue associated with a base station
$(R_{ev})_{tot}$	total annual revenue per kilometre
R_{max}	maximum value of the coverage distance
R_{opt}	optimum value of the coverage distance (in terms of the maximisation of the new connections traffic linear density)

R_p	Markov renewal process
R_S	gross symbol rate
R_{user}	ratio of the number of supported users between the cases of 288 and 384 channel/cell
R_v	revenue per kilometre per year
$(R_v)_{cell}$	revenue per cell per year
R_{vt}	revenue per transceiver per year
S	state space for an open Jackson network
S’	state space for the Markov and Markov-renewal traffic models
S_{ef}	spectral efficiency
$(S_{ef})_{TOT}$	total spectral efficiency
s_k	state k
t	time
T	total number of carriers
T_i	number of relevant tiers of interference
T_n	arrival instant n
T_s	slot duration
UBR	user bit rate
$UBR_{carrier}$	carrier user bit rate
UBR_{slot}	slot user bit rate
U_j	application j usage
v	velocity
V_{av}	average velocity
$v_j(\cdot)$	non-normalised marginal probabilities
V_{max}	maximum velocity
V_{min}	minimum velocity
X_n	random variable which defines the state at time n
y	normalised new connections traffic linear density
Υ	set of possible values for the occupancy
$\boldsymbol{Y}(t)$	vector that defines the temporal evolution of the current resource occupancy
Z_j	peakdness factor

Chapter 1

Introduction

1.1. Motivation

In the next years, a large demand is foreseen for mobile multimedia services, limitations on achievable data rates and system capacity leading to the use of mobile broadband communication systems operating at millimetre wavebands, e.g., MBS (Mobile Broadband Systems, [Fern95]). MBS will be deployed mainly in urban areas, to cover hotspots in the centre of large cities, main roads and highways, where the highest demand will occur; moreover MBS will be multi-service systems, i.e., they will support several services simultaneously over the same platform, for different, or even the same, user(s).

Owing to their high transmission data rate, and due to the saturation of the spectrum at lower frequency bands, MBS are intended to operate at the millimetre waveband, offering improved performance in system capacity [Fern95]. As low data rates (such as in speech) are not foreseen, if W-CDMA (Wideband Code Division Multiple Access) was to be used, a low spreading factor would be needed, e.g., 8 Mb/s through a 20 MHz bandwidth, and the system would not fully benefit from all the features of spread spectrum. Therefore, it still makes sense to consider some kind of frequency division access technique, where the available spectrum is divided into a number of frequency groups, each one allocated to a set of base stations, BSs. OFDM (Orthogonal Frequency Division Multiplexing) could be a solution [ChLS00], but in this work one is still assuming TDMA/FDMA (Time / Frequency Division Multiple Access), following the approach from RACE-MBS (Research in Advanced Communications in Europe – Mobile Broadband System) and ACTS-SAMBA (Advanced Communications Technologies and Services – System for Advanced Mobile Broadband Applications) European Commission projects [PrSv99], which developed the MBS concept and implemented demonstrators. While the RACE-MBS demonstrator operated at the 60 GHz band, the ACTS-

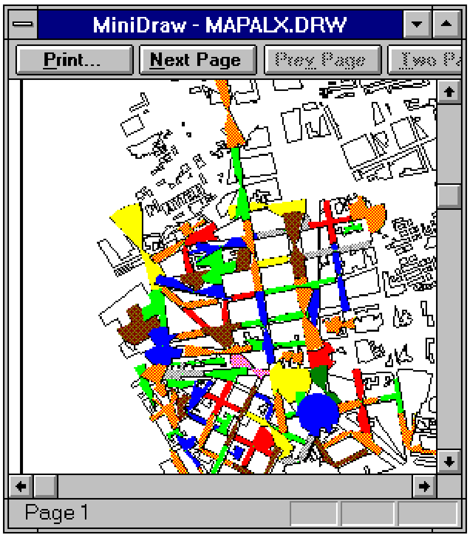
SAMBA demonstrator operated at the 40 GHz band, supporting two specific applications: High Definition Television Broadcast and a Medical Application in an Ambulance.

The main objective of RACE-MBS was to develop the scientific, technical and technological capabilities for MBS to take form, allowing the integration of fully mobile communications capability into Broadband-ISDN (Broadband Integrated Services Digital Network), and to examine some market aspects affecting this integration. As MBS were seen as systems whose operation begins just where UMTS (Universal Mobile Telecommunications System) operation ends, the foreseen UMTS, at that time (from 1992 until 1995, in the framework of the RACE II program) development, was taken into account, as well as the need for coexistence and interoperation. The project started the identification of future communication needs for mobile users and respective market characterisation. It addressed the new technical and technological issues posed by broadband mobility, mainly the ones resulting from the need of operating at much higher radio frequencies, and showed the feasibility of the MBS concept by building a demonstrator. At a more detailed level, some of the main objectives of the RACE-MBS project have been the following [Fern95]:

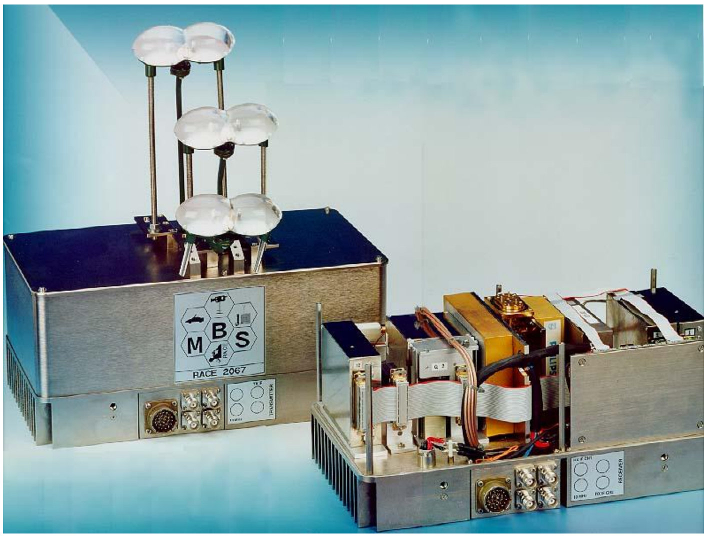
- system architecture and functionality of land interface to B-ISDN;
- characterisation of the mobile radio propagation environment at 60 GHz;
- low-cost antennas suitable for millimetre wave, including planar antennas;
- universal radio interface at the 60 GHz band;
- methods and techniques for coverage planning and cellular design at 60 GHz, Fig. 1.1.a);
- using the new monolithic millimetre wave ICs (MMICs) processes to design, implement and test the up-converter, power amplifier and preamplifier/mixer;
- demonstrator implementing a mobile connection operating at a gross bit rate of 32 Mb/s over a radio link at the 60 GHz band, offering a service bit rate of 16 Mb/s for the transmission of digitised video, Fig. 1.1.b).

While the RACE II programme was concentrated on system integration and prototyping of new services and applications, the ACTS programme addressed the need to provide seamless service across various radio environments and operational conditions, for a range of user-defined and customised advances multimedia services. Key issues were system and service integration with existing and future fixed networks, to ensure continuity of multimedia service provision [SiFe95].

The primary goal of ACTS-SAMBA was to promote the development of a broadband cellular radio extension to the fixed broadband network, thus allowing the use of fully interactive broadband multimedia services by mobile users. The project focused on a trial platform, which has demonstrated the possibility of MBS supporting high data rate user applications.



a) MBS Cellular planning tool.



b) Project demonstrator, operating at the 60 GHz band.

Fig. 1.1 – RACE-MBS project illustration [MBS96].

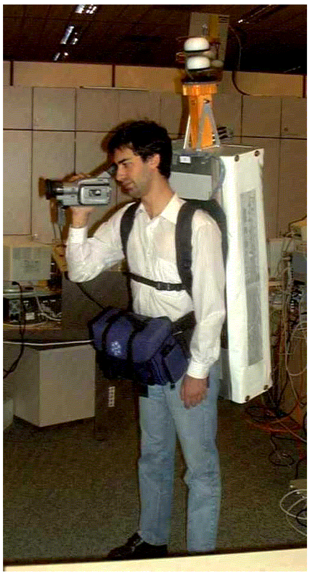
The key of objectives of SAMBA were the following:

- demonstrate mobile applications at up to 34 Mb/s;
- design and implement transparent ATM (Asynchronous Transfer Mode) connection via mobile radio transmission;
- specify and implement the main mobile broadband cellular functionalities, namely medium access and control, handover and dynamic resource management;
- implement an MBS Trial platform in the 40 GHz band, and perform technical trials and demonstrations;
- study MBS cellular planning aspects, namely frequency re-use, interference performance and traffic from mobility;
- advance the MBS concept and promote its standardisation.

SAMBA focused on a trial platform consisting of a digital radio network of two BSs, Fig. 1.2. a), one BS controller, an ATM switch, an ATM mobility server and two mobile stations (MSs), in form of a backpack, Fig. 1.2. b), or adapted to an ambulance (or to a Van).

This configuration allowed to verify the basic system aspects: reliable transmission of ATM cells through the radio interface in a mobile radio environment suffering from noise, co-channel and multipath interference, multiple access, dynamic resource allocation and mobility management, including seamless handover. The trial platform could be connected to the fixed broadband network via a standard STM-1 (Synchronous Transport Mode-level 1) ATM interface. Bearer services up to 34 Mb/s and a maximum mobile speed of 50 km/h were demonstrated.

a) Base Station tower , Aveiro [DFPH99].

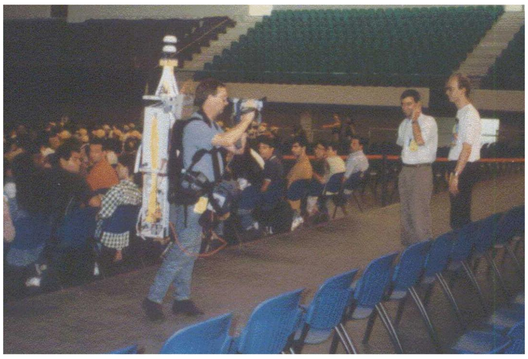


b) MS operation, EXPO' 98 [SAMB00].

Fig. 1.2 – ACTS-SAMBA Trial Platform, Portugal.

The trial platform integration was held in Bosch (Hildesheim, Germany) during the Summer of 1998. In September 1998, a set of SAMBA demonstrations occurred during EXPO' 98, the World Exposition that was being held in Lisbon, Portugal. An HDTV (High Definition Television) Broadcast applications was demonstrated in the Utopia Pavilion (Atlântico Pavilion today), Fig. 1.3 a), and a Medical Application was presented outdoors, in the surroundings of the Portugal Telecom building near EXPO' 98, Fig. 1.3 b). Additional details can be found in [SAMB00].

During 1999, another set of demonstrations took place at Cebit' 99, Hannover, Germany, ATM Developments'99 (Rennes, France), AMOS'99 – ACTS Mobile Communication Summit'99 (Sorrento, Italy), Fig. 1.4, and Telecom'99 (Geneva, Switzerland) Fig. 1.5. In AMOS'99, the MS was adapted to a small car in part of the demonstration, enabling easier movement during most of the days of the Conference. Some photos from EXPO' 98, AMOS'99, ATM Development'99 and Telecom' 99, Figs. 1.2-1.5, also show people using the MS as a backpack, they being totally free to walk around.



a) HDTV Broadcast in UTOPIA Pavilion.

b) Medical application in an ambulance.

Fig. 1.3 – Demonstrations at EXPO' 98, Lisbon, Portugal [SAMB00].

a) SAMBA stand. b) MS and BS. c) Demonstration team [SAMB00].

Fig. 1.4 – SAMBA demonstration in AMOS’99, Sorrento, Italy.

b) In ATM Developments’99, Rennes, France. a) In Telecom’99, Geneva, Switzerland.

Fig. 1.5 – HDTV Broadcast operation (the camera operator is totally free to move) [SAMB00].

An important part of the work of this thesis was precisely developed in the framework of the ACTS-SAMBA project, and part of it was initiated within the RACE-MBS project, during the graduation final work of the author, and also during his MSc [Vele95], when he developed an MBS graphical cellular planning tool [VeBr98], Fig. 1.1.

1.2. Some of the challenges in MBS

Today there is still some difficulty in the identification of the main services and applications for MBS, partly because of the delay on the introduction and widespreading of B-ISDN services in fixed networks. Moreover, even the set of applications for UMTS is not yet completely defined. The problem partly arises from the lack of accurate marketing inputs on the development of applications (e.g., What do the clients need? At what price would they buy them? What will be the market growth?), and also from ergonomic design aspects of portable terminals supporting multimedia information, which can ultimately determinate the customer acceptance and the level of subscriber base for those systems.

Owing to the diversity of characteristics of the services to be supported, different requirements arise for resource usage. A service corresponds to several applications, having a set of main parameters in common; each application supported by these services will then have access to various service components. Thus, the voice, data and video components of each application correspond to this system service components.

The amount of resources that need to be available in each cell depends on the mixture of applications being supported, as well as on the total number of users. Because of the sensitivity of system load on application parameters, e.g., average duration, service components characteristics and terminal mobility, an accurate identification of the deployment scenarios of such systems is needed, it being of crucial importance for cellular planning purposes.

The usage of each application, i.e., the percentage of connections of a given application relatively to the total number of applications, is one of the most important aspects to be determined, there being nowadays, however, few forecast results available for mobile communications. Since one is dealing with applications going beyond the simple voice service, the term *connection* is being used in this work instead of *call*. The RACE-TITAN (Tools for Introduction Scenarios and Techno-Economic Evaluation of the Access Network) project has already done some estimations for the residential market in fixed networks [StMu95], [OZSI96], whereas ETSI-RES (European Telecommunications Standard Institute-Radio Equipment and Systems) [ETSI97], the UMTS Forum [UMTS99], and the RACE-MBS project [RoSc94] have also presented some forecasts for Broadband Wireless LANs (Local Area Networks) and Mobile Broadband Systems.

Because of interference constraints, BSs in geographical proximity will, in general, have to use different frequency groups [Lee89]. Because the characteristics of the bands prospectively allocated by ITU (International Telecommunications Union) for these systems, the 40 and 60 GHz ones, are different from the UHF (Ultra High Frequency) bands, the attenuation from atmospheric elements, namely rain and oxygen, has to be taken into account. Besides, the desired high capacity leads, in conjunction with the low values for the achievable transmitter power, to micro-cellular architectures, employing a large number of cells, with BSs deployed at relatively low heights above ground level (e.g., around 5 m, on lamp posts). As a consequence of all these peculiarities, it makes sense to compare the two bands from the point of view of cellular planning, i.e., both cell coverage and frequency re-use.

The following specific bands are being considered for the implementation of MBS: [39.5, 43.5] and [62, 66] GHz, with an interval of 2 GHz in between 1 GHz bands, Fig. 1.6. Propagation characteristics are not the same in these two bands, with oxygen and rain presenting different values for their attenuation coefficients; moreover, these coefficients are not uniform within each of the bands.

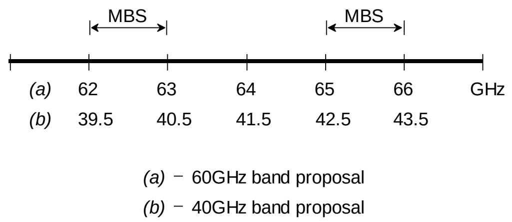


Fig. 1.6 – Frequency bands being considered for the implementation of MBS.

Since a larger attenuation leads to the possibility of reusing frequencies at a closer distance for approximately the same coverage (the attenuation is not substantial for short distances like the ones involved in cell coverage), the usage of one or the other frequency bands can have significant consequences on system capacity.

As propagation occurs essentially in line-of-sight (LoS), the shape of the cells and the co-channel interference are determined, to a large extent, by the location of the surrounding objects, buildings in particular (in urban outdoors scenarios). As a consequence, for cellular design purposes, an easy analytical treatment is only possible for environments with a regular structure, as the linear and the Manhattan grid (planar regular) geometries; a similar approach is taken in [CoFr94] for the 60 GHz band, where only a fixed value of the maximum coverage and re-use distances was considered, the variation of the frequency re-use parameters with these distances being disregarded. In these cases, it is important to establish the correspondence between, on the one hand, the maximum coverage and re-use distances, and on the other, the interference-to-noise and the carrier-to-interference ratios for both bands.

From these ratios one can extract conclusions about the range of coverage distances that allows us to obtain minimum values for the co-channel re-use factor, and under which conditions it is preferable to use one band or the other. In general, two situations can be distinguished: the ideal and the interference-plus-noise limited ones. In the ideal one, only the co-channel interference affects the quality of communications, i.e., only the relation between the carrier and interference powers is of interest. However, in certain cases, thermal noise also significantly affects the communication, and it is necessary to have a model to characterise the system in the range between the noise limited situation and the interference limited one; the noise-limited situation occurs, e.g., if low values are considered for the transmitter power or a very demanding modulation scheme is used.

For urban irregular geometries, conclusions on the quantities of interest related to cellular design, such as achievable frequency re-use and system capacity, can be obtained from specific cellular layouts and environments (but typical, as much as possible). An interactive computer graphic tool can be used to assist in the design procedure.

In MBS, cells will be confined to streets, with dimensions of the order of a few hundreds of metres. The high mobility associated with it yields a tele-traffic analysis, where both new connections and handover connections traffics must be considered simultaneously. As one of the goals of planning the cellular structure of such systems may be the maximisation of the new connections traffic in terms of cell dimension, in a first approach a linear coverage geometry, where mobiles travel randomly through cells located end-to-end, has been considered for single-service operation. The cell coverage range that leads to a maximum new connections traffic linear density has to be obtained; in order to have an insight into the trade-offs involved in the optimisation procedure, the behaviour of this traffic density in terms of the maximum coverage distance of a cell needs to be studied for various mobility scenarios (pedestrian, urban, main roads and highways). Due to the small length of cells, and to the possibility of high mobility terminals, handover will play a key role. The existence of guard channels exclusively for handover is then foreseen, i.e., from the total number of channels, a sub-set is used only for connections coming exclusively from handover (the rest remaining for both new and handover connections). This analysis is made assuming that handover traffic is Poisson distributed, and that there is independence among the number of connections being served at each cell [Jabb96]. MBS will enable multiple services, providing mobile multimedia communications, but in this first approach only two types of applications are taken into account, in order to simplify the analysis of the problem: short duration ones, with an average duration of 3 min, and long duration ones, with an average duration of 20 min [ZuAs94].

Although it is not necessary that future MBS will be based on ATM technology, the work from RACE-MBS [Fern95] and ACTS-SAMBA [PrSv99] projects considered so, this being the approach followed in this work. In ATM networks, the available resources are shared in a way that allows multiplexing of different traffic sources. As far as different sources do not take these peak values simultaneously, for a fixed number of users, the network can use less resources than would be required if resources were assigned according to the peak amounts required by each user, and a gain exists from this statistical multiplexing [Sait94].

In order to model multi-service traffic in MBS, one needs to know the model for the air interface access, as well as for the slot arrival process. Because traffic can be generated from different mixtures of voice, data or video sources, it is important to obtain performance measures for resource usage, making use of the characteristics of the frame structures [PrSv99] and of the MAC (Medium Access Control) protocols. The DSA++ (Dynamic Slot Allocation ++) MAC protocol, which in 1998/99 was being under consideration in the wireless ATM HIPERLAN-2 (High Performance Radio Local Area Network-type2) standardisation process of the Wireless ATM Group (WAG) of the ATM Forum and the ETSI/BRAN (Broadband Radio Access Networks) project [ALMH98], allows considering connection-oriented communications [KrSL98]. It extends the ATM like statistical multiplexing to the radio interface in order to fulfil the requirements of the wireless users. By allocating a so-called container, formed by a number of slots, a BS defines channels like in circuit-switched connections. Thus, the methodologies for circuit-switched network analysis supporting heterogeneous traffic can be applied, while the MAC protocol guarantees that the maximum delay is kept under a threshold value that does not affect the performance of applications [ALMH98], namely real-time ones. It is clear today that the 'merger' of the IP world with the mobile communications one puts different perspectives on traffic analysis, which are not considered in this work.

Therefore, the identification of relevant models for the characterisation of voice, data and video traffic sources is needed, in view of finding a unified model to evaluate the QoS (Quality of Service), which depends on the aggregate traffic. Hence, keeping in mind that these models are needed for MBS cellular planning and optimisation purposes, the implementation feasibility of the aggregate traffic model is crucial in the choice of the basic model(s) for the sources. An analytical approach is sought, instead of a simulation one.

The Bernoulli-Poisson-Pascal model is proposed for the computation of the blocking probability in such mobile multi-service systems, and an user model has to be conceived to characterise the way an equivalent user of an application generates an actual service component user. From tables with the results for the blocking probability (that generalise, in a way, the Erlang-B and Engset tables to multi-service traffic) it will be possible to obtain the supported fraction of active users given the blocking probability threshold (or even the handover failure probability threshold, if one considers that in the case of no guard channels for handover, the handover failure probability is given by the equation of the blocking probability, as an approximation).

The high capacity desired for MBS and the high operating frequency lead to micro-cellular configurations, hence, requiring a large number of BS to be deployed. For cost efficiency, these base stations should be inexpensive to manufacture and install; in particular, a small number of types should exist, and their installation should not require extensive adjustments. In [FeGa00], the MODAL (Microwave Optical Duplex Antenna Link) project concept is proposed to provide an alternative technique for the generation of millimetre waves by using optical technology, offering the perspective of reduced installation and maintenance costs when compared to more conventional solutions.

In this work, both regular and irregular coverage geometries are considered. The linear and the Manhattan grid geometries are examples of the former, whereas a totally irregular real urban geometry is an example of the latter. Because different frequency re-use patterns and coverage distances have a strong impact in the economic analysis of MBS, a cost / revenue function has to be developed, taking into account the cost of building and maintaining the infrastructure, and the way the number of channels available in each cell affects operators' revenues. This depends on the system capacity, and is stipulated by the supported multi-service traffic; fixed costs for licensing and bandwidth auctions (or ‘beauty contests’) should also be taken into account.

Some useful cost/revenue models were already developed in a simpler context [GaSr95], [BrVe96]: while a single service system is considered in the former case, some simplifications (not considering the multi-service traffic analysis) were assumed in the latter one. The economic analysis is referred as a cost/revenue performance analysis, because optimising costs does not necessarily mean optimising net revenues. In this work, one proposes a cost / revenue function for MBS, and one conceives some strategies for system deployment, in terms of the choice of the cell coverage distance, both in an initial phase of system deployment, when less users are foreseen, and in a medium term scenario, when more users have to be supported.

As a hypothetical scenario, one is considering that MBS will succeed when the costs of deploying its infrastructure and operating the system will be of the order magnitude of today’s voice systems, a little bit higher in an initial phase, decreasing down to values comparable to today’s GSM (Global System for Mobile Communications) ones in the following years. One is also expecting that, although the available average data rates increase from generation to generation by a factor of, say, $10\cdot\sqrt{2}$ (from circa 10 kb/s in GSM to 144 kb/s in UMTS, and to 2 Mb/s in MBS), users will not be willing to spend much more per minute of connection (or equivalent). It is worthwhile noting that in MBS the referred 2 Mb/s are faced as the net user load, i.e., the ‘silent’ periods of each application can be explored in order to allow the use of the shared resources by other applications, as it was previously explained. As ATM is used, resources are shared in a way that allows the multiplexing of different sources (the service components the applications have access to). Furthermore, by using the TDD (Time Division Duplexing) scheme, the asymmetric characteristics of the mixture of applications can be explored.

1.3. Structure of the Thesis

Although the organisation of the structure of this thesis does not correspond to its chronological development, the work associated with this thesis is based on an initial proposal for MBS services classification, characterisation and deployment scenarios, and it covers several important aspects of cellular planning in MBS, from coverage and frequency re-use, up to the cost / revenue optimisation, analysing in detail the aspect of the influence of mobility in single- and multi-service traffics. It has several original contributions on MBS services and applications classification, characterisation and deployment scenarios, frequency re-use and cellular planning, traffic from mobility, multi-service traffic and system capacity determination, and cost-revenue optimisation, that have already been reflected in the work developed in the framework of the SAMBA project [PrSv99], and in papers published, accepted for publication or submitted to evaluation both in conferences and journals:

- MBS Services and applications classification, characterisation and deployment scenarios [VeCo00a], [VeCo00b], [VeCo00c];
- frequency re-use and cellular planning [VeCo97], [VeCB01].
- traffic from mobility for short and long duration calls, with the consideration of guard channels for handover [VeCo98a], [VeCo98b], [Vele98], [VeCo98c], [VeCo98d],[VeCo99a]
- multi-service traffic and system capacity determination [Vele99], [VeCo99b], [VeCo01a], [GaVC01], [VeCo01b], [VeCo01c].

The outline of the thesis is described in what follows.

In Chapter 2, a classification for mobile broadband services and applications is proposed, which distinguishes between interactive and distribution services, and also identifies the types of information supporting each one. A taxonomy is proposed for applications characterisation parameters, divided into five different types: main ones, traffic and communications parameters, service components and operation environments as well. As the multi-service traffic analysis of MBS, with a given mixture of applications, requires the definition of their main operation environments, the respective deployment scenarios are defined, through the values for the usage of broadband, wideband and low-MBS applications.

Chapter 3 addresses the comparison of frequency re-use characteristics between the bands of 40 and 60 GHz, the ones prospectively allocated for systems like MBS. The key difference between the two bands is the oxygen absorption, which is negligible at 40 GHz, but presents high values at 60 GHz, decreasing from 14 dB/km (at 62 GHz) down to approximately 1 dB/km (at 66 GHz). Note that the impact of this excess absorption is two-fold: on the one hand, it reduces the received signal power, but on the other, it also reduces the co-channel interference. Because these two quantities may not suffer the same amount of reduction, differences in the re-use pattern may result.

In Chapter 4, considering a single-service system as a simplification, models allowing the study of the influence of the coverage distance and the velocity on the supported traffic and on the new connections traffic linear density are examined. Results are obtained for typical scenarios in MBS with linear coverage geometry. The blocking probabilities for both new and handover connections are assessed for configurations without guard channels for handover, via the consideration of a Markov chain, which, in certain conditions, can be approximated by a model that allows the use of the theory from Jackson networks. For systems without guard channels for handover, and for a fixed bounding value for the blocking probability, the new connections traffic linear density is analysed. It increases with the decrease of the maximum coverage distance and is upper limited by a value that depends on the characteristics of the mobility scenario. However, connection-dropping probability requirements also need to be fulfilled, leading to different values of the new connections traffic density in different scenarios. Because some limitations exist in system capacity, mainly for high mobility scenarios, the use of guard channels for handover is studied, and a comparison is done between short and long duration connections. Results for other geometries can be obtained by generalising these ones.

In Chapter 5, a Markov-Modulated Poisson Process model is proposed for the modelling of the superimposition of MBS data and video Interrupted Poisson Process sources. Given the correspondence between applications and their bearer service components, an algorithm for the Bernoulli case of the BPP model is used to compute the blocking probability for the service components of interest. The supported fraction of active users is computed by a simple inversion procedure using the tables for the blocking probability versus the fraction of active users generated in this way. From these results one can obtain the number of supported users and the spectral efficiency. Thus, as terminal mobility has a strong impact in system performance, its influence is also studied. Finally, the variation of the supported fraction of active users, of the supported number of users, and of the spectral efficiency with the maximum coverage distance is presented. The latter one is fed into the cost / revenue performance analysis of Chapter 6.

In Chapter 6, a model for cost/revenue performance analysis is proposed, in order to obtain some optimisation criteria for MBS. The cost and revenue components are first presented, and a net cost function is proposed, together with a normalised cost function. Then, based on some simple assumptions for model parameters, results are obtained for the cost function, both for linear and urban geometries. Finally, the choice of an optimum coverage distance is discussed, via the analysis of some alternative deployment strategies, and taking some results from frequency re-use (in the bands of 40 and 60 GHz) into account.

Conclusions are drawn in Chapter 7, where topics for further research are presented as well.

Chapter 2

Services and Scenarios

2.1. Introduction

Around ten years from now MBS will play an important role in the mobile communications market, mostly in urban areas to cover hotspots in the centre of large cities, where a very high demand is foreseen. However, there is still some difficulty in the identification of the main services and potential applications of such systems, primarily due to the emerging nature of future applications and today lack of customer interest in those content or applications. One of the main drawbacks in its introduction consisted in the insistence of developing these services only from the technical point of view of telecommunications and computer engineers, hence, not considering proper marketing inputs about what people really need.

Moreover, even the set of applications for UMTS is not yet completely defined. The problem arises, partly, from the lack of accurate marketing inputs on the development of applications, i.e., the answer to questions like: What do the clients need? At what would price they buy them? What will be the market growth? Customers would like to use these new services just like they use the phone: hang on, dial and 'talk'.

Computers, the cheapest broadband services terminal available nowadays, have the drawback of being conceived only like desktop workstations, and not like a real-time communications terminal. For this purpose, today they are too large, too heavy, difficult to handle and have a high complexity to be used like a communications terminal by common people. Besides, the time they last to start up, load every application (including the connection to network(s) and respective checks) and perform a large amount of device checks is enormous, compared with some usual applications actual duration, complicating its use like a communications terminal. People who usually are using a computer at their jobs (or at home) will probably use it for communications purposes, because they have one available and it is usually on. However, others, who only want a mere broadband communications device easy to handle, would prefer for sure to have their device on stand by – although ready to receive messages, like usual phones – being switched on and connected to the communication peer(s) only during the ‘call’. This may be partly the reason why internet services (E-mail, WWW, FTP, …) are some of the non-voice most widespread ones until now (but only in the computer users-community), because they are easy and intuitive to handle, people receive their messages on their network server even if their terminal is off, and they accelerate a lot the exchange of messages, files and the dissemination of all types of information. However, non-computer users also would like to exchange these kinds of information, like messages, data (e.g., generated by a digital measurement device) or images (photos or films) anywhere and anytime, but they cannot indeed. In the mobile communications market, apart from pricing, these problems aggravate, owing to the size and weight of terminals, other ergonomic reasons, power consumption, and nowadays unsuitability of operating systems, among other reasons.

MBS are expected to support the simultaneous provision of several services to single or multiple users, over the same platform. Owing to the diversity of characteristics of the services to be supported, different requirements arise for resource usage, and service components access by various applications. Thus, each application (supported by these services) has access to various service components. The amount of resources that have to be available in each cell depends on the mixture of applications being supported, and also on the total number of users.

In this chapter, the available data about mobile broadband services/applications classification is put together and their characterisation parameters are identified, enabling some insight into new approaches for performance analysis in MBS. Because of the sensitivity of MBS load to application usage and to other parameters (e.g., average duration, service components characteristics and terminal mobility), an accurate identification of its deployment scenarios is needed, it being of crucial importance for cellular planning purposes. These data will be essential for multi-service traffic analysis and engineering purposes, it being the main motivation for the realisation of this study.

The usage of each application, i.e., the percentage of connections of a given application relatively to the total number of applications, is one of the most important aspects to be determined, there being nowadays, however, few forecast results available for mobile communications. The RACE-TITAN project has already done some estimations for narrow-, wide- and broadband applications in the residential market of fixed networks [StMu95], [OZSI96], as well as ETSI-RES [ETSI97], the UMTS Forum [UMTS99] and the RACE-MBS project [RoSc94] have also presented some forecasts for future mobile broadband systems. However, this first approach is somehow limited by the lack of actual data for the usage of each application as well as for the stochastic characterisation of duration. Further work is needed when the data becomes available, but by now one uses the estimations already available, and, in some cases, some values are proposed (in order to enable a first approach to the cellular planning of MBS).

Because the MBS concept is not yet completely defined, and the boundaries in data rates, operation scenarios, and mobility can be a little bit dispersed, it is important to clarify the concepts and their evolution. Under RACE initiatives in mobile communication systems, a first definition of MBS and related systems was presented, where it was assumed that UMTS supports data rates up to 2 Mb/s in every mobility scenario, Fig. 2.1 [Fern95], [CoPr97]. However, with the standardisation of UMTS, this concept evolved, and the current MBS/UMTS boundary is the one presented in Fig. 2.2, [UMTS98], [BuCN99]. Besides, the concept of GSM evolved itself and new modes are beginning to operate: HSCSD (High Speed Circuit Switched Data), GPRS (General Packet Radio Service) and EDGE (Enhanced Data Rates for GSM Evolution).

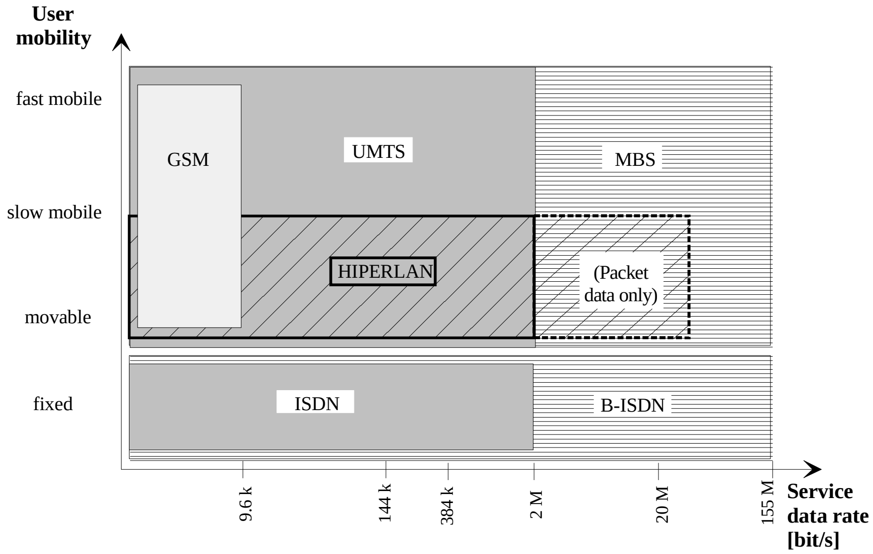


Fig. 2.1 – RACE UMTS/MBS boundary.

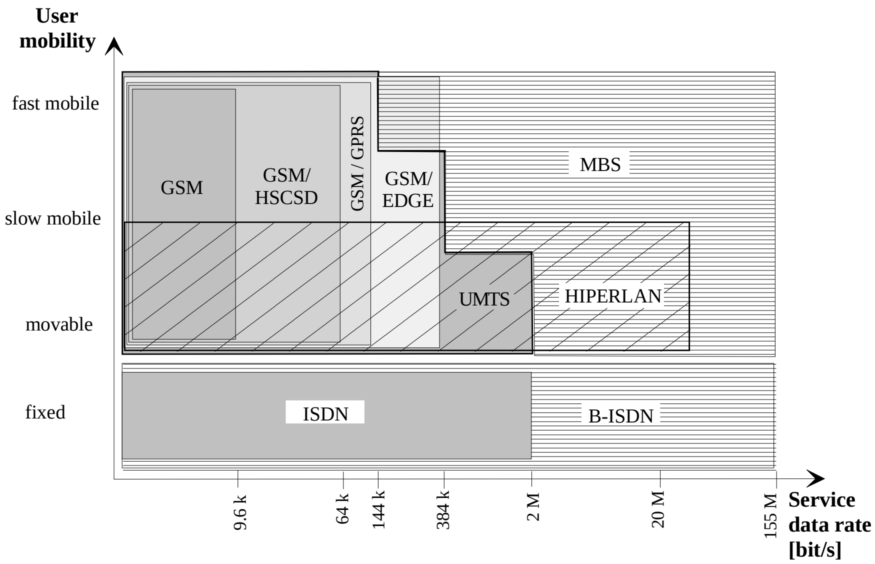


Fig. 2.2 – UMTS/MBS boundary after UMTS standardisation.

From Figs. 2.1 and 2.2, it is important to stress that, in terms of terminal mobility and supported data rates, MBS operation will begin where UMTS ends. However, because MBS is a micro-cellular system where propagation is mainly in LoS, a drawback is identified in its operation scenarios: it will not be developed in rural areas because it seems to be impracticable [SiBa99]. Although a staircase shape is also likely to appear at the upper data rates in MBS, corresponding to limitations in achievable data rates for higher mobility scenarios as well, one still considers that 155 Mb/s will be achieved. This inaccuracy is due to the lack of data to accurately define the boundary of these limitations for fast mobiles.

This part of the work results from a complex systematisation of information from multiple sources, which is the main motivation for the work associated with this chapter: to join the available data on broadband services / applications together, and to propose a new approach for the analysis of the performance of mobile broadband communication systems.

In Section 2.2, the ITU-T I.211 Recommendation [ITUT93a], on B-ISDN service aspects, is analysed, and a set of possible characterisation parameters is proposed. Then, the classification from ITU-T I.211 is generalised, in order to take also into account mobile broadband specific services and applications. It distinguishes between interactive and distribution services, i.e., between bi-directional and unidirectional ones, widely speaking. Finally, all listed services are briefly described, their correspondence to the supported applications is presented, and other types of classifications, different from the ITU-T I.211 one, are referred.

In Section 2.3, a taxonomy is proposed for characterisation parameters, which are divided into five different types: main ones, traffic and communications parameters, service components and operation environments as well. ATM terminology is being used, although is not necessary that future MBS will be based on it (from the point of view of applications-characterisation parameters). Each parameter is described in detail, and a set of tables is presented for each application, with a list of values for these parameters, and organised according to the classification of the ITU-T I.211 Recommendation.

In Section 2.4, the keystone perspectives for the definition of MBS deployment scenarios are described, and several references to previous work on applications usage for MBS, HIPERLAN and UMTS are given.

In Section 2.5, a proposal for eight MBS deployment scenarios is presented, partly based in the forecasts for narrow-, wide- and broadband applications from the RACE TITAN project. They are defined by the density factor, and also by the values for the usage of 26 applications, divided into low-MBS, wide- and broadband ones. These deployment scenarios will be very useful for multi-service traffic analysis purposes, because the usage of each application will be fed into the multi-service traffic evaluation procedure. Finally, conclusions are drawn in Section 2.6.

2.2. Broadband Services Classification

2.2.1. ITU-T I.211 Recommendation

2.2.1.1. Main Characteristics

In fixed B-ISDN, the classification of broadband services and applications is done according to the ITU-T I.211 Recommendation [ITUT93a]. An application is defined as a task that requires communication of one or more information streams, between two or more parties that are geographically separated, being characterised by the main attributes, and also by traffic and communications characteristics [Kwok95], [AwVl97]. A set of applications with similar characteristics, or even a single application, can be classified as a service if they have a common set of characteristics, the main attributes mentioned above, widely speaking. This is a general way to classify applications, and group them in classes (of services), as it is done in ITU-T I.211.

In this context, services are firstly classified obeying to their main characteristics, i.e.,

- intrinsic time dependency (time or non-time-based information);
- delivery requirements (real-time or non-real-time);
- directionality (unidirectional or bi-directional);
- symmetry of the communications (symmetric or asymmetric);
- interactivity;
- number of parties.

Communications can be either unidirectional or bi-directional. The bi-directional ones can be either symmetric or asymmetric. For example, a usual telephone call is a symmetric application, while internet browsing is clearly an asymmetric one (only commands are transmitted in the reverse link direction). An example of an unidirectional application is TV broadcasting.

It is also important to immediately distinguish the concepts of intrinsic time dependency and of delivery requirements. Time-based information must be presented at specific instants to convey its meaning, i.e., time is an integral part of the information to be communicated or the information has a time component; typical time-based types of information are video, audio and animation, while non-time based information includes images, graphics and text. An application can include both time-based and non-time based information. When an application involves multiple streams of information (possibly of different intrinsic time dependency), synchronisation among them is an important issue. Regarding the delivery requirements, an application can be defined either as real-time or non-real-time [Kwok95]. A real-time application is one that requires information delivery for immediate consumption; in contrast, non-real-time applications information is stored (perhaps temporarily) at the receiving points for later consumption. The former requires enough bandwidth, while the latter requires sufficient storage (and potentially bandwidth as well, if delivered at high speed). Examples are given in [Kwok95] that illustrate the difference; for example, a telephone conversation is considered a real-time application, while sending electronic mail is a non-real-time application. In other words, users who communicate via a real-time application must be present at the same time, whereas those who communicate via a non-real-time application can participate at different times.

In general, the communications requirements for supporting an application depend on both the intrinsic time dependency and delivery requirement of the application. The difference between the two is illustrated by examples, Table 2.1.

Table 2.1 – Examples of applications making the distinction between intrinsic time dependency and delivery requirements [Kowk95].

Examples of Applications	Real-time delivery	Non-real-time delivery
Time-based information	Video conferencing telephony	Video clip transfer
Non-time-based information	Image browsing	Electronic mail

Video conferencing and image browsing are examples of real-time applications, while sending video clips and electronic mail are non-real-time applications. In the case of image browsing, although the image is non-time-based information, a maximum response time constraint is imposed to ensure an interactive response for the user, and therefore it is considered a real-time application (with non-time-based information). On the other hand, sending video clips is a non-real-time application because, even though the information content is time-based, the video clip communication can be treated as a single file transfer (similar to electronic mail), since it is not being displayed in real-time during delivery.

2.2.1.2. Remaining Characterisation Parameters

According to the I. 211 Recommendation, different services are distinguished by the type of information that supports them, so that each of these types maps into a set of service components. So, besides the main characteristics and the traffic and communications requirements, one also identifies the service components (and their statistical behaviour). Another important aspect in the characterisation of applications is the operation environment, from which, in the mobile domain, terminal mobility (characterised by the distribution of velocity and its average value) is of key relevance. Hence, it has also to be focused in the analysis. Therefore, the remaining characterisation parameters are the following:

- traffic characteristics [AwVl97]:
  - traffic generation process, which can either be Poisson or Bernoulli;

- distribution of the duration, which is referred as exponentially distributed by many authors; however, according to the approach to multi-service traffic analysis presented in [AwVl97], it is enough to be i.i.d. (independent and identically distributed);
  - average duration;
  - transmission rate;
  - latency / delay;
- communication requirements [Kwok95]:
  - burstiness;
  - class of service;
  - error guarantees;
- service components:
  - distribution of the generation process – it can be either Poisson or Bernoulli;
  - distribution of duration – it is enough to be i.i.d.;
  - average duration;
  - the number of times each one is assessed;
- operation environments:
  - framework;
  - nature of applications – business or familiar / residential;
  - environment – indoors or outdoors;
  - mobility scenario;
  - service provision – public or private;
  - deployment scenario – set of services / applications operating simultaneously in the system.

2.2.1.3. Classification

According to ITU-T I.211, the services provided by B-ISDN can be classified as interactive or distribution services [HäAS95], Fig. 2.3.

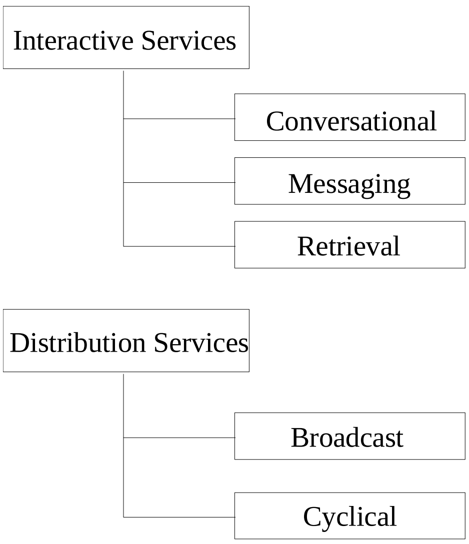


Fig. 2.3 – Classification of services and applications according to ITU-T I.211 recommendation [Stal99].

Interactive services are those in which there is a two-way exchange of information (other than control-signalling one) between two subscribers or between a subscriber and a service provider, including the following three different categories: conversational, messaging and retrieval services. Distribution services are the ones whose information transfer is primarily one-way, from service provider to B-ISDN subscriber, including broadcast services, where the user has no control over the presentation of the information, and cyclical services, which allow the user some measure of presentation control. A brief description of these categories follows:

- Conversational services provide the means for bi-directional dialogue communication with bi-directional, real-time (not store-and-forward), end-to-end information transfer between two users, or between a user and a service provider host [Stal99]. The flow of information may be bi-directional symmetric, bi-directional asymmetric, and in some specific cases (e.g. such as video surveillance), the flow of information may be unidirectional. The information is generated by the sending user or users, and is dedicated to one or more of the communication partners at the receiving site. These services support the general transfer of data specific to a given user application, i.e., the information is generated by, and exchanged between, users, not being 'public' one. This category encompasses a wide range of applications and data types, including moving pictures (video), data and document (e.g., facsimile), or a mix of them (including text, facsimile images, voice annotation, and/or video component). Examples are video-telephony, videoconference, video surveillance or exchange of data (file transfer in a distributed architecture of computer and storage systems, large volume or high speed transmission of measured values or control information, programme downloading, CAD/CAM/CAE (Computer Added Design / Engineering/ Manufacturing) and connection of LANs at different locations).
- Messaging services offer user-to-user communication between individual users via storage units with store and forward, mailbox, and/or message-handling (e.g., information editing, processing, and conversion) functions [Stal99]. In contrast to conversational services, messaging services are not in real-time. Hence, they place lesser demands on the network, and do not require that both users be available at the same time. Analogous narrowband services are X.400 and teletext. One new form of messaging service that could be supported by ISDN is video mail, analogous to today's electronic mail (text/graphic mail), and voice mail. Just as electronic mail replaces the mailing of a letter, so video mail replaces mailing a video-cassette. This may become one of the most powerful and useful forms of message communication. Similarly, a document mail service allows the transmission of mixed documents, containing text, graphics, voice, and/or video components. Examples of broadband messaging services are message handling services and mail services for moving pictures (films), high- resolution images and audio information.

- Retrieval services provide the user with the capability to retrieve information stored in information centres that is, in general, available for public use. This information is sent to the user on demand only, with the possibility of being retrieved on an individual basis, i.e., the time at which an information sequence is started is under the control of the user. Examples are broadband retrieval services for film, high-resolution image, audio information and archival information. An analogous narrowband service is videotex [Stal99]. Broadband videotex is an enhancement of the existing videotex system. The user would be able to select sound passages, high-resolution images of standard TV, and short video scenes, in addition to the current text and simplified graphics. Examples of broadband videotex services are retrieval of encyclopaedia entries, results of quality tests on consumer goods, computer-supported audio-visual entries and electronic mail-order of catalogue, and travel brochures with the option of placing a direct order or making a direct booking.
- Broadcast services provide a continuous flow of information, which is distributed from a central source to an unlimited number of authorised receivers connected to the network. Each user can access this flow of information but has no control over it; in particular, the user cannot control the starting time or order of the presentation of the broadcasted information. All users simply tap into the flow of information. Depending on the instant of time the user accesses, the information may not be presented from the beginning. The most common examples of this service are broadcast of television and audio programmes. Currently, broadcast television is available from network broadcast via radio waves and through cable television distribution systems, but with the capabilities planned for B-ISDN, this service can be integrated with the other telecommunications services; in addition, higher resolution can now be achieved, and it is anticipated that these higher quality services will also be available via B-ISDN. An example of a non-video service is an electronic newspaper broadcast service; this would allow the transmission of facsimile images of newspaper pages to subscribers who had paid for the service.
- Cyclical services allow distributing information from a central source to a large number of users. However, the information is provided as a sequence of information entities (e.g., frames) with cyclical repetition. So the user has the ability of individual access to the cyclical distributed information and can control start and order of presentation. Due to cyclical repetition, the information entities, selected by the user, will always be presented from the beginning. An analogous narrowband service is teletext, which is oriented primarily to the home market, with different set of pages offered on different channels (e.g., stock market reports, weather reports, news, leisure information, and recipes). With B-ISDN, an enhancement of teletext known as cabletext can be provided: whereas teletext uses only a small portion of an analogue TV channel, cable text would use a full digital broadband channel for cyclical transmission of pages with text,

images, and possible video and audio passages. As an electronic newspaper that uses public networks, or as an in-house information system for trade fairs, hotels, and hospitals, cabletext will provide low-cost access to timely and frequently requested information. One example of such service is full channel broadcast videography.

In this work, a kind of generalisation of these categories is done in order to take also into account mobile broadband specific services and applications (including the perspective of some work developed in the RACE-MBS project [AZDS94]). These applications will allow getting somewhere, feeling comfortable, being informed, having fun, doing e-commerce, providing car maintenance and travel assistance, having remote access to computers and databases, communicating in general, and supporting mobile emergency services.

This corresponds to add, e.g., the following applications to the Messaging Interactive ones: Mobile Property Surveillance, HDTV Outside Broadcast, Industrial Wireless LAN and Business Communications, Wireless LAN interconnection, as well as some mixed document (multimedia) mobile specific applications (Mobile Emergency Services, Mobile Repair Assistance, Mobile Tele-working and Freight and Fleet Management), and also Tourist Information, Urban Guidance and Vehicular Assistance in Travel to the Retrieval Interactive ones. The final objective is to allow a multi-service traffic analysis in MBS, according to the characteristics and parameters here identified.

2.2.2. Description of Services and Applications

The description of B-ISDN services and applications is organised according to ITU-T I.211 Recommendation. Besides the services and applications described in the Recommendation, one has introduced mobile broadband services and applications, namely mobile multimedia ones. A given application can be supported by different services, having as a consequence, different characteristics in terms of type of information (and service components that support them) and main characteristics. For example, Tele-education and E-commerce are applications from the Broadband Video-telephony, the Broadband Video-conference, the ISDN Video-conference and Broadband Videotex services.

Besides sound, which will not be relevant for MBS traffic analysis purposes (since it corresponds to very low data rate service components), the following types of information were identified in ITU-T I.211: moving pictures or video, document (multimedia), data, text, graphics and still images. The classification of services in terms of I. 211 Recommendation categories and types of information is done in Tables 2.2-2.6, where a short description is presented for each of the services. For example, Broadband Video-telephony (high definition) is a communication for the transfer of voice (sound), moving pictures, and video-scanned still images and documents (multimedia) between two locations (person-to-person).

Table 2.2 – Description of Interactive Services – Conversational.

Type of Information	**Examples of Broadband Services**	**Description**
Moving Pictures (Video) and Sound	Broadband Video-telephony (High definition)	Communication for the transfer of voice (sound), moving pictures, and video-scanned still images and documents (multimedia) between two locations (person-to-person).
	Broadband Video-conference	Multi-point broadband communication for the transfer of voice (sound), moving pictures and video-scanned still images and documents (multimedia) between two or more locations (person-to-group, group-to-group). Differs from the videophone in the nature of the equipment to be used and in the number of parties.
	ISDN-Video-conference	Multi-point narrowband communication for the transfer of voice (sound), moving pictures and video-scanned still images and multimedia) between two or more locations (person-to-group, group-to-group).
	Video Surveillance	Communication where the information delivery is limited to a specific intended subscriber. It can be uni- or bi-directional (depending on the existence of a reverse flow channel to control the camera orientation, zoom, etc) and its purpose is to transmit images and sound generated by surveillance cameras.
	Video/Audio Information Transmission Service	It has essentially the same capability of video-telephony, but higher-quality image may be required (e.g., a detailed engineering design may require higher resolution than ordinary human-to-human conversation).
Sound	Multiple Sound Programme Signals	Communication of sound programs and high quality audio (30 Hz - 7 kHz), and also the ability to transmit and receive audio signals with quality similar to the one offered by compact disks (20 Hz - 20 kHz).
Data	High-speed Unrestricted Information Transmission Service	Communication of unrestricted data, where the term *data* means arbitrary information whose structure is not visible to B-ISDN.
	High Volume File Transfer Service - FTP	Transmission of computer files.
	High-speed Tele-action	Large volume or high-speed transmission of measured values, remote data or control information.
Document (multimedia)	High-speed Tele-fax	Very high-resolution facsimile or the transfer of mixed documents, that might include text, facsimile images, voice, annotations and/or video components.
	High Resolution Image Communication Service	Exchange of large files or real time data with high-resolution images.
	Mixed Document Communications Service	Communications that may include text, facsimile, images, voice, annotations, and/or video components (it is commonly called multimedia) for the exchange of documents between users at workstations or user-to-user transfer of multimedia (mixed document).

Video-telephony simply means that the telephone equipment includes a video transmit and receive / display capability so that dial-up include both voice and life pictures. The first use of this service is likely to be the office environment [Stal99]. It can be used in any situation where the visual component of a connection is advantageous, including sales, consulting, instruction, negotiation, and the discussion of visual information such as reports, charts, advertising layouts, and so on.

Another example is Multi-point Video-conference. It is a multi-point narrowband communication for the transfer of voice (sound), moving pictures, and video-scanned still images (and multimedia) between two or more locations (person-to-group, group-to-group). Accordingly, the service must specify the interface and protocols to be used to assure compatible equipment between conference rooms. A Point-to-point Video-conference would additional features, such as facsimile and document transfer, and the use of special equipment such as electronic blackboards. A different sort of video-conference is a multi-point service. This would allow participants to tie together single video-phones in a conference connection, without leaving their work places, using a video-conference server within the network. Such system would support a small number (e.g., five) of simultaneous users. Either one participant would appear on all screens at a time, as managed by the Video-conference server, or a split-screen technique could be used.

Table 2.3 – Description of Interactive Services – Messaging.

Type of Information	**Examples of Broadband Services**	**Description**
Data	Electronic Mail/Paging	Point-to-point one-way connectionless transmission of data messages between users.
Video and Sound	Video/Image Mail	Replaces the mailing of a video-cassette.
Voice (sound)	Voice Mail	Replaces the mailing of an audio-cassette. A common feature in today's telephony systems.
Document	Multimedia Mail	Communication via e-mail of a mixed document (multimedia).

Table 2.4 – Description of Interactive Services – Retrieval.

Type of Information	**Examples of Broadband Services**	**Description**
Text, Data, Graphics, Sound, Still Image, Video	Broadband Videotex	Communication where the user would be able to select sound passages, high-resolution images of TV standard, and short video scenes, in addition to current text and simple graphics.
	Video Retrieval Service - on Demand (MPEG1*)	Communication that allows the user to order full-length MPEG1 films or videos from a film/video library facility.
	Video Retrieval Service - on Demand (MPEG2-4)	Communication that allows the user to order full-length MPEG2-4 films or videos from a film/video library facility.
	Video Browsing	Communication that allows the user to order full-length films or videos from a film/video library facility.
	High-resolution Image Retrieval Service	Retrieval of high-resolution non-MPEG still images.
	Data Retrieval Service	Retrieval of unrestricted data.
	Multimedia Retrieval Service	Applications for the retrieval of multimedia.

* MPEG – Moving Pictures Experts Group.

Table 2.5 – Description of Distribution Services – Broadcast.

Type of Information	Examples of Broadband Services	Description
Data	High Speed Unrestricted Digital Information Distribution Services	Distribution of data without any pre-specified format.
Text, graphics, still images	Document Distribution Service	Distribution of documents, either from a newspaper to subscribers who had paid for it, or from journalist anywhere to the office databases, where they can store their documents.
Moving pictures and sound	Broadband Video Information Distribution Service	Broadcast of advertising films, mini-documentaries or any TV or radio program.
Video	Existing Quality TV Distribution Service (NTSC[1], PAL[2], SECAM[3])	Broadcast of TV programs.
	Extended Quality TV Distribution Service (enhanced and high quality TV distribution services)	Broadcast of TV programs.
	HDTV Service (non-MPEG)	Broadcast of TV programs.
	MPEG-2-4 Services	Broadcast of TV programs in MPEG2-4.
	Pay TV (pay-per-view, pay-per-channel)	Broadcast of TV programs. In a pay-per-view or pay-per-channel basis.

[1] National Television System Committee.
[2] Phase Alternate Line
[3] *Sequentiel Couleur Avec Memoire*.

Table 2.6 – Description of Distribution Services – Cyclical.

Type of Information	Examples of Broadband Services	Description
Text, Graphics, Sound, Still images	Full Channel Broadcast Videography	Cyclical communication of text, graphics, sound, and still images.
	Cabletext (timely and frequently requested information)	Enhancement of teletext to B-ISDN.

The applications that are considered in this work are presented and extensively described in Appendix A. However, in Tables 2.7-2.11, one already establishes the correspondence between the services presented in Tables 2.2-2.6 and these applications. Even if an application appears again in a different context, i.e., in a service with a different type of information, it will not be described again, because an application is fundamentally characterised by its purpose, while the corresponding service is basically characterised by the type of information that supports it. Note that each application is numbered by the order of its first appearance, so that the reader can follow its correspondence to the respective services. The third column in Tables 2.7-2.11 indicates whether services are either Bi-directional (Bid) (either Symmetric (Sym) or Asymmetric (Asy)) or Unidirectional (Und).

Table 2.7 – Interactive Services – Conversational.

Type of Information	**Examples of Broadband Services**	**Directionality/ Symmetry**	**Applications**
Moving Pictures and Sound	Broadband Video-telephony (High definition)	Bid-Sym/Asy	1) Tele-education 2) E-commerce 3) Tele-advertising
	Broadband Videoconference	Bid-Sym/Asy	1) Tele-education 2) E-commerce 3) Tele-advertising
	ISDN-Videoconference	Bid-Sym/Asy	1) Tele-education 2) E-commerce 3) Tele-advertising
	Video Surveillance	Bid-Sym Und	4) Building Security 5) Traffic Monitoring 6) Mobile Video Surveillance
	Video/Audio Information Transmission Service	Bid-Sym/Asy	7) TV Signal Transfer 8) Video/Audio Dialogue 9) Mobile HDTV Outside Broadcast 10) Journalist Contribution of Informat.
Sound	Multiple Sound Programme Signals	Bid-Sym/Asy	11) High Quality Voice 12) Multi-lingual Commentary Channel 13) Multiple Programmes Channel
Data	High-speed Unrestricted Information Transmission Service	Bid-Sym/Asy	14) High Speed Data Transfer - LAN Interconnection - MAN Interconnection - Computer-computer Interconnection 15) Wireless LAN Interconnection 16) Transfer of Video Information 17) Transfer of Other Information Types 18) Still Image Transfer 19) Multi-rate Interactive Computer 20) Industrial Wireless LAN 21) CAD/CAM/CAE 22) Business Communications
	High Volume File Transfer Service - FTP	Bid-Sym/Asy	23) Data File Transfer (FTP) 24) Tele-software
	High Speed Tele-action	Bid-Asy	25) Real Time Control 26) Telemetry 27) Alarms 28) Remote Terminal
Document (multimedia)	High Speed Tele-fax	Bid-Sym/Asy	29) User-to-user Transfer of Text, Image, Drawing, etc.
	High Resolution Image Communication Service	Bid-Asy	30) Professional Images 31) Medical Images (X-ray and MRI-CAT* Scan) 32) Remote Games (Network) 33) Tele-robotics
	Mixed Document Communications Service	Bid-Sym/Asy	34) Web browsing 35) Multimedia Conference 36) Interactive Multimedia 37) *Real Time* Desktop Multimedia 38) Document Storage System
		Bid-Sym (mostly)	39) Mobile Emergency Services 40) Mobile Repair Assistance 41) Mobile Tele-working 42) Freight and Fleet Management 43) High Speed Trains

* MRI-CAT – Magnetic Resource Imaging - Computational Axial tomography.

Table 2.8 – Interactive Services – Messaging.

Type of Information	Examples of Broadband Services	Directionality/ Symmetry	Applications
Data	Electronic Mail/Paging	Bid-Asy	44) Paging 45) Visual E-mail (with attachments)
Video and Sound	Video/Image Mail	Bid-Asy Und	46) Audio / Video Mailbox
Voice (sound)	Voice Mail	Bid-Asy	47) Electronic Mailbox Service for Voice
Document	Multimedia Mail	Bid-Asy Und	48) Electronic Mailbox Service for Multimedia

Table 2.9 – Interactive Services – Retrieval.

Type of Information	Examples of Broadband Services	Directionality/ Symmetry	Applications
Text, Data, Graphics, Sound, Still Image, Moving Pictures	Broadband Videotex	Bid – Asy	49) Videotex Including Moving Pictures and Sound - Results for Quality Tests on Consumer Goods - Computer Supported Audio-visual Entries - Electronic Mail-order Catalogues and Travel Brochures - Retrieve of Encyclopaedia Entries 1) Tele-education 24) Tele-software 2) E-commerce 3) Tele-advertising 50) News Retrieval 51) Multimedia Library 52) Retrieve of Encyclopaedia Entries 53) Tourist Information
	Video Retrieval Service - on Demand (MPEG1)	Bid – Asy	54) Entertainment Purpose 55) Remote Educational and Training
	Video Retrieval Service - on Demand (MPEG2-4)	Bid – Asy	56) Entertainment Purpose 57) Remote Educational and Training
	Video Browsing	Bid – Asy	58) Entertainment or Business Purposes
	High-resolution Image Retrieval Service	Bid – Asy	59) Entertainment Purposes 60) Remote Educational and Training 61) Professional Image Communica-tions 62) Medical Image Communications (X-Ray, MRI-CAT Scan)
	Data Retrieval Service	Bid – Asy	24) Tele-software 63) Remote Educational and Training 64) Remote Database Access 65) Large Files Download 66) Mixed Media Documents 67) Remote Procedure Call
	Multimedia Retrieval Service	Bid – Asy	68) Urban Guidance (Public transport information) 69) Assistance in Travel (Vehicular) - City Guidance - Traffic Advice and Road Conditions

Table 2.10 – Distribution Services – Broadcast.

Type of Information	Examples of Broadband Services	Directionality/ Symmetry	Applications
Data	High Speed Unrestricted Digital Information Distribution Services	Und	70) Distribution of Unrestricted Data
Text, graphics, still images	Document Distribution Service	Bid – Asy Und	50) Electronic Newspaper 10) Electronic Publishing
Moving pictures and sound	Broadband Video Information Distribution Service	Und	71) Distribution of Video/Audio Signals
Video	Existing Quality TV Distribution Service (NTSC, PAL, SECAM)	Bid – Asy Und	72) TV Programme Distribution
	Extended Quality TV Distribution Service (enhanced and high quality TV distribution services)	Bi-d – Asy Und	72) TV Programme Distribution
	HDTV Service (non-MPEG)	Bid – Asy Und	72) TV Programme Distribution
	MPEG-2-4 Services	Bid – Asy Und	72) TV Programme Distribution
	Pay TV (pay-per-view, pay-per-channel)	Bid – Asy Und	72) TV Programme Distribution

Table 2.11 – Distribution Services – Cyclical.

Type of Information	Examples of Broadband Services	Directionality/ Symmetry	Applications
Text, Graphics, Sound, Still images	Full Channel Broadcast Videography	Und – only commands in the reverse channel	73) Remote Educational and Training 3) Tele-advertising 74) News distribution 24) Tele-software 10) E-newspaper
	Cabletext (timely and frequently requested information)	Und – only commands in the reverse channel	10) E-newspaper 75) In House Information Systems for Trade Fairs, Hotels and Hospitals

Besides the ITU-T I.211 Recommendation, there are other related types of classification allowing distinguish services/applications by some of their characteristics. The following are in the literature:

1. Main Service Classes in UMTS [UMTS98]

2. Purpose of Services/ Applications in UMTS [UMTS98]

3. Distinction between Business and Residential Services/Applications [Stal99]

The first two types of classification correspond to a context slightly different from broadband systems one – although belonging to the mobile communications domain. The last one corresponds to a broadband service classification, but not from the mobile communications domain. They are presented in Appendix B in order to illustrate other possible approaches for this classification.

2.3. Characterisation Parameters

2.3.1. Taxonomy

Although a different approach could be followed, e.g., distinguishing between functional and technical requirements, the following taxonomy for the classification of broadband services and applications is proposed, Table 2.12, different types of characteristics being identified. The objective is to obtain a first systematisation for the characteristics of services and applications, partly based on the previous considerations, and also to propose values for the range of variation of each of the parameters, allowing a better and clearer understanding of the involved complexity. Nevertheless, this is a proposal still opened to discussion. The main characteristics have already been described in Section 2.1; the remaining ones are addressed in what follows.

Table 2.12 – Characteristics of Broadband Services and Applications.

Characteristics	Parameters
Main	• Intrinsic time dependency: time-based (TB) or non-time-based (NTB) • Delivery requirements: real-time (RT) or non Real-time (NRT) • Directionality: unidirectional (Und) or bi-directional (Bid) • Symmetry of the connection: symmetric (Sym) or asymmetric (Asy), and the respective ratio between the uplink and the downlink • Interactivity: existence or not • Number of parties: one-to-one, one-to-many or multi-party
Traffic	• Generation process (Poisson or Bernoulli) and average generation rate • Distribution of the duration (i.i.d. – independent and identically distributed) • Average duration of connections • Transmission rate • Latency/delay
Communications	• Burstiness • Class of service (constant, variable, available or unspecified bit rate) • Bit Error Rate, BER
Service components	• Distribution of the generation process and generation rate (Poisson or Bernoulli) • Distribution of duration (e.g., i.i.d.) • Average duration • Number of times each service component is accessed

Operation environments	• Framework:
	  • Public – Business city centre, urban, road, public transports and commercial zones
	  • Private – *Emergency dedicated*, *TV broadcast dedicated, office dedicated* and *industry dedicated*
	• Nature of applications: business (BUS) or familiar (FAM)
	• Environment: indoors (Ind), outdoors (Outd) or trains (TRA)
	• Mobility scenario: static (ST), pedestrian (PD), urban (UB), main roads (MR) or highways (HW)
	• Service provision: public (PUB)/ private (PRIV)
	• Deployment scenario – it is defined by the set of services / applications operating simultaneously in the system, their usage and mobility scenarios

i. Traffic Characteristics

From the traffic characteristics, it is important to describe accurately the assumptions on latency/delay and channel hierarchy/bandwidth, i.e., bit rates. Absolute delay, or latency, is one of the key QoS performance parameters that must be satisfied by the broadband network [Kwok97].

To provide interactive response to viewers the response time between a user action and its effect should be less than 100 ms. To support network-based video games, a response time of 50 ms or less is required to support twitch actions. This puts an upper bound on the transmission time in each way of a link, which imposes a minimum upstream and downstream bandwidth requirement. Delay variation is another important QoS parameter, which, however, is not presented here. Real time video probably requires the most demanding delay variation constraint to minimise the buffering requirement for end-to-end synchronisation.

By definition, latency requirements only apply to real-time applications [Kwok97], thus there is no latency requirement for non-real time applications, although one identifies the associated delay to a good QoS. At the application layer, the latency requirement arises from the human response time for different real-time applications. It translates into end-to-end packet latency (absolute delay) at the network layer. Such packet latency is the sum of processing delay, packetisation delay, transmission delay, queuing delay and propagation delay. For example, for image browsing applications, a full-screen photo image of 3 MB has 300 kB after JPEG (Joint Photograph Experts Group) compression [Kwok97]. This requires about 24 Mb/s link (peak) transmission rate to satisfy the response time requirements (about 100 ms end-to-end from the application level) [Kwok95]. However, this can be decreased with reduced image size, or high compression ratio, or relaxed response time to less than 10 Mb/s. Specifying the average bandwidth requirement for a 'bursty' application is a challenge, because it varies according to the duration for which the average is taken. Furthermore, the values obtained vary widely across different users (such as the ones from image browsing), even for the same applications, because everyone has a unique usage pattern.

In the context of broadband services, each active subscriber may require about 10 Mb/s peak downstream bandwidth to support at least one MPEG-2 compressed stream that requires 4 to 6 Mb/s, plus additional bandwidth for downloading applications or graphics with acceptable latency (less than 100 ms). The minimum average bandwidth should be about 5 Mb/s to support at least one video stream, while the other applications may share the bandwidth among multiple users. In the upstream, a peak bandwidth of about 1-2 Mb/s should satisfy the latency requirement for a variety of interactive applications; of course, this 1-2 Mb/s bandwidth can be shared among multiple users. Again, a symmetric bandwidth of 10 Mb/s or higher should be available in the future to allow any user in the network to become an information source.

From the ITU-T I.211 Recommendation, one can conclude that, for CBR (constant bit rate) services, the circuit mode n x 64 kb/s (n = 1, 2, …) of the 64 kb/s based ISDN, and the bit rates of the 1.544 and 2.048 Mb/s hierarchies from Recommendation G.702 will be supported in B-ISDN, whereas other specific bit rates are now being resented for further study. For VBR (variable bit rate) services, a set of discrete bit rates is foreseen to be chosen, further study being needed yet.

The bandwidth requirement of an application (in each way) is typically specified in terms of peak and average bandwidth; for CBR applications, the peak and average bandwidth are the same. To support broadcast quality movies, a CBR MPEG-2 compressed stream requires 3 to 4 Mb/s; the bandwidth requirements can increase to 6 or even 9 Mb/s for real-time compression of live sports events, due to fast motion content. Since the amount of compressed information varies according to the content and instantaneous scene changes, compressed video is VBR in nature. The CBR MPEG-2 stream is created by traffic shaping, using a rate buffer and real-time adjustment of compression ratio (quantisation level) to maintain the buffer fullness without overflow or underflow.

On the one hand, the existing system of multiplexing and demultiplexing of information streams is referred as the plesiochronous network PDH [DuSm94], [HäAS95] (Plesiochronous Digital Hierarchy). In PDH, it is assumed that resources are divided in a hierarchy internationally accepted under the auspices of ITU-T, i.e., 2.048, 8.448, 34.368 and 139.264 Mb/s [ITUT93b], which is the European plesiochronous digital hierarchy, or TDM (time division multiplexing) carrier standard. In North America, such hierarchy is defined in a different way: 1.544, 6.312, 44.736 and 274.176 Mb/s. In both hierarchies the bit rates are multiples of a basic 64 kb/s bit rate (although the value are only approximated ones in the 1 544 kb/s hierarchy), the respective number of 64 kb/s channels being presented in Table 2.13.

Table 2.13 – Plesiochronous Digital Hierarchy [DuSm94]

Digital Hierarchy Level	**1544 kb/s based hierarchy**		**2048 kb/s based hierarchy**	
	No. channels	Bit rate [kb/s]	No. channels	Bit rate [kb/s]
1	24	1 544	32	2 048
2	96	6 312	132	8 448
3	672	44 736	537	34 368
4	4 032	274 176	2 176	139 264

On the other, SDH (Synchronous Digital Hierarchy) is a transport mechanism which can accommodate the existing network, but which is also capable of carrying ATM packets. It is important to note that, in order to isolate one 2 Mb/s stream in an ITU-T PDH multiplexer, it is necessary to completely demultiplex the hierarchy (from 139.264 Mb/s down to 2.048 Mb/s), and then multiplex it up again. For POTS (Plain Old Telephone System, a term used to describe the network prior to the development of ISDN), this clumsy structure did not cause much of a problem, but as various traffic types are linked on the network, there is a frequent need to be able to isolate a particular channel, or to insert a new one along the transmission path. However, the expense of having multiplexing equipment at each access point is prohibitive in terms of both complexity and cost. Thus, SDH not only offers clear advantages over the plesiochronous network (it is a cheaper, more convenient and more flexible approach [DuSm94]), but it also avoids the effects of obsolescence, something that is essential in any feasible replacement system. The basic ITU-T SDH signal is the synchronous transport module of level 1, or STM-1, and corresponds to a data rate of 155.52 Mb/s. The data rates of higher hierarchies are multiples of this value by a factor of $N = 4^n$ (n = 1, 2, …) leading to signals STM-N, Table 2.14.

Table 2.14 – Synchronous Signals Characterisation [DuSm94].

SDH Signal	SONET Signal	Bit rate [Mb/s]
STM-0	STS-1	51.84
STM-1	STS-3	155.52
STM-4	STS-12	622.08
STM-16	STS-48	2 488.32
STM-64	STS-192	9 953.28

The SONET (Synchronous Optical NETwork) specification defines the North American hierarchy of standardised digital data rates. The lowest level, referred as STS-1 (Synchronous Transport Signal level 1) corresponds to 51.84 Mb/s. This rate can be used to carry a single Level-3 PDH signal (DS-3 [Stal99]) or a group of lower-rate signals, such as DS-1, DS-2 or DS-1C (3.152 Mb/s) from the American PDH plus ITU-T rates (e.g., 2.048 Mb/s). Multiple STS-1 signals can be combined to form an STS-N signal. The signal is created by interleaving bytes from N STS-1 signals that are mutually synchronised [Stal99]. The ITU-T SDH STM-1 corresponds to SONET STS-3. The reason for the discrepancy is the following: STM-1 is the lowest-rate signal that can accommodate an ITU-T PDH level 4 signal (139.264 Mb/s).

Generally speaking, one can consider the data rates presented in Table 2.15 as the possible indicative ones for future mobile advanced services. Although 64 kb/s is the basis data rate of ISDN, it will not be supported by MBS. The 128 kb/s and 384 kb/s data rates are defined by UMTS, and can be extremely used in it, while the remaining ones are the ones defined by PDH, below 155.52 Mb/s, the higher data rate foreseen for MBS, and which is precisely the lowest rate of ITU-T SDH. Only applications with a data rate higher than 128 kb/s will be supported by MBS, because otherwise, according to the UMTS definition (Fig. 2.2) they can be supported by other existing systems.

Table 2.15 – Possible Data Rates for Mobile Advanced Services

Data rate [kb/s]	128	384	512	1544	2 048	3 152	6 312	8 448	34 368	44 736	139 264
Number of 64 kb/s channels	2	6	8	24	32	48	96	132	537	672	2 176
Number of 128 kb/s channels	1	3	4	12	16	24	48	66	268.5	336	1 088

Considering that reconfigurable systems (software radios) [BuCA99] will be in use by the time MBS operation will begin, the system will route applications for GSM, UMTS or MBS, according to their data rates and associated mobility, as defined in Fig. 2.2.

ii. Communications Characteristics

From the communications characteristics, the burstiness and the service classes are described here. Burstiness is defined as the ratio between the peak bit rate and the average bit rate [HäAS95], several types of communication being highly 'bursty' in nature. If this feature was adequately reflected in network design, namely in the stochastic characterisation of service components, considerable economising in network design should be achieved because of the associated statistical multiplexing gain. In the case of TV and HDTV distribution, the statistical multiplexing gain is hard to realise, because of the nature of the source signals. So, in the next tables burstiness is set to 1, corresponding to assuming codec smoothing.

Regarding service classes, and according to ITU-T terminology, the service traffic may be classified into two major categories [PCMF99]:

- **Isochronous traffic** – It is circuit switched to avoid time delay variations, and integrity is guaranteed in case of congestion;
- **Non-isochronous traffic** – it can be fragmented in independently delivered and switched packets (out of sequence also).

In any system, capacity is a scarce resource that is shared among its users. In ATM systems, the sharing method is arbitrated by the switch, in opposition to the random sharing method of Ethernet; an ATM switch shall know the needs of terminal nodes in order to be able of playing its role as service arbitrator. ATM terminal nodes request services in terms of destination(s), bit rate(s) and QoS parameters; if the request can be guaranteed without impact in the services already committed to, the switch will guarantee the request. In such a case, the node can expect to obtain the requested service – if it does not exceed the requests – until it changes the requested service level. The switch would deny access to new users if it would cause degradation on the already existing services.

To support broadband applications, and based on QoS parameters, three classes of services must be supported [Kwok95]:

- **Best-effort delivery –** It is being addressed by the ATM Forum with the ABR (available bit rate) class of service;
- **Real-time delivery of time-based information –** It is the CBR or VBR (constant or variable bit rate) with time requirements (bounds on delay variation). It can be supported by reserving peak bandwidth for each application over a QoS-based network;

- **Real-time delivery of non-time based information –** It is probably the most challenging class of service to support, because it is ‘bursty’ and has an absolute delay requirement. Such unpredictability poses difficulties in the allocation of the bandwidth that supports this class of service.

For non real-time information, only best effort delivery is necessary, and information should be stored at the receiver. Low data rates are used, except when non-used resources are available.

These more general service classes map into the following five specific ATM service classes:

- **Constant Bit Rate (CBR) –** The bit rate is constant during the connection; the switch serves the node at a rate that is consistent with the bit rate agreed during connection set-up. This service is well suited to conventional digital voice and video traffic; it is sometimes referred as *Circuit Emulation*.
- **Variable Bit Rate – Real Time (RT-VBR) –** The bit rate varies between zero and a peak value as agreed at connection set-up. In addition, the terminal advertises a sustained, or average cell rate and a maximum burst size, i.e., the maximum time during which the source generates cells at a peak rate. This service makes the use of switch capacity more effective, as it allows some statistical multiplexing to occur between variable bit rate sources. The delay is bounded, which makes this type of service especially suitable for compressed data traffic (as TCP/IP – Transmission Control Protocol / Internet Protocol).
- **Variable Bit Rate – Non Real Time (NRT-VBR) –** It is essentially VBR-RT, except that there is no guaranteed delay boundary. This type of service would be appropriated for data traffic, which has less stringent delay requirements, but still needing throughput guarantees, an example is LAN interconnection. A typical use is for connection-oriented traditional data traffic (such as X.25), and for connectionless traditional data traffic (such as TCP/IP).
- **Available Bit Rate (ABR) –** ABR is like VBR-NRT but with only a minimum bandwidth guarantee - although the cell loss probability will still be bounded. This service allows an ATM system to fill its channels to the maximum capacity when there are periods when CBR and VBR traffics are low. The source terminal can negotiate a minimum rate. The network will guarantee cell transfer at this minimum rate and provide additional capacity on a best effort basis. This service would typically be used to carry non time-critical computer data traffic, e.g., to feed a Web browser. For this application, users want an acceptable response time as a basic service, plus nothing else that the network can offer in addition.
- **Unspecified Bit Rate (UBR) –** is a best effort service without any performance guarantees. Typical use is for non-real time applications, such as file transfer, backup traffic and e-mail.

Examples are presented in Table 2.16, where the actual service classes are identified.

Table 2.16 – Service Classes.

Traffic Category	Service Classes	Example of Applications
ISO Isochronous	**CBR** Constant Bit Rate	Interactive Video (videoconferencing, interactive audio, video & audio distribution, video & audio retrieval)
	RT-VBR Real Time Variable Bit Rate	The ones from the CBR list from which the end-system can benefit from statistical multiplexing by sending at variable bit rate
NISO Non-Isochronous	**NRT-VBR** Non-Real-Time Variable Bit Rate	Response Time Critical Transaction Processing (airline reservations, banking transactions) Frame Relay Inter-working
	UBR Unspecified Bit Rate	Text/Data/Image Messaging and Distribution, Text/Data Retrieval (file transfer, browsing) Aggregate LAN, Remote Terminal (telnet)
	ABR Available Bit Rate	Supercomputer Application Distributed File Service

iii. Service Components

There is lack of information about the stochastic characterisation of applications in terms of the service components that will support them. In the RACE-MBS project there was a first attempt to characterise some applications [AZDS94]. Although the future broadband communications market will possibly support hundreds of applications simultaneously [Kwok95], the work performed in the RACE-MBS project has already identified some applications for the mobile domain [AZDS94], which are being considered as the starting point for the discussion to be presented here.

The final objective of this part of the study is to obtain a complete characterisation of the service components for each application (average duration, and respective distribution of connections and service components, number of times they are accessed and distribution of the connection generation and service components processes). However, it will not be done in the context of this chapter yet, but only later, after multi-service traffic models being defined.

Basic components are audio, video and data. Moreover, audio can be subdivided into voice (VOI) and high-fidelity audio (HIF), video can be supported by interactive video (IVI) and high definition video (HDV), whereas data can be low- (LOD), medium- (MED) or high-data rate (HID), Fig. 2.4.

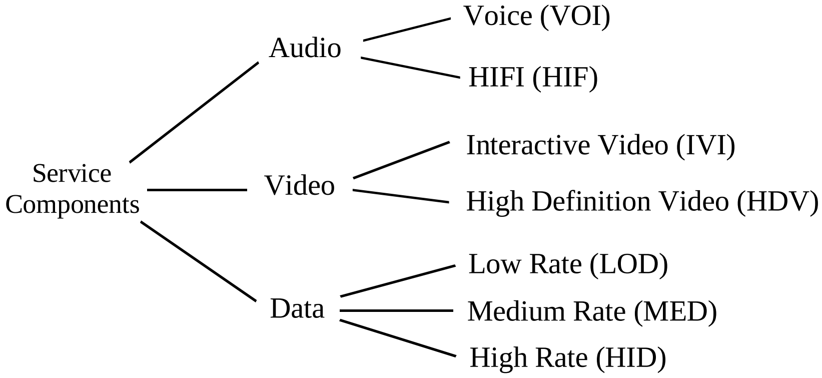


Fig. 2.4 – Basic service components.

From the types of information already identified in Section 2.2.2, the combinations from Table 2.17 are distinguished, where examples of the foreseen service components (audio, video and data) fully supporting them are given. There still is, however, a lot of flexibility for the choice of service components in this phase, and other hypothesis can be chosen for them, different from the ones already presented in [Carv98], [CaBr98] (e.g., data can be divided in real time and non-real time [BuCN99]). The choice of data rates associated with these components is also of interest. However, the lack of information does not allow going beyond this first description, postponing a deeper analysis to Chapter 5, where our own values will be proposed.

Table 2.17 – Service Components versus Types of Information.

		Service Components						
		Audio		Video		Data		
No.	Combinations of Types of Information	VOI	HIF	IVI	HDV	LOD	MED	HID
i	Moving Pictures and Sound	X	X	X	X			
ii	Document – Multimedia	X	X	X	X	X	X	X
iii	Sound	X	X					
iv	Data					X	X	X
v	Text, Data, Graphics, Still Images and Moving Pictures			X	X	X	X	X
vi	Text, Graphics, Sound and Still Images	X	X			X	X	X
vii	Video	X	X	X	X			

Another parameter of importance, not included in Tables by now, is the *mode of establishment*: it describes how a connection is established or released for each component service. For the on demand service, setup time and the blocking probability must be specified. Possible values are *on demand*, *reserved* and *permanent* [LoBe94]:

- **On demand –** The communication path is established as soon as possible in response to a user request effected by means of user-network signalling.
- **Reserved –** The communication path is established at a time specified in advance by the user by means of user-network signalling.
- **Permanent –** The communication path is established in response to an user request by means of an operational or administrative message.

iv. Operation environments

The framework of applications here defined is a mixture of the *purpose of applications* from UMTS, Table B.2 (Appendix B), and the *operating environment* from UMTS [UMTS99]. The following ones are identified for MBS, divided into public and private, although some users of private MBS can simultaneously use the public MBS:

- **Public** – Business City Centre, Urban, Road, Public Transportation and Commercial Zones.
- **Private** – *Emergency Dedicated (police, firemen, medical emergency), TV Broadcast Dedicated, Office Dedicated* and *Industry Dedicated*.

The possible nature of applications are Business (BUS) and Familiar (FAM), whereas the environments can be Indoors (Ind), Outdoors (Outd) and Trains (TRA). The scenarios of mobility are characterised by a triangular distribution for the velocity with average velocity, V_{av} =1, 10, 15 and 22.5 $m \cdot s^{-1}$, for the pedestrian (PD), urban (UB), main roads (MR) and highways (HW) scenarios, respectively. The service provision can be Public (PUB) or private (PRIV).

The deployment scenarios are defined by the set of services / applications operating simultaneously in the system. Although there are several hypotheses for this parameter, further analysed in the next section, the following were identified for MBS, also corresponding to geographical areas / zones of operation:

a) Business city centre
b) Urban residential areas
c) Primary roads
d) Trains
e) Commercial Zones
f) Offices
g) Industry
h) Home

The services in the last four scenarios (e-f) can also be supported by a Wireless LAN, e.g., HIPERLAN, whereas the others (a-d) can only be supported by mobile communication systems (and only if terminal mobility is considered).

2.3.2. Parameters Evaluation

The main parameters are presented in Table 2.18 for a sub-set of 21 applications (the ones with higher foreseen usage). However, there are two parameters of this category that are not presented in this Table: interactivity and number of parties. Regarding the interactivity, every application in this set is interactive (even TV Programme Distribution, considered here already with a return channel). For the number of parties, conversational and messaging interactive services are ‘one-to-one’ communications, except Video-conference, which is ‘one-to-many’. Retrieval interactive services are ‘one-to-one’ communications, whereas distribution services are ‘one-to-many’ communications.

Table 2.18 – Classification of Services and Applications in terms of Categories and Types of Information.

Service Hierarchies	Type of Information	Examples of Broadband Services	Examples of Applications	Main parameters			
				Intrinsic time dependency	Delivery requirements	Direc-tionality	Symmetry/ Asymm.
Interactive, Conversa-tional	Moving Pictures and Sound	HD Video-telephony	1. Tele-education	TB	RT	Bid	Sym/Asy
		ISDN-Videoconference	2. Tele-advertising				Asy
		Video Surveillance	3. Mobile Video Surveillance				
		Video/Audio Information Transmission Service	4. HDTV Outside Broadcast				
	Data	High-speed Unrestricted Information Tx. Service	5. Wireless LAN Interconnection		NRT/RT		
		High Volume File Transfer Service - FTP	6. Data File Transfer (FTP)	NTB	RT		
	Document (multimedia)	High Resolution Image Communication Service	7. Professional Images	TB/NTB	RT		
		Mixed Document Communications Service	8. Desktop Multimedia	TB	RT		
			9. Mobile Emergency Services				Sym
			10. Mobile Repair Assistance				
			11. Mobile Tele-working				
			12. Freight and Fleet Managmt.				
Interactive, Messaging	Mixed Document	Multimedia Mail	13. Electronic mailbox Service for Multimedia	TB	NRT	Bid	Asy
Interactive, Retrieval	Text, Data, Graphics, sound, Still Images, Moving Pictures	Broadband Videotex	14. E-commerce	TB	RT	Bid	Asy
			15. Multimedia Library				
			16. Tourist Information	NTB			
		Data Retrieval Service	17. Remote Procedure Call		NRT/RT		
		Multimedia Retrieval Service	18. Urban Guidance	TB			
			19. Assistance in Travel				
Distribution, Broadcast	Video	MPEG2-4	20. TV Programme Distribution	TB	RT	Bid	Asy
Distribution, Cyclical	Text, Graphics, Sound and Still Images	Full Channel Broadcast Videography	21. E-newspaper	TB	NRT	Bid	Asy

Considering the same set of 21 applications, one presents in Table 2.19 values for the traffic and communications parameters, as well as for the operation environments. In this Table, the applications are now organised by increasing order of foreseen approximated data rates. A complete list of the main, the traffic, and the communications parameters for the services / applications under analysis in this thesis is presented in Appendixes C, D and E, respectively. The values of parameters for the service components are not presented yet because of the lack of available data in the literature, and further work is needed, our contribution being presented later, in Chapter 5. The operation environments parameters for all applications are presented in Appendix F.

Table 2. 19 – Traffic, Communications and Operation Environment Parameters.

Applications	Traffic characteristics			Communications characteristics			Operation environments			
	Data Rate [kb/s]	Average duration [min]	Latency/ delay [ms]	Burstiness	Service class	BER	Nature	Environ-ment	Mobility Scenario	Service Provi-sion
Low-MBS										
ISDN Videoconference	384	30-45	200	1-5	ISO&CBR/ RT-VBR	10^{-6}	BUS/ FAM	Ind, Outd	St / H	PUB
Data File Transfer (FTP)	384	few secs.	1000	1-50	NISO& CBR				All	PUB/ PRIV
Desktop Multimedia (Web browsing)	384	1-10	NRT	1-20	ISO& RT-VBR					
Broadband Videotex (E-commerce)	384	-	500	1-20	ISO& RT-VBR					
Wideband										
E-mailbox for Multimedia	1 500	0.1-3	5 min	1-20	NISO& UBR	10^{-6}	BUS/ FAM	Ind, Outd	All	PUB/ PRIV
Remote Procedure Call	1 500	-	-	1-50	NISO& ABR	10^{-6}-10^{-4}				
HD Video-telephony	2 000	3	200	1-5	ISO&CBR/ RT-VBR	10^{-6}				PUB
Mobile Tele-working	2 000	15-25	500	1-20	ISO/CBR (VBR)				MR/H	
Assistance in Travel	2 000	20-180	500	1-5	ISO&CBR/ RT-VBR				All	
Urban Guidance	2 000	5-10	500	1-5	ISO&CBR/ RT-VBR					
Mobile Video Surveillance	2 000	120	200	1-5	ISO&CBR/ RT-VBR		BUS	Ind, Outd		PUB/ PRIV
Tourist information	2 000	15	500	1-20	ISO& RT-VBR		BUS/ FAM	Ind, Outd		
E-newspaper	2 000	20	500	1-5	ISO& CBR					
Broadband										
Freight and Fleet Management	2 200	2-5	200	1-5	ISO& CBR(VBR)	10^{-6}	BUS	Outd	St/URB/ MR/H	PUB
Mobile Repair Assistance	2 400	20-40	200	1-5	ISO& CBR(VBR)				St / PED / URB	PUB/ PRIV
Multimedia Library	2 400	-	500	1-20	ISO&RT-VBR		BUS/ FAM	Ind, Outd	All	PUB/ PRIV
Mobile Emergency Services	2 800	20-45	200	1-5	ISO& CBR(VBR)		BUS	Outd	St/URB/ MR/H	
TV-programme (MPEG2-4)	8 000	90	500	1	ISO& CBR		BUS/ FAM	Ind, Outd	All	
Professional Images	10 000	6-20	1000	1-20	ISO& CBR(VBR)	10^{-6}	BUS	Ind, Outd		
HDTV Outside Broadcast	10 000	50	500	1-20	ISO& CBR	10^{-10}-10^{-9}				
Wireless LAN Interconnection	32 000	15	1000	1-50	NISO& UBR	10^{-6}		Ind, Outd	St/URB/ MR/H	

2.4. Keystone Perspectives for System Operation Environments

2.4.1 Introduction

As it was already mentioned, MBS will be deployed mainly in urban areas, to cover hotspots in the centre of large cities, main roads and highways; moreover, they will support several services simultaneously, over the same platform, for different, or even the same, user(s).

Depending on the mixture of applications being supported, and also on the total number of users, different values are going to be obtained for the system load, with consequences on the amount of resources that have to be available in each cell. Because of the sensitivity of system load to application parameters, e.g., average duration, service components being accessed and terminal mobility, an accurate identification of the deployment scenarios of such systems is needed, which is crucial for cellular planning and system capacity determination. The usage of each application, i.e., the percentage of connections of a given application relatively to the total number of every application, is one of the most important aspects to be determined.

In this work, one proposes eight deployment scenarios for MBS, as well as values for applications usage in each of them, this being the main motivation for the realisation of this part of the work. The values were obtained by combining the results available in the works mentioned earlier. They are merely an example of a mixture of applications that may exist in MBS; however, they will be very useful for multi-service traffic analysis purposes, since real data is not available yet in literature.

2.4.2. RACE-MBS Project Perspective

In the perspective of RACE-MBS project, mobile applications can be divided into movable, slow mobile and fast mobile, each of them having different associated data rates [RoSc94].

From the set in Tables 2.18 and 2.19, the fast mobile ones are:

- City Guidance
- Freight and Fleet Management
- Emergency
- Pictorial Data for Travel
- Public Transport Information
- Electronic Newspaper
- Traffic Advice
- HDTV Contribution
- Audio Visual Library
- Surveillance of Property

The ones with associated slow mobility (< 36 km/h) are

- Access to Banking Services
- Special Needs (health)
- Repair Assistance
- CAD Interconnection
- HD Videophone

whereas the movable ones are

- Tele-consultation
- Wireless LAN.

RACE-MBS has also identified user groups and estimated their market penetration:

A – Emergency professionals 70 %

B – Commuters	30 %
C – Mobile / On-call Professionals	50 %
D – Families / Tourists	20 %
E – Specialist Group – not related to other applications	-

The following five geographical areas have also been identified

- Primary roads
- City centre
- Residential areas
- Industrial areas
- Hotspots

Estimations have been made for mature MBS on the busy hour rate (BHR). The percentage of total potential users that are active during the busiest hour [RoSc94] are presented in Table 2.20. These values can be used as a basis for the definition of certain mixtures of services in a given deployment scenario.

Different notations were adopted for applications usage in the various sources [ETSI97], [UMTS98], [RoSc94]. In order to have a common notation some definitions follow.

The total number of application *j* subscribers during the busy hour, M_j, is given as a function of the penetration, P_j, by

$$M_j = P_j \cdot M_T, \tag{2.1}$$

where M_T is the total number of potential users.

The busy hour connection attempt (BHCA) for application *j*, $BHCA_j$, is given by the ratio between the total number of active connections, $(N_{conns})_j$, and the total number of subscribers using that application in the considered area, measured during the busy hour, i.e.,

$$BHCA_j = \frac{N_{conns\,j}}{M_j}. \tag{2.2}$$

From (2.1) and (2.2) the total number of active connections from application *j* is given by

$$N_{conns\,j} = BHCA_j \cdot M_j = BHCA_j \cdot P_j \cdot M_T. \tag{2.3}$$

The usage of application *j*, U_j, is defined by the percentage of each application use relatively to all applications usage, and can be obtained as a function of $BHCA_j$,

$$U_j = \frac{N_{conns\,j}}{\sum_i N_{conns\,i}} = \frac{BHCA_j \cdot P_j}{\sum_i BHCA_i \cdot P_i}, \tag{2.4}$$

where the sum is done for all applications operating in the considered deployment scenario.

Table 2.20 – Estimation of Active Users Busy Hour Rate for Mature MBS.

Application	User group	Primary Roads [%]	City Centre [%]	Residential Areas [%]	Industrial Areas [%]	Hotspots [%]	Application holding time
Emergency Services	A	0.3	0.5	0.02	0.05	0.002	45 min
Special needs	*	0.1	0.1	0.03	0.1	0.2	30 min
HD Videophone	B, C, D	3	4	1	3	5	3 min
Mobile office incl. LAN access	B, C	1	2	0.2	1	2	15 min
Repair assistance	C	0.05	0.05	0.02	0.05	0.001	30 min
Tele-consultation	C	0.1	0.1	0.02	0.1	0.1	30 min
City guidance incl. Road congestion info.	B, C, D	5	5	1	5	3	3 hrs. (primary roads) 20 min (other)
Public transport info.	B, C, D	0.1	1	0.3	1	2	2 min
Temp. surveillance (e.g., traffic)	A	0.05	0.1	0.05	0.1	0.005	2 hrs.
Fleet management	*	0.4	0.2	0.05	0.02	0.001	2 min
Tourist information	B, D	0.7	1	0.001	0.001	1	15 min
Multimedia library (incl. entertainment)	B, C, D	1	2	1	1	3	20 min
TV ENG	*	0.01	0.01	0.001	0.005	0.1	10 min
Population type		vehicular	vehicular	vehicular	vehicular	pedestrian	
Density factor (approx.)		300 per km	500 per km	20 per km	50 per km	2500 per hectare	
Basis for density calculation		6 lane road, 20 m each (high speed)	4 lane road, 8 m each (low speed)	2 lane road, 10 m each (larger vehicles)	2 lane road, 40 m each (larger vehicles)	1 person per 2mx 2m (rail staion, rush hour)	

The other measure for application *j* 'usage' of system resources, which is the busy hour rate, BHR_j, is given by the ratio between the total number of active connections from application *j* and the total number of potential users

$$BHR_j = \frac{N_{conns\,j}}{M_T} = \frac{N_{conns\,j} \cdot P_j}{M_j} . \tag{2.5}$$

From this, the following relation between BHR and BHCA holds for application *j*

$$BHR_j = BHCA_j \cdot P_j , \tag{2.6}$$

which leads to the following equation for the usage of application *j* as a function of the busy hour rate

$$U_j = \frac{BHR_j}{\sum_i BHR_i} , \tag{2.7}$$

where the sum is done for all applications operating in the considered deployment scenario.

These definitions allow to use data from each reference in a uniform manner.

2.4.3. ETSI-HIPERLAN Perspective

The following three deployment scenarios were identified for HIPERLAN [ETSI97]:

- Office
- Industry
- Studio.

In Table 2.21, the usage of applications deployed in the office scenario is presented, as well as their average data rate.

In the case of the industrial scenario, a different set of applications exists, values for usage and data rate being presented in Table 2.22.

The results for the scenario of a TV, radio or recording studio are presented in Table 2.23.

These values are also being used as a basis for the definition of certain ‘mixtures’ of services, in the cases of MBS deployment scenarios with movable or low mobility terminals.

Table 2.21 – Predicted Average Data Rate and Usage for HIPERLAN, Office Deployment Scenario.

Office Application	Link direction	Usage [%]	Average data rate [kb/s]
1. Video applications			
1.1. Multimedia Conference (large displays)	Uplink	1	1 500
	Downlink	1	7 500
1.2. General Video Conferencing	Uplink	3	750
	Downlink	3	2 250
1.3. Asymmetric Video	Uplink	1	750
	Downlink	1	128
2. Telephone	Uplink & Downlink	6	34
3. General networked computing applications			
3.1. Data Transmission	Uplink & Downlink	3	25 000
3.2. Document Retrieval	Uplink & Downlink	5	2
3.3. E-mail	Uplink & Downlink	10	50
3.4. Processing (Host 0.5 MIPS)	Uplink & Downlink	15	50
3.5. Processing (Host 5.0 MIPS)	Uplink & Downlink	15	300
3.6. Monochrome Laser Printing	Uplink & Downlink	5	128
4. Multimedia database	Uplink	8	10
	Downlink	2	100
5. Security and monitoring	Uplink	0.5	750
	Downlink	0.5	64
6. Internet and intranet browsing	Uplink	8	2.4
	Downlink	2	100
7. Tele-working	Uplink	5	100
	Downlink	5	500
	TOTAL	**100**	

Table 2.22 – Predicted Average Data Rate and Usage for HIPERLAN, Industrial Deployment Scenario.

Office Application	Link direction	Usage [%]	Average data rate [kb/s]
1. File transfer	Uplink & Downlink	2	2 000
2. Software transfer	Uplink & Downlink	1	400
3. Configuration data	Uplink & Downlink	1	600
4. Control data	Uplink	25	21 000
	Downlink	25	21 000
5. Alarms	Uplink & Downlink	1	20
6. Surveillance	Uplink & Downlink	3	14 000
7. Monitoring	Uplink & Downlink	20	500
8. Video multi-point monitoring	Uplink	10	750
	Downlink	10	2 250
9. High bandwidth video multi-point monitoring	Uplink	1	1 500
	Downlink	1	7 500
	TOTAL	**100**	

Table 2.23 – Predicted Average Data Rate and Usage for HIPERLAN, Studio Deployment Scenario.

Office Application	Link direction	Usage [%]	Average data rate [kb/s]
1. Audio distribution, 8 channels	Uplink & Downlink	10	3 070
2. High quality audio uplink, 1 stereo channel	Uplink	10	384
3. Telephone headsets, 10 lines	Uplink & Downlink	10	640
4. Radio microphone, 30 off	Uplink & Downlink	30	11 500
5. High quality video distribution, 8 channels	Downlink	30	12 000
6. High quality video uplink, 1 channel	Uplink	10	1 500
	TOTAL	**100**	

2.4.4. UMTS Perspective

The UMTS Forum has identified six operational environments [UMTS99], Table 2.24 (where the density of potential users per kilometre and the foreseen cell types are also identified). The user model assumes that no user occupies two operational environments at the same time. In [UMTS99], additional operating environments, such as aeronautical (telecommunications to subscribers who are passengers on board of a moving aircraft), vehicles with mobile stations (telecommunications to pedestrians subscribers in a bus or train), and all satellite environments are left out in this estimation.

It was assumed, at least initially, that services are deployed on a platform based on the existing DECT (Digital Enhanced Cordless Telecommunications) and GSM. UMTS capability will be higher than for GSM, and it also depends on service bit rates / classes and on the use of low / high mobility terminals. Table 2.25 presents the foreseen cell dimensions for each of the operating environments.

Table 2.24 – Density of Users in each of the Operating Environments and the Corresponding Cell Types.

Operational environments	Density of potential users/km^2	Cell type
1. City Business District – CBD (in building)	180 000	Micro/Pico
2. Suburban (in building or on street)	7 200	Macro
3. Home (in building)	380	Pico
4. Urban (pedestrian)	108 000	Macro/Micro
5. Urban (vehicular)	2 780	Macro/Micro
6. Rural in-& out-door	36	Macro

Table 2.25 – Cell Dimensions per Operating Environment.

Operational Environments	Sectors per base station	2005		2010	
		Cell radius [km]	Area of hexagon sectors [km^2]	Cell radius [km]	Area of hexagon sectors [km^2]
1. City Business District – CBD (in building)	3	0.075	0.005	0.075	0.005
2. Suburban (in building or on street)	3	3.0	7.79	2.0	3.46
3. Home (in building)	1	0.02	0.001	0.02	0.001
4. Urban (pedestrian)	3	0.7	0.424	0.6	0.312
5. Urban (vehicular)	3	0.7	0.424	0.6	0.312
6. Rural in-& out-door	3	8	55.43	8	55.4

By 2010 the cell radii will be on the limit, and further reduction may not be economically feasible. However, a system capability improvement is expected to satisfy further capacity requirements.

In Tables 2.26 and 2.27 UMTS penetration figures are presented for years 2005 and 2010 in each operating environment, and for each service class. The considered service classes are High Interactive Multimedia (MM), High MM, Medium MM, Switched Data, Simple Messaging and Speech; CBD stands for City Business District. These figures are based on extensive market research within Europe [UMTS99], and represent the fraction of the density of potential users given in Table 2.24.

Table 2.26 – UMTS Penetration Rates for the Year 2005.

Service class	CBD/Urban (in building)	Suburban (in building or on street)	Home (in building)	Urban (pedestrian)	Urban (vehicular)	Rural in-& out-door
High Interactive MM (128 kb/s)	0.01	0.005	0.005	0.005	0.005	0.005
High MM (2 Mb/s)	0.05	0.047	0.047	0.047	0.047	0.047
Medium MM (384 kb/s)	0.08	0.047	0.047	0.077	0.077	0.047
Switched Data (14 kb/s)	0.10	0.10	0.10	0.10	0.10	0.10
Simple Messaging (14 kb/s)	0.25	0.25	0.25	0.25	0.25	0.25
Speech (16 kb/s)	0.60	0.60	0.60	0.60	0.60	0.60

Table 2.27 – UMTS Penetration Rates for the Year 2010.

Service class	CBD/Urban (in building)	Suburban (in building or on street)	Home (in building)	Urban (pedestrian)	Urban (vehicular)	Rural in-& out-door
High Interactive MM (128 kb/s)	0.050	0.053	0.053	0.053	0.053	0.053
High MM (2 Mb/s)	0.180	0.180	0.180	0.180	0.180	0.180
Medium MM (384 kb/s)	0.180	0.180	0.180	0.180	0.180	0.180
Switched Data (14 kb/s)	0.100	0.100	0.100	0.100	0.100	0.100
Simple Messaging (14 kb/s)	0.400	0.400	0.400	0.400	0.400	0.400
Speech (16 kb/s)	0.750	0.750	0.750	0.750	0.750	0.750

However, it should be noted that the use of each service is not exclusive. Each penetration figure, P_j, refers to the penetration of this service j as a proportion of the total potential user base, i.e., it is the percentage of the total number of users who potentially can use the applications from this service. Since users can use more than one service, it is possible that the *total penetration rate* in an environment (across all services) exceeds 100 %, if a high proportion of users are using more than one service. The CBD environment is assumed to be the only one with offices, meaning that the penetration rate in the CBD area comes primarily from people in those offices.

Finally, it is worthwhile noting that, from the point of view presented in [UMTS99], only three operational environments are considered for the frequency requirement estimations, namely those that coexist on the highest traffic area:

- CBD / Urban (in building)
- Urban (pedestrian)
- Urban (vehicular)

To achieve the number of active users / connections it is necessary to know the BHCA [UMTS97], Table 2.28.

Table 2.28 – UMTS Busy Hour Connection Attempt.

Service class	2005			2010		
	CBD/Urban (in building)	Urban (pedestrian)	Urban (vehicular)	CBD/Urban (in building)	Urban (pedestrian)	Urban (vehicular)
High Interactive MM (128 kb/s)	0.12	0.06	0.004	0.24	0.12	0.008
High MM (2 Mb/s)	0.12	0.06	0.004	0.12	0.06	0.004
Medium MM (384 kb/s)	0.12	0.06	0.004	0.12	0.06	0.004
Switched Data (14 kb/s)	0.06	0.03	0.002	0.06	0.03	0.002
Simple Messaging (14 kb/s)	0.06	0.03	0.002	0.06	0.03	0.002
Speech (16 kb/s)	1.00	0.6	0.6	1.00	0.85	0.85

However, it is worthwhile noting that these traffic characteristics are hard to predict, mainly for MM type of services. New services will have different temporal characteristics, so that the relative spectrum balance between speech and other services varies through the day. Besides, different tariffs during the day will change traffic characteristics drastically.

Furthermore, the assumed BHCA for MM services have a lack of proper comparison material, due to the fact that similar charged services do not exist yet in public use today.

2.5. System Deployment Scenarios

2.5.1. RACE-TITAN Forecasts

It is still difficult the have a clear view for the deployment scenarios in MBS. However, as it is referred in Section 2.3.1, it is already possible to clearly distinguish the following deployment scenarios, Fig. 2.5.

a) Business City Centre – BCC (vehicular or pedestrian)
b) Urban Residential Areas (vehicular or pedestrian) – URB
c) Primary Roads – ROA
d) Trains – TRA
e) Commercial Zones – COM (airports, railway and bus stations, hospitals, commercial centres, university campus)
f) Offices – OFF (buildings)
g) Industry – IND (large factories plant)
h) Home – HOM

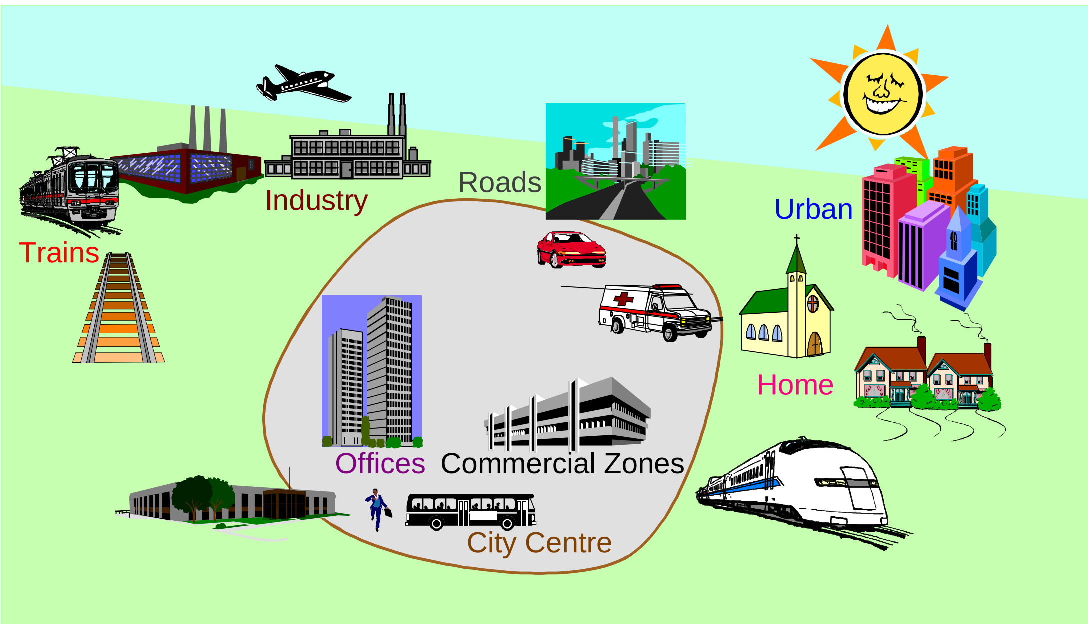


Fig. 2.5 – MBS deployment scenarios.

From the RACE-TITAN project [StMu95], [OZSI96], the following forecasts were extracted for the residential market demand in the years 2005 and 2010, defined as a percentage of the total residential market, Table 2.29. From these forecasts, one can assume that applications with data rates in the range [128, 384] kb/s will be supported by MBS; thus, they are designated by low-MBS ones. Consequently, one has considered that from ISDN applications (25 % of the total), 2/5 can be included as low-MBS applications (10 %), whereas the remaining 3/5, i.e., 15 %, are ISDN-data applications, Table 2.30.

Table 2.29 – RACE-TITAN Project Forecasts.

Demand as percentage of the residential market		2005	2010
ISDN	< 144 kb/s	20 %	25 %
Wideband	< 2 Mb/s	10%	15 %
Broadband	< 8 Mb/s	2 %	5 %

Table 2.30 – MBS Possible Scenario.

Demand as a percentage of the market		Residential	MBS
Voice	-	55 %	
ISDN-data	< 128 kb/s	15 %	
Low-MBS	[128,384] kb/s	10 %	~33 %
Wideband	[384, 2000] kb/s	15 %	50 %
Broadband	> 2 Mb/s	5 %	~17 %

Although TITAN has defined 8 Mb/s as an upper value for the data rate, one can assume that higher data rates can be achieved in MBS, up to 32 Mb/s in the examples presented in this work. Even higher data rates, up to 155 Mb/s, will be achieved in the future with the ABR (available bit rate) service class, i.e., a variable bit rate service class with a minimum bandwidth guarantee. It allows the ATM system to fill the resources to the maximum capacity when there are periods when CBR and VBR (constant / variable bit rate) traffics are low.

From the UMTS forecasts for 2005, one can also conclude that in the mobile market, from ISDN applications, 18 % are going to be ISDN-data ones (< 128 kb/s), whereas only around 2 % are going to be low-MBS applications ([128, 384] kb/s). This means that in 2010 the usage of these applications relatively to others in the mobile market (10%) will be five times larger than in 2005. However, as the demand is normalised to the total usage of whole applications, these quantities do not reflect the increase in the total number of users, which will possibly lead to an additional increase.

2.5.2. Proposal for Mobile Broadband Communications

From the data available for UMTS (applications with data rates from 128 kb/s up to 2 Mb/s), MBS and HIPERLAN (from this, one considered applications with data rates higher than 2 Mb/s), it is possible to perform an updated extrapolation for mobile broadband communications. Because the data from the RACE-TITAN project is for the residential market, some changes have to be done for the business and the mixed (half-business/half-residential) ones, Table 2.31.

Table 2.31 – Assumptions for the Various Markets.

Services	Data rates	Demand as a percentage of the market [%]					
	[kb/s]	Residential		Mixed		Business	
Voice	-	55		40		25	
ISDN-data	< 128	15		15		15	
Low-MBS	[128,384]	10	30	15	45	20	60
Wideband	[384, 2000]	15		20		25	
Broadband	> 2000	5		10		15	

One considers an increase of 15 % on the demand from the residential market to the mixed one and also from the mixed to the business market, corresponding to a high relative increase in the wideband and the broadband classes, and to a decrease in the traditional markets, mainly voice.

These forecasts for the demand correspond to the values for MBS-alone usage of Table 2.32. Values are also proposed for the industrial market, assuming that the usage of broadband applications is the same as in the business market, whereas the usage of low-MBS applications is lower, resulting in a higher usage for wideband ones. Again it does not reflect the difference in the number of potential users for the area considered, but only the 'mixture' of services operating simultaneously.

Table 2.32 – MBS Usage for each of the Markets.

MBS usage (percentage of the market)		Residential	Mixed	Business	Industrial
Low-MBS	[128,384] kb/s	33 %	33 %	33 %	22 %
Wideband	[384, 2000] kb/s	50 %	45 %	42 %	53 %
Broadband	> 2 Mb/s	17 %	22 %	25 %	25 %

One further assumes that there is a correspondence between deployment scenarios and envisaged markets, Table 2.33. The deployment scenarios that are suitable for further study in terms of multi-service traffic in outdoor scenarios, with considerable mobility of terminals, are the following: BCC, URB, ROA and COM. However, in order to have a wide view of the problem, values for the usage are proposed for all the eight deployment scenarios.

Table 2.33 – Correspondence between Deployment Scenarios and Envisaged Markets.

Deployment Scenario	Envisaged Market
BCC	Business
URB	Residential
ROA	Mixed
TRA	Mixed
COM	Mixed
OFF	Business
IND	Business
HOM	Residential

The correspondence between applications and these deployment scenarios have been presented in Appendix F. The set of applications considered for further study are the ones from Table 2.18-2.19, representing all the categories and main types of information from Tables 2.2-2.6. From these, a large number has already been presented as MBS applications in Table 2.20, namely

- Mobile Emergency Services
- HD Videotelephony
- Mobile Tele-working (as Mobile Office)
- Mobile Repair Assistance
- Assistance in Travel (as City Guidance including Road Congestion Info.)
- Urban Guidance (as Public Transport Info.)
- Mobile Video Surveillance
- Freight and Fleet Management
- Tourist Information (in the Broadband Videotex service)
- Multimedia Library (in the Broadband Videotex service)
- HDTV Outside Broadcast (as TV ENG)

whereas the following were not included on that table

- Wireless LAN Interconnection
- Professional images
- E-mailbox for Multimedia
- TV Programme (MPEG2)
- E-newspaper (in the Full Channel Broadcast Videography service)
- Remote Procedure Call.

Besides those applications, the following low-MBS were considered

- ISDN Videoconference (tele-advertising)
- Data file Transfer (put/get)
- Desktop multimedia

- Broadband Videotex (E-commerce)

The proposed values for the usage are presented in Table 2.34 for each application in the eight deployment scenarios, where the following five applications were also considered, but only for the industrial deployment scenario (extracted from the data available for the industrial deployment scenario in HIPERLAN)

- Configuration data (600 kb/s)
- Monitoring (500 kb/s)
- Video Multi-point Monitoring (2 Mb/s)
- High Bandwidth Video Multi-point Monitoring (8 Mb/s)
- Control Data

where the foreseen approximated data rates are the ones in parenthesis.

In Table 2.34, the envisaged approximated data rates are also introduced for all applications, in order to establish the service class associated with the application (low-MBS, wideband or broadband). The density factors for each of the scenarios in MBS are presented as well [RoSc94]. In this table, five industrial additional applications were introduced, allowing to properly characterise the industrial scenario.

The following assumptions have been done:

- For low-MBS applications the usage is 33 %, except in the industrial scenario where it is 22%. For the former 15 % are from Desktop Multimedia (because of Web Browsing), 7 % of Data Transfer, 7 % of Broadband Videotex for E-commerce (because of the increasing importance of this application), and the remaining 4 % of from ISDN Videoconference (e.g., for Tele-advertising, E-commerce and Tele-education). In the industrial deployment scenario, it was considered that 15 % of the usage is from Desktop Multimedia (because of Web Browsing) and 7 % from Data Transfer.
- For Wideband applications the usage varies between 42 % and 53 %. The data from the MBS project, Table 2.20, and from HIPERLAN, Tables 2.21 and 2.22, were used, except for E-mailbox for Multimedia, E-newspaper and Remote Procedure Call, since data was not available. The names of the deployment scenarios are approximately the same from Table 2.20, the data from hotspots having been considered for the Train and Commercial Zones deployment scenarios; the Home scenario was considered as being similar to the Urban one, with slight changes in the usage, except for the one of Tele-working (higher usage at home), Assistance in Travel and Urban Guidance (lower usage at home). In the Office and Industrial deployment scenarios one used data from HIPERLAN. An example follows on the way that parameters have been obtained for this class of service in the BCC scenario: one considers an usage of 3% of E-mailbox for Multimedia, 5 % for E-newspaper and 3 % of Remote Procedure Call; next, the sum of these values was

subtracted from the 42 % of usage of Wideband applications, a value of 31 % being obtained; finally, this usage was distributed by the remaining applications in the Wideband service class proportionally to the values for the usage extracted from Table 2.20, which are used as weights.

Table 2.34 – Proposal for Applications Usage in each of the Deployment Scenarios.

Applications Usage [%]	Data Rate [kb/s]	BCC	URB	ROA	TRA	COM	OFF	IND	HOM
Low-MBS									
ISDN Videoconference (Tele-advertising)	384	4	4	4	4	4	5.6		4
Data File Transfer (ftp)	384	7	7	7	7	7	5.6	7	7
Desktop Multimedia (Web browsing)	384	15	15	15	15	15	14.8	15	15
Broadband Videotex (E-commerce)	384	7	7	7	7	7	7		7
total		**33**	**33**	**33**	**33**	**33**	**33**	**22**	**33**
Wideband									
Monitoring	500	-	-	-	-	-	-	11	-
Configuration Data	600	-	-	-	-	-	-	1	-
E-mailbox for Multimedia	1 500	3	3	2	3	4	7.5	7.5	4
Remote Procedure Call	1 500	3	8	3	8	8	14	7.5	8
HD Videotelephony (Tele-education)	2 000	15	11	9.8	8	9.2	0.9	1	15
Mobile Tele-working	2 000	7.3	2.2	3.3	3.2	3.7	4.7	5	10
Assistance in Travel	2 000	3.6	11	16.3	4.8	5.5	3	-	1
Urban Guidance	2 000	1.1	3.3	3.3	3.2	3.7	1	-	0.5
Mobile Video Surveillance	2 000	0.4	0.5	0.2	-	0.4	0.5	15	0.5
Tourist information	2 000	3.6	1.0	2.1	4.8	5.5	1	-	1
E-newspaper	2 000	5	10	5	10	5	9.4	-	10
Video Multi-point Monitoring	2 000	-	-	-	-	-	-	5	-
total		**42**	**50**	**45**	**45**	**45**	**42**	**53**	**50**
Broadband									
Freight and Fleet Management	2 200	0.7	0.2	2.3	6	-	0.2	-	0.2
Mobile Repair Assistance	2 400	0.2	0.1	0.3	-	1	-	3	0.1
Multimedia Library	2 400	7.4	4.4	5.6	-	6	6	3	3.5
Mobile Emergency Services	2 800	1.8	0.1	1.6	-	-	-	-	0.1
TV-programme (MPEG2-4)	8 000	7.4	9	5	12	10.9	4.8	-	10
High BW Video Multi-point Monitoring	8 000	-	-	-	-	-	-	0.5	-
Professional images	10 000	2	1	1.5	2	2	4	2	1
HDTV Outside Broadcast	10 000	0.1	0.1	0.1	-	0.1	3	-	0.1
Control Data	21 000	-	-	-	-	-	-	12.5	-
Wireless LAN Interconnection	32 000	5.4	2.1	5.6	2	2	7	4	2
total		**25**	**17**	**22**	**22**	**22**	**25**	**25**	**17**
Density Factor (Number of users/m^2)		0.031	0.012	0.012	0.111	0.150	0.150	0.004	0.015

- For Broadband applications the methodology is similar to the one presented for Wideband applications. Data from Table 2.20 was used, except for Professional Images and TV-programme. Whereas professional images has a high demand in business like scenarios, as the office one, TV-programmes have a higher demand in the Residential and Mixed-type of markets, where entertainment is more likely to occur (e.g., in the urban, the home or commercial zones deployment scenarios).

In the industrial deployment scenario, from the applications used in other scenarios fewer applications are used, while some specific new ones were considered. Thus, the values for the usage of applications common to other scenarios were adapted from the office scenario, according to what one expects on what their relative importance will be in the industrial scenario.

Finally, it is worthwhile to note that the values presented for the maximum data rates are approximated ones, and refer to the link with higher bit rate (either the up- or the downlink). Asymmetric applications (e.g., FTP) will only need such high bit rates in one of the ways whereas, for bursty VBR applications (e.g., Desktop MM), the average bit rate can be much lower, leading to an improvement of the resource usage, a statistical multiplexing gain occurring.

2.6. Conclusions

In this chapter, the available data about target services and applications, as well as their characteristics, has been put together enabling some insight into new approaches for performance analysis in MBS, namely its foreseen deployment scenarios.

Based in the recent UMTS standardisation, one has started by identifying the new UMTS / MBS boundary in terms of data rates and user mobility. The associated staircase shape shows that 2 Mb/s is only being achieved by movable terminals in UMTS, whereas slow and fast mobile terminals are accessing to communications up to 384 and 144 kb/s, respectively.

Then, two different aspects of importance have been identified. On the one hand, a classification for services and applications has been proposed, based on the I.211 ITU-T Recommendation about *B-ISDN Services Aspects*. It distinguishes between interactive and distribution services, i.e., between bi-directional and unidirectional ones, widely speaking. On the other, a taxonomy for applications characterisation parameters has been proposed. In this context, the parameters are divided into five different types: main, traffic and communications parameters, and service components and operation environments as well.

The classes of conversational, messaging and retrieval have been identified for interactive services, whereas distribution services can be broadcast or cyclical. A generalisation of this classification has been done in order to take also into account mobile broadband services and applications. In another level of classification, the types of information have been analysed, allowing the set up of the service components supporting audio, data and video. Eight types of information have been identified: moving pictures, multimedia document, data, text, graphics, sound, still images and video, several combinations being used. A complete description of the identified services and applications has been presented, and other types of classification, used in UMTS or B-ISDN, have been referred as alternative examples for these hierarchies.

Besides the description of applications characterisation parameters, and of their range of variation, an evaluation of each of them has been presented. However, some lack of updated data has been noticed, at least on the characterisation of service components, and further work is needed.

Finally, the main system deployment scenarios have been identified, based on the available data for UMTS, B-ISDN and HIPERLAN, as well as on some data from RACE-TITAN and RACE-MBS projects. This allows the definition of target scenarios for MBS operation with a given mixture of applications, which will be very useful for the purpose of multi-service traffic analysis. The deployment scenarios that have been listed are: primary roads, business city centre, urban residential areas, trains, commercial zones, offices, industry and home. Moreover, they correspond to four types of market, i.e., the residential, the mixed, the business and the industrial ones, for which the usage of low-MBS ([128, 384] kb/s), wide- ([384, 2 000] kb/s) and broadband (data rates higher than 2 Mb/s) applications was defined.

The usage of broadband applications increases from the residential market (17%) to the business one (25%), corresponding to a decrease in the usage of wideband applications (from 50 % down to 42 %), and to a constant value for the usage of low-MBS (33%); slight differences exist from the business to the industrial markets. However, the actual number of users also depends on the density factor, which varies from 0.004 users/m^2 in industries to 0.150 users/m^2 in hotspots (e.g., commercial zones and offices). However, this first approach is somehow limited by the lack of actual data for the usage and for the stochastic characterisation of duration of each application, and for the respective service components they access to as well. Further work is needed to fully reach the objective of this chapter, when the data becomes available. By now, one uses the estimations already available, and in some cases, one proposes some values (in order to enable a first approach to the cellular planning of MBS).

Chapter 3

Comparison of the Frequency Re-use between the 40 and 60 GHz Bands

3.1. Introduction

Owing to the high transmission data rate, and due to the saturation of the spectrum at lower frequency bands, MBS is intended to operate at the millimetre waveband, offering improved performance in system capacity. In the perspective of RACE-MBS and ACTS-SAMBA projects, a frequency division access technique is considered, where the available spectrum is divided into a number of frequency groups, each one allocated to a set of BSs. Thus, owing to interference constraints, BSs in geographical proximity will, in general, have to use different frequency groups.

Because the characteristics of the bands prospectively allocated by ITU for these systems, the 40 and 60 GHz ones, are different from the UHF bands, the attenuation from atmospheric elements, namely rain and oxygen, has to be taken into account. Besides, the desired high capacity leads, in conjunction with the low values for the achievable transmitter power, to micro-cellular architectures, employing a large number of cells, with BSs deployed at relatively low heights above ground level (e.g., around 5 m, on lamp posts). As a consequence of all these peculiarities, it makes sense to compare the two bands from the point of view of cellular planning, i.e., both cell coverage and frequency re-use.

The following specific bands are being considered for the implementation of MBS: [39.5, 43.5] and [62, 66] GHz, with an interval of 2 GHz in between 1 GHz bands. Propagation characteristics are not the same in these two bands, with oxygen and rain presenting different values for their attenuation coefficients; moreover, these coefficients are not uniform within each of the bands. Since a larger ate-nuation leads to the possibility of reusing frequencies at a closer distance for approximately the same coverage (the attenuation is not substantial for short distances like the ones involved in cell coverage), the usage of one or the other frequency bands can have significant consequences on system capacity.

As propagation occurs essentially in LoS the shape of the cells and co-channel interference are determined, to a large extent, by the location of the surrounding objects, buildings in particular (in urban outdoors scenarios). Consequently, for cellular design purposes, an easy analytical treatment is only possible for environments with a regular structure as the linear and the 'Manhattan grid' (planar regular) geometries; a similar approach is taken in [StPr85] for the 60 GHz band, where only fixed values of the maximum coverage and re-use distances were considered, the variation of the frequency re-use parameters with these distances being disregarded. In these cases, it is important to establish the correspondence between, on the one hand, the maximum coverage and re-use distances, R and D, and, on the other, the interference-to-noise ratio, I/N, and the carrier-to-interference ratio, C/I, for both bands. From these, one can extract conclusions about the range of coverage distances that allows us to obtain minimum values for the co-channel re-use factor, and under which conditions it is preferable to use one band or the other. In general, two situations can be distinguished: the ideal and the interference-plus-noise limited ones. In the ideal one, only the co-channel interference affects the quality of communications, i.e., only the relation between the carrier and interference powers is of interest. However, in certain cases, thermal noise also significantly affects the communication, and it is necessary to have a model to characterise the system in the range between the noise limited situation and the interference limited one; the noise-limited situation occurs, e.g., if low values are considered for the transmitter power or a very demanding modulation scheme is used.

For urban irregular geometries, conclusions on the quantities of interest related to cellular design, such as achievable frequency re-use and system capacity, can be obtained from specific cellular layouts and environments (but typical, as much as possible). This can be done by using an interactive computer graphic tool to assist in the design procedure.

The remaining of the chapter is organised as follows. In Section 3.2 propagation characteristics at 40 and 60 GHz are analysed, namely the difference in the oxygen absorption between both bands.

In Section 3.3, the frequency re-use problem is analysed for the simplest situation, where only a pair of isolated co-channel cells is considered. First, the thermal noise is not considered, and the dependence of C/I on the co-channel re-use factor, r_{cc}, with R as a parameter, is analysed. Then, co-channel interference and thermal noise are considered simultaneously, and a model is presented to characterise the phenomenon. Results for r_{cc} as a function of R are finally obtained in order to clarify the fundamental differences between the two bands.

In Section 3.4, actual regular coverage geometries are considered, and the study presented in the previous Section, for only a pair of cells, is generalised for the linear and the 'Manhattan grid' geometries. The dependence of the carrier-to-noise-interference ratio on R is also examined for specific system parameters, and an analysis of the resulting interference-to-noise ratio and co-channel re-use factor is done.

In Section 3.5, micro-cellular design results are presented for a specific urban geometry by using an interactive planning tool. The main assumptions are described and results for urban coverage, frequency re-use and achieved system capacity are obtained; some final remarks are also made about the comparison of system capacity between the planar regular and the irregular urban geometries.

Conclusions are drawn at the end of the chapter, in Section 3.6.

3.2. Propagation Characteristics

In micro-cellular systems like the ones being considered in this work (100 m ≤ R ≤ 750 m), a LoS path between a BS and MSs is likely to exist, Ricean fading being considered instead of Rayleigh one [GiRL99]. However, as cell interferers still experience Rayleigh fading, such Rice/Rayleigh fading condition clearly presents an advantage from the carrier-to-interference ratio point of view [YaSh90], i.e., ignoring fading clearly is a worst case situation. As a result from this perspective, fading is not considered in what follows, except in the cellular planning tool used for irregular urban geometries, where a 8 dB fade margin was considered for the coverage.

At the millimetre waveband the average power received at a distance d from a transmitter can be found by considering an almost free space received power, plus the attenuation due to oxygen and rain [CoFr94]

$$\begin{aligned} P_{r\,[\mathrm{dBm}]}(d) = & -32.4 - 30 \cdot n + P_{t\,[\mathrm{dBm}]} + G_{t\,[\mathrm{dBi}]} + G_{r\,[\mathrm{dBi}]} - 10 \cdot n \cdot \log\left(d_{[\mathrm{m}]}\right) \\ & - \gamma_{r\,[\mathrm{dB/km}]}\, d_{[\mathrm{km}]} - \gamma_{o\,[\mathrm{dB/km}]}\, d_{[\mathrm{km}]} - 20 \cdot \log\left(f_{[\mathrm{GHz}]}\right) \end{aligned} \tag{3.1}$$

where: P_t is the transmitted power; G_t and G_r are the gains of the transmitting and receiving antennas, respectively; n is the average power decay exponent; γ_r is the rain absorption coefficient; γ_o is the oxygen attenuation coefficient; and f is the frequency. For an outdoor environment n is in the range [2.0, 2.5], a value of $n = 2.3$ being used [CoFr94].

There is only a small difference for the free space path loss between both bands, approximately equal to $20 \cdot \log(60/40) = 3.5$ dB; therefore, it is obvious that the difference between the two bands is not imposed by this parameter.

However, for the oxygen absorption, the difference is relevant. Using the formulas from ITU-R [ITUR94a] for $f < 57$ GHz and the formulas presented in [CoFr94] for $60 \le f \le 66$ GHz, one obtains the curves presented in Fig. 3.1, where the frequency scale is normalised in order to superimpose the 40 and 60 GHz bands in the same graph (-2 GHz corresponds then to the lower limit of each band, 39.5 or 62 GHz respectively, and 2 GHz to the upper one). In the 40 GHz band, γ_o is almost constant and negligible (less than 0.07 dB/km), whereas in the 60 GHz band it has to be considered, decreasing from 14 dB/km (at 62 GHz) down to approximately 1 dB/km (at 66 GHz). In the case of the higher frequency band, the additional path loss caused by the oxygen absorption is negligible for short coverage distances, but it can present high values, larger than 10 dB, for typical re-use distances.

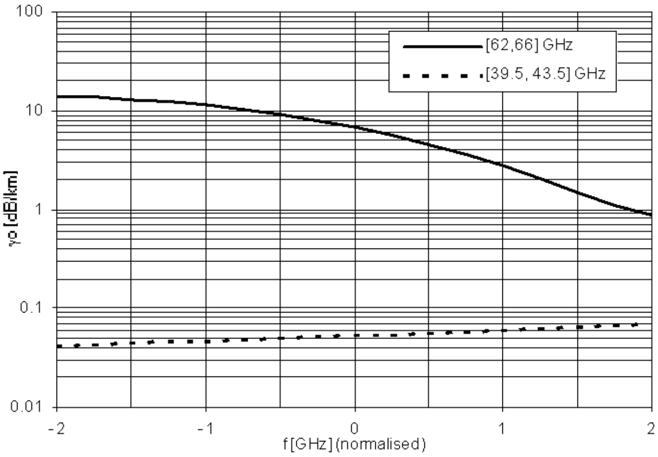


Fig. 3.1 – Oxygen attenuation coefficient as a function of normalised frequency for the 40 and 60 GHz bands (0 corresponds to the centre frequency of each band).

Rain attenuation has also to be considered, and the model presented by ITU-R [ITUR94b] has been used

$$\gamma_{r\,[\mathrm{dB/km}]}\,(f_{[\mathrm{GHz}]}, I_{r[\mathrm{mm/h}]}) = k(f)\;I_r^{\alpha(f)} \qquad (3.2)$$

where I_r is the rain intensity, and $k(f)$ and $\alpha(f)$ are parameters from the model. For a rain intensity of $I_r = 30$ mm/h, which occurs in Europe with a probability less than 0.03% (circa 2 h 38 m per year), the rain attenuation is approximately 8 dB/km in the 40 GHz band, and it is slightly increasing throughout the band; in the 60 GHz band, the behaviour is similar, with a value of the order of 12 dB/km. Nevertheless, the difference between the two bands is not as significant as the one concerning oxygen.

For each of the bands, one can compare the resulting total attenuation (the almost free space, oxygen and rain) as a function of frequency and for several distances, Figs. 3.2-3.3, and observe the differences. The total attenuation is almost constant with frequency at the 40 GHz band, and is lower than the one at 60 GHz. However, at 60 GHz the behaviour is different: the total attenuation decreases with frequency following the dependence of the oxygen attenuation.

Because of the reduced cell size in these outdoor micro-cellular environments, the delay spread is smaller than in conventional cellular systems, allowing the use of higher data rates [GiRL99]. For such high data rates, the envisaged slot duration is too short (of the order of tens of micro-seconds), and the impact of channel non-stationarity (e.g., Doppler effect) is not relevant [DiGu95].

Besides, the possible use of lens antennas [FeFe98] can improve cellular coverage, a quite uniform illumination being achieved throughout a cell. With these antennas, using the appropriate techniques (adjusting the height of antennas or tilting them downwards), channel time dispersion is kept under values that allow the transmission of high data rates with a low equalisation effort, whilst controlling interference.

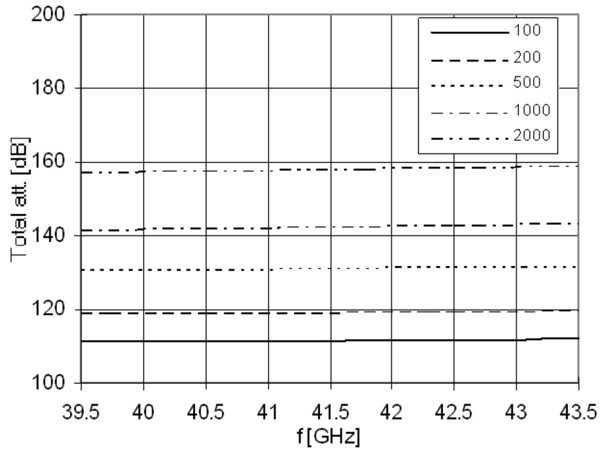


Fig. 3.2 – Total attenuation as a function of frequency, with the distance as a parameter (d = 100, …, 2000 m) for the 40 GHz band.

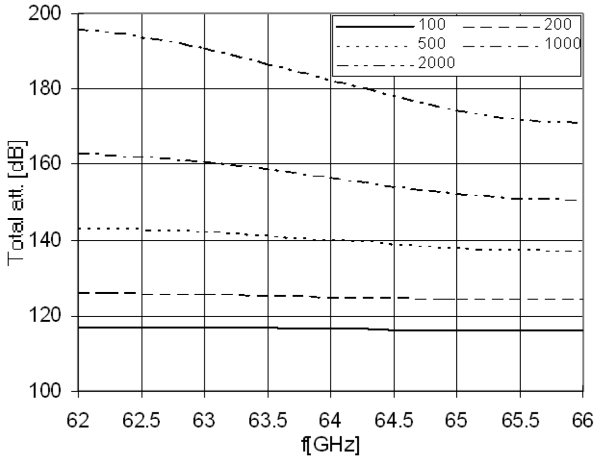


Fig. 3.3 – Total attenuation as a function of frequency, with the distance as a parameter (d = 100, …, 2000 m) for the 60 GHz band.

In [FeFe98], space diversity is presented as a solution to combat fading, two diversity lens antennas being used together with the maximal ratio combining technique. However, it is worthwhile noting that these techniques to combat time dispersion and fading are outside of the scope of this work, since one is interested in cellular planning.

3.3. Frequency Re-use Trade-offs

In the ideal situation, thermal noise is not considered and only the limitation from the carrier-to-interference ratio is of interest for the frequency re-use problem. However, in actual cases, the communication is also degraded by the presence of thermal noise, and a model is needed to take the simultaneous contribution of interference and thermal noise into account in the design. These two different aspects will be pursued below.

3.3.1. Analysis of the Carrier-to-Interference Ratio

It is well known that the attempt to re-use each frequency to a maximum in close cells is limited by the interference between co-channel cells. The simplest geometry to study the problem of frequency re-use in a cellular system is the one corresponding to a pair of cells, where only two co-channel cells exist with maximum coverage distance *R* and with their centres separated by a distance *D*, Fig. 3.4.

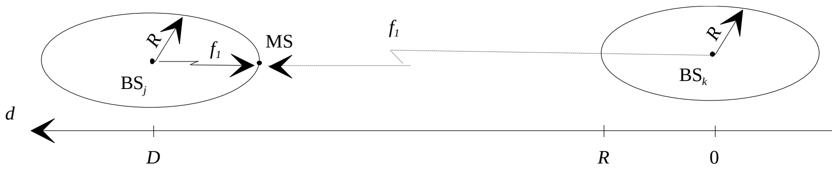


Fig. 3.4 – Geometry for a pair of interfering cells.

In a pair of cell, the study of the carrier-to-interference ratio at MSs and BS receivers is important because it has a direct influence on the co-channel re-use factor, r_{cc}, and on system capacity. It is easily obtained from (3.1) that

$$C/I_{[dB]} = \gamma_t \cdot (r_{cc} - 2) \cdot R + 10 \cdot n \cdot log(r_{cc} - 1) \qquad (3.3)$$

where γ_t represents the total attenuation by atmospheric elements, $\gamma_t = \gamma_o + \gamma_r$ and $r_{cc} = D/R$; the usual assumptions for *C/I* analysis have been considered (concerning transmitted power, antenna gains, and so on). In this ideal situation, where thermal noise is not considered, the dependence of *C/I* on r_{cc} has, on the one hand, a logarithmic term that depends on the average power decay exponent [Lee89], and, on the other hand, a linear term that depends on the oxygen and rain attenuations, hence on the coverage distance. As the same average power decay exponent is considered for both the 40 and 60 GHz bands [CoFr94], the difference between them is mainly due to different values of the oxygen and the rain attenuation coefficients.

At 40 GHz (where the oxygen absorption is negligible), if rain is not considered, Fig. 3.5, only the logarithmic term will remain, and a case of invariance to linear scaling of re-use and coverage distances will occur, since *C/I* will only depend on r_{cc} , presenting values of the order of 16 dB for r_{cc} = 6, both at 39.5 GHz and 43.5 GHz. These values are similar to those found in the UHF band.

However, in the other cases (40 GHz with rain, or 60 GHz – either with or without rain), the linear term is not negligible, and the conclusions are different. At 60 GHz, for a given r_{cc}, different values for *C/I* result from different values of *R*, and the larger *R* is the larger *C/I* becomes. As an example, for r_{cc} = 6 the values of *C/I* range from 18 up to 44 dB at 62 GHz, and from 16 up to 18 dB at 66 GHz, when *R* varies one order of magnitude from 50 to 500 m, Fig. 3.6. Conversely, it is worthwhile to note that for each r_{cc}, *C/I* varies linearly with *R* with slope $\gamma \cdot (r_{cc}$-2), as it can be observed from (3.3).

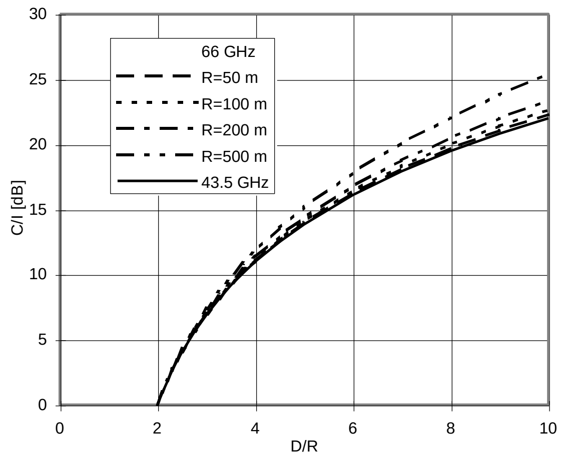


Fig. 3.5 – Carrier-to-interference ratio in terms of the co-channel re-use factor with *R* as a parameter, in the absence of rain for 43.5 and 66 GHz.

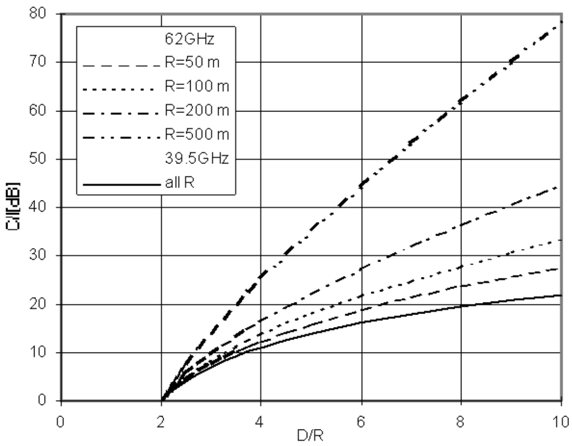


Fig. 3.6 – Carrier-to-interference ratio in terms of the co-channel re-use factor with *R* as a parameter, in the absence of rain for 39.5 and 62 GHz.

In the presence of rain, a larger value for the attenuation coefficient is obtained, and basically the previous behaviour at 60 GHz without rain, is observed for the two bands, Table 3.1. In the 60 GHz band, the main difference consists in a larger value for *C/I*; for $r_{cc} = 6$, it ranges from 21 up to 68 dB at 62 GHz [VeCo97] and from 19 up to 42 dB at 66 GHz, when *R* varies from 50 to 500 m.

Table 3.1 – Boundary Values for *C/I* in the Presence of Rain.

R [m]	*C/I* [dB]			
	f = 39.5 GHz	*f* = 43.5 GHz	*f* = 62 GHz	*f* = 66 GHz
50	17	18	21	19
500	33	35	68	42

At 40 GHz the previous behaviour changes and different curves exist for different coverage distances, since the attenuation coefficient is not negligible. The values of *C/I* range from 17 up to 33 dB at 39.5 GHz and from 18 up to 35 dB at 43.5 GHz, also when *R* varies from 50 to 500 m.

3.3.2. Influence of Noise

Although it is not usual in cellular systems, limitations on maximum cell coverage can be imposed by noise rather than traffic, if for example low values are considered for the transmitter power or a very demanding modulation scheme is used. Thus, depending on the maximum coverage distance and on the co-channel re-use factor, the system operates either interference limited or noise limited. For a proper system operation, the carrier-to-noise-interference ratio should exceed its minimum value, which depends on the maximum bit error rate, BER, and on the modulation type; this implies the consideration of the technologic parameters of the system in the analysis of its performance.

The BER at a receiver is a function of the received carrier and co-channel interference powers, as well as of the thermal noise or, more precisely, it depends on the carrier-to-noise-interference ratio. While the carrier power only depends on *R*, the interference power also depends on *D*; in order to obtain a given BER, there are several options for the choices of *D* and *R* in between two limit situations: on the one hand, the noise limited situation, where $D \to +\infty$, $I \to 0$, and only the thermal noise should be considered to compute the carrier-to-noise-interference ratio, and on the other, the interference limited situation, which occurs for low re-use distances, i.e., for $I >> N$, and where only co-channel interference should be considered.

Using the parameterisation of constant BER contours presented in [BrVe96], for a situation where the same equipment and data rates are used, an equation for the minimum carrier-to-noise-interference ratio was obtained

$$\left(\frac{C}{N+\alpha_c \cdot I}\right) = \left(\frac{C}{N}\right)_0 \qquad (3.4)$$

where $\alpha_c = (C/I)_0/(C/N)_0$ is a constant specific of each modulation, $(C/N)_0$ and $(C/I)_0$ being the minimum values for the carrier-to-noise and carrier-to-interference ratios in the absence of interference and noise, respectively, yielding the desired BER.

The calculation of the re-use and maximum coverage distances can be separated once the parameter $M = I/N$ is fixed. This parameter defines the co-channel interference power, and provides a uniform mechanism to control the cell size and the re-use distance. Two uncoupled equations can then be obtained, one for the coverage (i.e., noise limitation) and another for the *C/I* constraints

$$\left(\frac{C}{N}\right) = \left(\frac{C}{N}\right)_0 \cdot (1+\alpha_c \cdot M) \qquad (3.5)$$

$$\left(\frac{C}{I}\right) = \left(\frac{C}{N}\right)_0 \cdot \left(\alpha_c + M^{-1}\right). \tag{3.6}$$

From (3.6) one can observe that, for each value of M, a minimum value for the carrier-to-interference ratio is needed to guarantee the quality of communications. In the case of the pair of interfering cells, the following equation for M can be obtained, using (3.5) and considering the propagation model,

$$M = \frac{1}{\alpha_c} \cdot \left(\frac{P_t G_t G_r \lambda^2 10^{-\gamma_t \cdot R/10}}{N \left(4\pi\right)^2 R^{\gamma_t} \left(C/N\right)_0} - 1 \right). \tag{3.7}$$

$M(R)$ (in [dB]) is a decreasing function, having a vertical asymptote that can be obtained by solving (3.7) for $M = 0$, which corresponds to solving the equation $C/N = (C/N)_0$. Coverage distances near this asymptote are associated to a noise limited system operation.

Using (3.3) and (3.6) one can obtain the equation that relates D with R

$$10^{\gamma_t \left(r_{cc}-2\right) R/10} \cdot \left(r_{cc} - 1\right)^n = \left(\frac{C}{N}\right)_0 \left(\alpha_c + M^{-1}\right). \tag{3.8}$$

Note that the dependence of r_{cc} on R is established by replacing (3.7) in (3.8). The co-channel re-use factor at $R = 0$ can be obtained by noting that when $R \to 0$, $M \to +\infty$ and the exponential in (3.8) converges to 1

$$\left(r_{cc}\right)_{R=0} = \sqrt[n]{\left(\frac{C}{I}\right)_0} + 1. \tag{3.9}$$

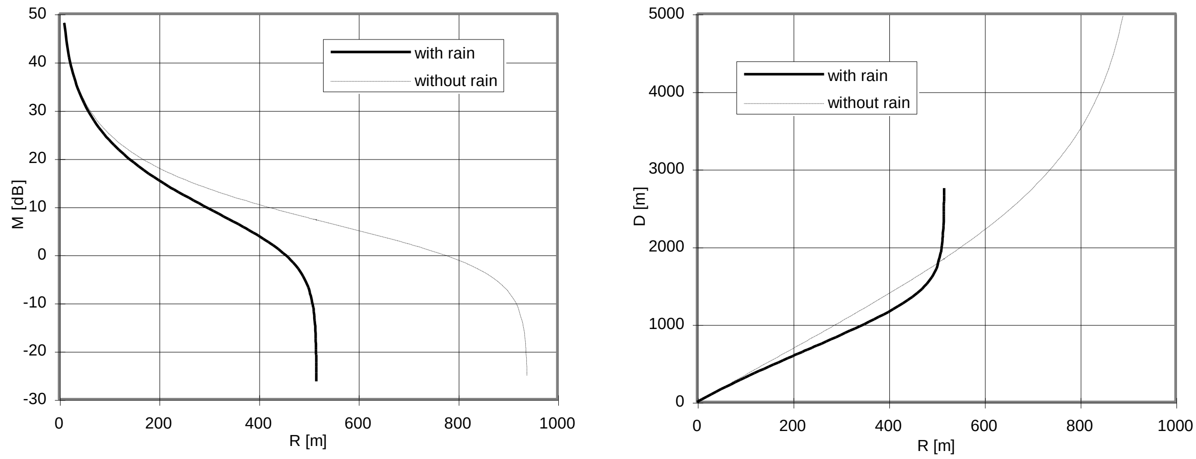
It depends only on the modulation type and the propagation exponent, and not on the specific attenuations of rain and oxygen.

Further analysing (3.8) in more detail, one also concludes that for the lowest values of γ_t, and low R, the exponential in the left hand is approximately equal to 1, and the solution for r_{cc} increases with R so that the polynomial term follows the left hand of the equation, where M^{-1} is increasing with R. This is the case for the 40 GHz band, if rain is not considered (e.g., γ_t = 0.04 dB/km at 39.5 GHz). However, for higher values of γ_t, r_{cc} has to decrease with R so that the polynomial term in the left hand of (3.8) compensates the fast increase of the exponential one, which is the case of the 60 GHz band (e.g., γ_t = 14.1 dB/km at 62 GHz, without rain). As an example, one can numerically observe that considering r_{cc} = 3.46, at 39.5 GHz, the exponential term varies from 1.0001 to 1.0010, when R varies from 10 to 100 m, while at 62 GHz the variation is from 1.049 to 1.610.

For the purpose of numerical evaluation, a typical configuration envisaged for MBS is considered [BrVe96] using a vehicle-mounted antenna, and with the following design parameters: transmitted power of 20 dBm, BS antenna gain of 20 dBi, MS antenna gain of 14 dBi, receiver noise figure of 6 dB, and noise power of -95 dBm. For a $BER_{max} = 10^{-3}$, the values of $(C/N)_0$ = 11 dB and

$(C/I)_0$ = 9 dB were obtained for the OQPSK (Offset Quadrature Phase Shift Keying) modulation by simulation [DiGF95], leading to α_c = -2 dB.

In a two-cell situation, Fig. 3.4, the worst case interference situation occurs when a BS receives the desired signal from a MS at its cell boundary, and the co-channel interference from MSs in co-channel cells placed at the boundary of those cells closest to that BS, or vice-versa, Fig. 3.4. Results for $M(R)$ and $D(R)$ are presented in Fig. 3.7 for f = 66 GHz, for both the cases of presence and absence of rain (I_r = 30 mm/h). One can see in Fig. 3.7 the vertical asymptotes in the presence and absence of rain (at 516 and 939 m, respectively), corresponding to the limitations in coverage imposed by thermal noise alone. The region $M >> 0$ dB corresponds to interference limited operation, while the noise limitation corresponds to $M << 0$ dB.



a) Interference-to-noise ratio

b) Re-use distance as a function of R.

Fig. 3.7 – Characteristics of interference and frequency re-use as a function of R at 66 GHz.

Since worst case situations should be considered in the design, for each value of R, the situation that yields the larger value for D is chosen (smaller re-use distances correspond to larger co-channel interference power). The worst case consists on absence of rain for all the range of cell coverage distances, except for values of R near the asymptote of the coverage with rain. From a practical point of view, only the values up to the intersection of the curves for the cases of absence and presence of rain are of interest, because beyond those values, in the presence of rain, system operation will be noise limited, and r_{cc} will increase rapidly with R. It is worthwhile to note that, although rain limits the maximum achievable coverage distance, it has a low influence for R < 200 m.

The co-channel re-use factor is then easily obtained by dividing D by R for the worst case situation, Fig. 3.8. The curve for f = 43.5 GHz is also presented, whose asymptotes are at 733 and 1451 m for the cases of presence and absence of rain, respectively. One also observes that $(r_{cc})_{R=0}$ is 3.46 at both bands, in agreement with (3.9). In this case, as only a pair of cells is considered, no restriction exists for r_{cc} being an integer or even number, and any value higher than or equal to the minimum can be chosen (e.g., in the cases of interest, at 66 GHz, r_{cc} slightly decreases from 3.46 to 3.40, at R = 200 m, and then increases up to 3.60 before the asymptote, while, at 43.5 GHz, it always increases and is in between 3.46 and 3.70, again before the asymptote).

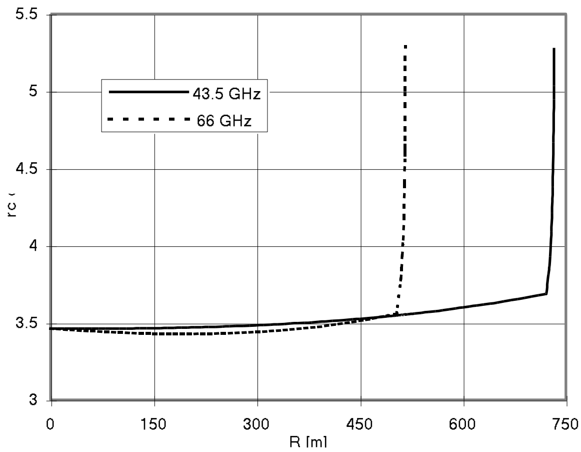


Fig. 3.8 – Co-channel re-use factor as a function of R at both bands.

The corresponding curves for $M(R)$ are presented in Fig. 3.9. The curves show a discontinuity when the worst case situation changes from absence to presence of rain. An increase in M corresponds to a decrease in the cell coverage; as an example, at 43.5 GHz, one obtains M = 29, 25 and 22 dB for R = 100, 150 and 200 m, respectively.

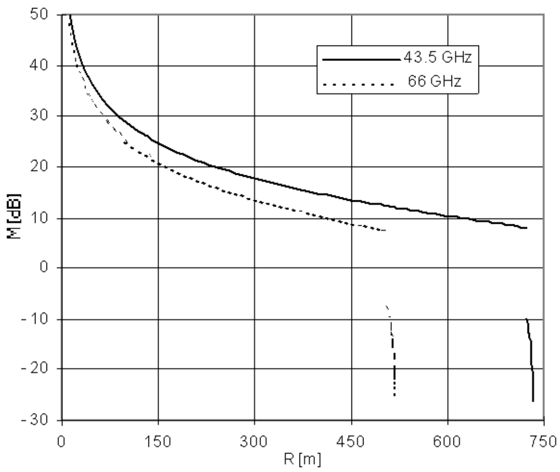


Fig. 3.9 – Interference-to-noise ratio factor as a function of R at both bands.

The difference between the values of M at both bands ($\Delta M = M_{43.5\text{GHz}} - M_{66\text{GHz}}$) is increasing with R, typical values being ΔM = 3.7, 3.8 and 3.9 dB for R = 100, 150 and 200 m, respectively, ΔM = 4.7 dB being the maximum difference, obtained for R = 504 m.

One concludes that the quality of communications depends both on the carrier-to-interference ratio and on thermal noise. There is only a slight difference between the 40 and 60 GHz bands owing to different values of the attenuations oxygen and rain, leading to a dependence on R of the carrier-to-interference ratio in all cases, except the one of the 40 GHz in the absence of rain. It results only on slightly lower values for the co-channel re-use factor in the 60 GHz band, and to higher values for the interference-to-noise ratio. However, larger coverage distances can be obtained at 43.5 GHz (720 m against 500 m, at 66 GHz). The cases of interest occur for the absence of rain in both bands.

3.4. Analysis of Regular Geometries

Cellular systems operating at the UHF band are modelled by hexagonal shaped cells, where co-channel interference in a cell is originated by surrounding co-cells, with an angular separation of 60º from one another [Lee89]. However, the consideration of such geometries is impossible in systems operating at millimetre wavebands because propagation is mainly in LoS, and the obstruction from buildings and other urban obstacles imposes limitations both on the propagation of co-channel interference and on the coverage of cells. Therefore, in these bands the feasible regular geometries are the linear and regular urban ('Manhattan grid') ones, which are analysed in this section from the point of view of frequency re-use. For such geometries, co-channel interference is originated only from co-cells at given directions, placed at regular distances, multiples of the re-use distance. Although the re-use distance can conceptually take any value, only the ones multiple of the cell *length*, L_c, allow that cells adjust to each other, without superpositions or lack of continuity.

3.4.1. Carrier-to-noise-interference Ratio

The linear coverage geometry consists of cells with total *length* of $L_c = 2R$ and re-use distance D, corresponding to the coverage of an indefinitely long street or highway, Fig. 3.10. The worst case situation for the received carrier at a BS occurs when the transmitting MS is at the boundary of the cell, at a distance R from the BS. There are interfering MSs at both sides of the cells, whose interference, also in the worst case, comes from MSs located at distances $mD–R$, $m=1, ..., T_i$, where T_i is the number of relevant tiers of interference.

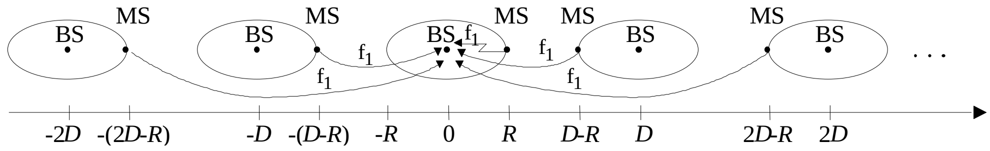


Fig. 3.10 – Linear coverage geometry.

For this geometry, by using (3.1), the following equation results for *C/I*

$$\left(\frac{C}{I}\right)_{dB} = \gamma_t \cdot R \cdot \left[T_i \left(r_{cc} \left(T_i + 1\right) - 2\right) - 1\right] + 10 \cdot n \cdot \left(2T_i - 1\right) \log\left(R\right) + 20 \cdot n \cdot \log\left(\prod_{m=1}^{T_i} \left(m \cdot r_{cc} - 1\right)\right). \quad (3.10)$$

Values approximately 3 dB below those of the case of only two cells are obtained; in the present situation, there are co-channel interfering sources from both sides of the cell, which explains the degradation.

A similar difference exists for the planar regular geometry: a regular urban structure with streets perpendicular to each other, Fig. 3.11, also commonly called Manhattan grid geometry. In this case, the cells, which form re-use patterns also with an associated re-use distance *D* and maximum coverage distance *R*, have four main lobes in the directions of orthogonal streets. There is no interference between cells from each pair of orthogonal avenues, except from the cell on the respective cross that is common to both avenues (e.g., cells 7, 3, 1, and 5 do not interfere with cells 6, 2, 4 and 8, due to the absence of LoS among them).

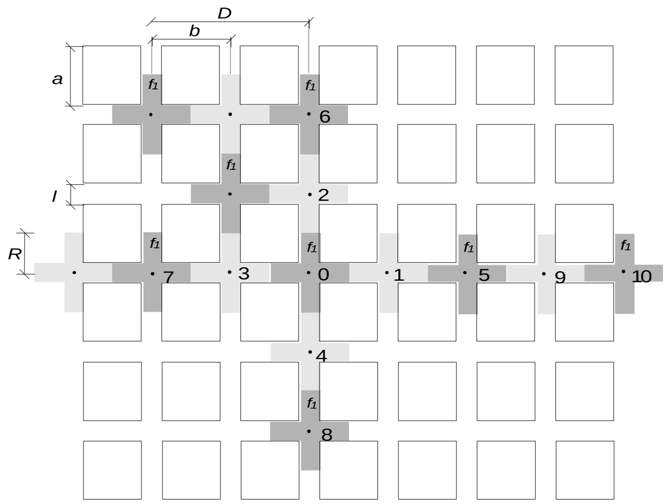


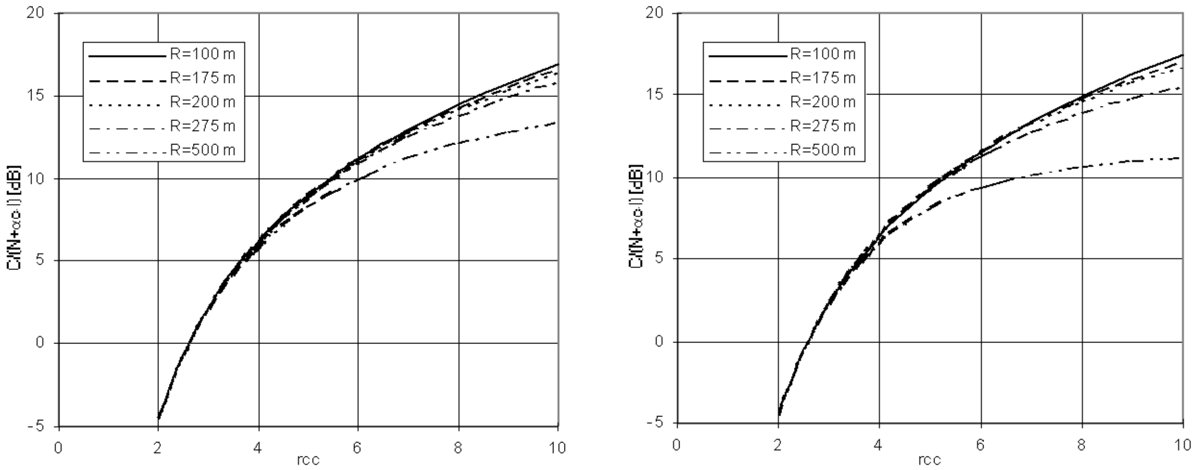
Fig. 3.11 – Coverage structure for the planar regular geometry.

Everything occurs as in the linear coverage geometry, except that the co-channel interference power has twice the value owing to interference coming from both orthogonal avenues. Besides the restriction of *D* being multiple of the cell *length*, there is also the need of adaptation of the cellular structure to the urban grid, i.e., the need of placing BSs in the middle of each crossing, there being a perfect tessellation between the cells and the urban grid, i.e., $a = b – l$ and $b = 2R$, Fig. 3.10.

Whereas it is highly probable to found the linear geometry in practice, e.g., in main roads, large avenues or highways, this is not the case for the ‘Manhattan grid’, it being a very specific and somehow artificial geometry, which only models urban configurations where blocks of buildings are square shaped. Although difficult to find, it is easy to implement and very useful for analysis purposes, because it allows to easily extract analytical conclusions about the influence of obstructions by blocks of buildings in micro-cellular urban scenarios.

Due to the obstruction by blocks of buildings, interference occurs only in LoS, coming from the directions associated to each street (the West/East and South/North directions); as a consequence, *C/I* is 3 dB lower than the value corresponding to the linear coverage case. Moreover, the value of EIRP (effective isotropic radiated power) decreases 3 dB from case to case, resulting from a decrease of 3 dB in antenna gains from the case of two cells to the linear coverage, and a similar situation from the linear coverage to the urban one.

For the planar regular geometry, although the charts are not presented here, the carrier-to-noise-interference ratio was analysed as a function of the maximum coverage distance, with r_{cc} as a parameter; values of r_{cc} = 4, 6 and 8 were considered. At 66 GHz, maximum values were obtained for R ~ 100-200 m [VeCo97], whereas at 43.5 GHz the function is almost constant up to R ~ 150 m, showing afterwards a slightly decreasing behaviour; slightly higher values were obtained at 66 GHz, mainly due to the difference in the oxygen absorption. From the analysis of these results, one also concludes that it is enough to consider three tiers of interference at both bands for numerical purposes. From the dependence of the carrier-to-noise-interference ratio on the co-channel re-use factor, Fig. 3.12, it is observed that the carrier-to-noise-interference ratio is increasing with the co-channel re-use factor.



a) 43.5 GHz. b) 66 GHz.

Fig. 3.12 – Carrier-to-noise-interference ratio as a function of the co-channel re-use factor r_{cc}, with the maximum coverage distance as a parameter, for the planar regular geometry.

A feasible re-use factor of r_{cc}= 6 is achieved for both bands, corresponding to a re-use pattern of $K = r_{cc}/2 = 3$.

3.4.2. Co-channel Re-use factor

Given the coverage distance R, the minimum co-channel re-use factor that can be achieved and the corresponding value of M can both be obtained by using the approach of Section 3.3. In this case, $(r_{cc})_{R=0}$ is obtained by solving an equation different from (3.8), although similar, when $R \to 0$ ($M \to +\infty$), leading to

$$\sum_{m=1}^{T_i} \left[m \left(r_{cc} \right)_{R=0} - 1 \right]^{-n} = \left[2 \cdot \left(\frac{C}{I} \right)_0 \right]^{-1} . \qquad (3.11)$$

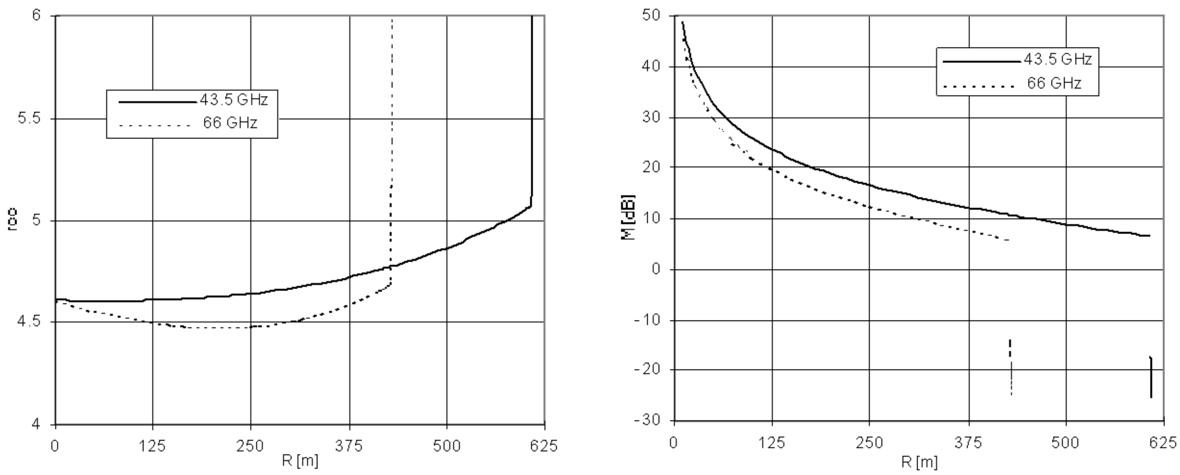
Similar conclusions are obtained for the planar geometry, with the difference that the number 2 in the second member of the equation should be replaced by 4. The equation for M is still (3.7) – although the BS antenna gains are different, G_t = 17 or 14 dBi, owing to the power splitting into two or four antenna lobes, in the linear and the planar regular geometries, respectively.

Table 3.2 presents, for both geometries, with the use of OQPSK, asymptotes for the maximum coverage distances, R_{asymp}.

Table 3.2 – R_{asymp} for the Linear and Planar Regular Geometries.

R_{asymp} [m]	Presence of rain		Absence of rain	
Geometry	43.5 GHz	66 GHz	43.5 GHz	66 GHz
Linear	610	429	1076	709
Planar regular	500	351	798	533

Worst-case results for the co-channel re-use factor and interference-to-noise ratio are presented in Fig. 3.13 for the linear geometry, and in Fig. 3.14 for the planar geometry.

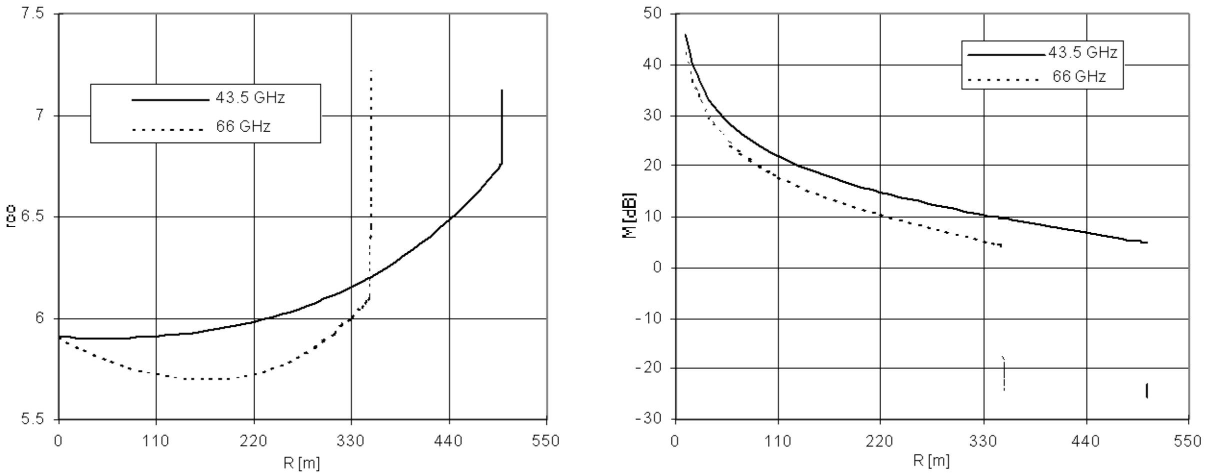


a) Co-channel re-use factor.

b) Interference-to-noise ratio.

Fig. 3.13 – Characteristics of interference and frequency re-use as a function of R, for the linear coverage geometry.

The increasing behaviour of r_{cc} near the origin is verified in the 40 GHz band, as well as its initially decreasing behaviour in the 60 GHz band, as it has already been verified in Fig. 3.8 for the case of the pair of cell. As the feasible co-channel re-use factors need to be an even number it is necessary to analyse which are their minimum feasible values. A value of r_{cc} = 6 is obtained for both geometries, agreeing with the analysis in last section. Minimum values of r_{cc} = 4.5 and 5.7 are obtained at 66 GHz for R = 175 and 150 m for the linear and planar regular geometries, respectively.

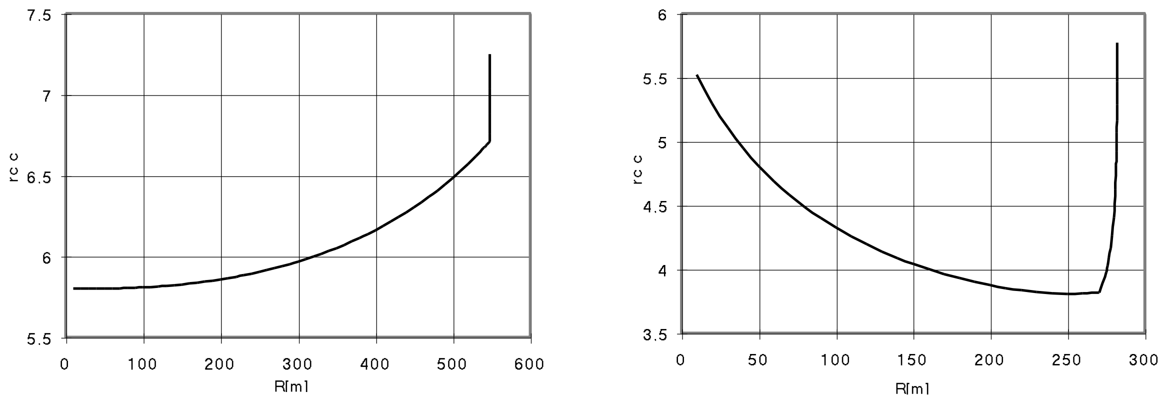


a) Co-channel re-use factor. b) Interference-to-noise ratio.

Fig. 3.14 – Characteristics of interference and frequency re-use as a function of *R*, for the planar regular geometry.

At 43.5 GHz, the values obtained for those coverage distances are r_{cc} = 4.6 and 5.9, respectively. A difference however exists in the achievable maximum coverage distances, and values at 43.5 GHz are more than 20 % larger than at 66 GHz. It is also worthwhile to note that, for the planar regular geometry, $r_{cc} \leq 6$ is only obtained for maximum coverage distances up to 240 m, whereas in the other cases (pair of cells and linear geometry) it is obtained for distances up to values near the asymptotic ones (in the presence of rain). As an example, at 43.5 GHz, for the linear coverage geometry one obtains M = 26, 22 and 19 dB for R = 100, 150 and 200 m, respectively. For the planar regular geometry, the respective results are M = 23, 19 and 16 dB, a difference of 3 dB existing from the pair of cells geometry to the linear coverage geometry, and from this one to the planar regular geometry. In this range of coverage distances, the values of ΔM (the difference of the values of M between the 40 and 60 GHz bands) vary from 3.7 to 3.9 dB for the linear coverage geometry, and from 3.9 up to 4.2 dB for the planar regular geometry, maximum ones being obtained for R = 426 and 350 m, in the range of interest, corresponding to ΔM = 4.9 an 5.3 dB, for the respective geometries.

Results for r_{cc} at 39.5 and 62 GHz are also presented in Fig. 3.15 for the ‘Manhattan grid’ geometry; a value of r_{cc} = 4 is achievable for the latter. At the 62 GHz, lower coverage distances are obtained as a consequence of the larger oxygen absorption attenuation; consequently, the minimum r_{cc} is 3.75. At 39.5 GHz one has the minimum r_{cc} of 5.8. However, because of the need of using even values for the co-channel re-use factor, corresponding to an integer number of cells, a value of r_{cc}=4 is obtained for OQPSK at 62 GHz, corresponding to D = 640 m (R = 160 m) and M~12 dB. At 39.5 GHz one obtains r_{cc}=6, corresponding to D = 1860 m (R = 310 m) and M~12 dB. Thus, from the high value of M, one can conclude that both configurations are limited by the interference. For the linear geometry, although the results are not presented, one obtained slightly smaller minimum values, and equal feasible values for the co-channel re-use factors for both the bands.



a) 39.5 GHz band b) 62 GHz band

Fig. 3.15 – Co-channel re-use factor as a function of the maximum coverage distance for a 'Manhattan grid' geometry.

One further concludes, by analysing the results, that for the linear geometry one has r_{cc} = 4 for frequencies up to 63 GHz for $R \geq 66$ m while, for the planar regular geometry, one has r_{cc} = 4 only for frequencies up to 62.5 GHz for $R \geq 175$ m. Therefore, the conclusion from this analysis is that r_{cc} varies between the values obtained at 62 GHz and 66 GHz, and results for other frequencies are in between the range defined by these extreme frequencies. When a given band is used, the design must be done for the worst-case situation, i.e., the cellular planning must be done by considering the frequency where the total attenuation is lower, for the typical re-use distances.

Some results were also obtained for the 16-OQAM (16^{ary} Offset Quadrature Amplitude modulation) in the framework of the SAMBA project, which can be found in [PrSv99].

3.5. A Case Study for Urban Irregular Geometries

For arbitrary irregular urban geometries a cellular planning tool [VeBr98] was used, which allows the placement of BSs over a 2-D representation of an area to be covered, computes the associated coverage and interference between cells, and inputs these results into frequency assignment algorithms to determine achievable values of frequency re-use. This tool was totally developed by the author of this thesis, in the framework of the RACE-MBS project, during his MSc [Vele95]. It includes the propagation model earlier presented and the capability of computing visibility between a BS and the boundary of the cell (and also between cells), for the purpose of obtaining the coverage area of cells and the interference among them. Generic considerations about the number of needed frequency groups, hence system capacity, can then be obtained via case studies. In the initial version it only supported the 60 GHz band propagation model, but it was generalised later also to support the 40 GHz band one.

3.5.1. Case-by-case Cellular Planning

In this particular case, a part of the city of Lisbon [Lisb93] was considered for coverage. A choice of placement of BSs and the definition of the associated coverage areas, or cells, so as to satisfy a given signal quality requirement, is first done. After a cellular layout is obtained, the achievable system capacity is determined; for this purpose an estimate of the achievable frequency re-use is obtained by determining the number of frequency groups required for system operation under static frequency assignment policies, i.e., the bandwidth available per cell. Even if dynamic resources allocation is used during system operation, the minimum number of frequency groups required under the optimal static assignment policy will provide an upper bound on the achievable frequency re-use.

Cellular layouts were produced for various cell sizes, as defined by the parameter M according to the approach described in the previous sections. An estimate of feasible re-use patterns was obtained by producing frequency assignments based on a variant of the *frequency exhaustive* insertion algorithm known as the *uniform assignment* algorithm [ZoBe77]; from this an estimate for the system capacity was then obtained.

In this study, system parameters are grouped into two categories: (i) system-wide and (ii) cell-specific. The former are common to all cells and include propagation, BS, MS and some additional communication parameters [VeBr98], whereas the latter (i.e., the transmitted power and the antenna characteristics of BSs) can be tailored to individual cells. Three kinds of horizontal directivity patterns (omnidirectional, sector, and bi-sector) have been considered in the tool. For sector and bi-sector antennas, the power radiates to one or two characteristic directions, it being characterised by a half power beamwidth α_{3dB}, and the angle between antenna sectors for the latter, ϕ. The upperbounds for antenna gains are 6, 12 and 15 dBi, respectively, while the restrictions for angles are $30^{o} \leq \alpha_{3dB} \leq 60^{o}$ and $90^{o} \leq \phi \leq 180^{o}$. Here, the same parameters used for regular geometries are assumed, except for these different characteristics of BS antennas, and the consideration of a fade margin of 8 dB, taken only for coverage purposes. Nevertheless, using different antenna gains in each BS affects only M, and does not affect C/I, because it equally influences C and I.

3.5.2 Frequency Re-use

A city area of approximately 2.54 km^2 was considered for coverage, of which about 22.4 %, corresponds to ‘net’ street area effectively covered. In the cases worked out, a common set of system-wide parameters were used, except for M, both at the 42.5 and 65 GHz. These frequencies were chosen in between the two extreme values of the respective band, in order to correspond to a normalised frequency value of 1 GHz, Fig. 3.1. As described in Section 3.3, the parameter M provides a uniform mechanism to control the cell size and system capacity, whereby an increase in M

yields smaller cells and therefore higher capacity. The coverage of each cell is obtained by computing R according to (3.5), while the re-use of each group of frequencies is only possible, according to the frequency assignment algorithm, if the carrier-to-interference constraint (3.6) is verified for the frequency group to be chosen. To do so, a computation of the sum of interferences coming from co-cells is needed. Such interference power depends not only on the distance between cells but also on the existence of visibility between the boundary of co-channel cells and the desired BS. Fig. 3.16 shows an example of a layout.

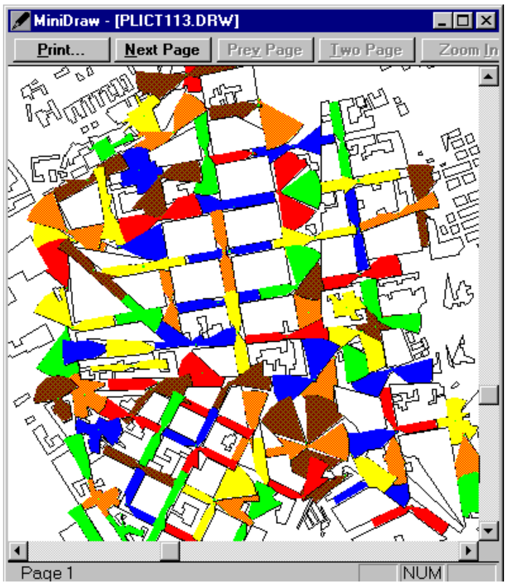


Fig. 3.16 – Example cell layout and frequency assignment (42.5 GHz, M = 11.3 dB).

Tables 3.3 and 3.4 show the number of cells N_c, re-use pattern K, and coverage *length* R for the different values of M considered, the comparison among the different cases being done for a BS antenna with a gain of 12 dBi. A wide range of values for the re-use pattern is obtained, ranging from K = 11, for a coverage distance of R = 219 m at 40 GHz, down to K = 5, for a coverage distance of R = 84 m at both 42.5 GHz and 65 GHz. Intuitively, this decrease can be related to the fact that larger coverage lengths lead to cells spanning a larger number of street intersections, thus being exposed to interference from a larger number of cells and consequently requiring the use of a higher number of frequency groups.

Table 3.3 – Coverage and Frequency Re-use Results at 65 GHz.

M [dB]	N_c	K	R [m]
-3	70	9	147
0	79	9	136
3	85	7	121
6	86	6	103
9	114	5	84

Table 3.4 – Coverage and Frequency Re-use Results at 42.5 GHz.

M [dB]	N_c	*K*	*R* [m]
-3	61	11	219
0	64	9	203
3	66	8	179
6	70	7	152
9	83	7	124
11.3	94	6	103
13.8	117	5	84

For shorter coverage distances, lower than or equal to 124 m, corresponding to system configurations clearly limited by interference, the re-use factors obtained for the 40 and 60 GHz bands are the same in situations with similar coverage *length* (K = 5-7). This is because the difference between the bands is not so important as if the 62-63 GHz band was considered alone, as it was observed for the planar regular geometry in Section 3.4. Again, larger coverage *lengths* can be achieved at 40 GHz, although with a higher associated K.

3.5.3. System Capacity Results

The available one-way (i.e., either uplink or downlink) bandwidth per cell, B_c, is defined as

$$B_c = \frac{B_t}{2 \cdot K} \tag{3.12}$$

where B_t is the total bandwidth assigned to the system and K is the re-use pattern.

While at 40 GHz the difference between the two sub-bands ([39.5, 40.5]$\cup$[41.5, 43.5] GHz) is negligible, even for typical re-use distances (higher than 500 m), Fig. 3.2, at the 60 GHz band there is a slight, but important, difference in the range [62, 63] GHz compared to [65, 66] GHz, Fig. 3.3, a higher attenuation existing for the first (5, 8 and 11 dB being the difference at 500, 750 and 1000 m, respectively). However, as the worst-case in terms of C/I occurs for the [65, 66] GHz sub-band, the main principles and conclusions presented before remain, i.e., taking advantage of the highest attenuation of the [62, 63] GHz sub-band is only possible if it has been the only one in use.

Both for the linear and the planar regular geometries, a value of B_c = 333.3 MHz is obtained, where B_t = 2 GHz and K = 3 are considered, the range of possible maximum coverage distances being the ones presented in Section 3.4. A factor of approximately two in system capacity (per unit area or unit length) between both geometries will exist in practice, because of the difference in total cell areas/*lengths* – cigar or four lobes shaped cells.

For the chosen irregular urban geometry, Table 3.5 shows the available one-way bandwidth per cell. Higher bandwidths are obtained with the decrease in cell size because of the decrease in the re-use pattern as M increases above 0 dB, a maximum of B_c = 200 MHz being obtained for R = 84 m and

K = 5 in both bands among the cases considered. It should be noted that the actual data rates supported depend on further system parameters, such as the spectral efficiency of the modulation scheme, and the FEC (Forward Error Correction) coding rates.

Table 3.5 – Available One-way Bandwidth.

K	B_c [MHz]
11	91
9	111
8	125
7	143
6	167
5	200

It is important to compare the values for system capacity between the two urban geometries, in order to extract general conclusions of this study, apart from the comparison between the 40 and 60 GHz bands, where, in practice, no substantial difference was identified in system capacity. A value of B_c = 333 MHz is obtained for the planar regular urban geometry, corresponding to K = 3, which is higher than the 200 MHz obtained for the irregular urban geometry because of the lower value for the re-use pattern. For comparison purposes, considering the use of cells with R = 84 m in both geometries (valid for an antenna gain of 12 dBi for the irregular urban geometry), and a 'net' street area of 22.4 %, the values obtained for the number of cells N_c, K and M are the ones presented in Table 3.6.

Table 3.6 – Comparison between Urban geometries.

Geometry	N_c	K	M [dB]	
			42.5 GHz	65 GHz
Planar regular	90	3	24.5	21.0
Irregular urban	115±2	5	13.8	9.0

The highest values for N_c and K result from the highest complexity of the irregular geometry. A higher number of cells (N_c = 115 ± 2) is needed to overcome the difficulties in coverage resulting from urban obstacles, originating a higher number of interference sources, coming from different directions – although obstructions from buildings to interference exist; the highest system capacity value for the planar regular geometry is then explained by the lowest value of K.

Regarding the difference in the values of M between the two geometries, it is partly explained by the consideration of the 8 dB fade margin in the irregular urban geometry, the remaining 3-4 dB of the difference being partly due to the difference in antenna gains (from 14 to 12 dBi). However, this difference in M only results on a difference of 2 % in the carrier-to-interference ratio threshold of (3.6), not having a relevant influence in the comparison from the point of view of frequency re-use.

3.6. Conclusions

In this chapter one has considered the problem of frequency re-use and system capacity in MBS, a comparison is done between the bands of 40 and 60 GHz. The fundamental difference between the two bands is the oxygen absorption attenuation, which is negligible at 40 GHz, but presents high values at 60 GHz, decreasing from 14 dB/km (at 62 GHz) down to approximately 1 dB/km (at 66 GHz).

For the two-cell case, in the absence of rain, at 40 GHz the carrier-to-interference ratio does not depend on the value of the maximum coverage distance, but only on the ratio between the re-use and coverage distances, presenting a value of the order of 16 dB for $r_{cc} = 6$. However, at 60 GHz the behaviour is different, because the oxygen attenuation is not negligible. For different values of the maximum coverage distance, different values for the carrier-to-interference ratio exist, and the larger R is the larger C/I one gets, with values, at $r_{cc} = 6$, ranging from 18 up to 44 dB at 62 GHz and from 16 up to 18 dB at 66 GHz, when R varies one order of magnitude from 50 to 500 m. In the presence of rain, a larger value for the attenuation coefficient is obtained, and basically the previous behaviour for the 60 GHz band is observed for the two bands. At $r_{cc} = 6$, C/I ranges from 21 up to 68 dB at 62 GHz, and from 19 dB up to 42 dB at 66 GHz, when R varies from 50 to 500 m. At 40 GHz the previous behaviour changes and different curves exist for different coverage distances, since the linear attenuation coefficient is not negligible in this case. The values of C/I range from 17 up to 33 dB at 39.5 GHz, and from 18 up to 35 dB at 43.5 GHz, for the same range of coverage distances.

Considering the thermal noise, at 43.5 GHz and 66 GHz the difference between the bands result only in slightly lower values for the co-channel re-use factor in the 60 GHz band, negligible in practical terms, and in higher values for the interference-to-noise ratio. However, larger coverage distances can be obtained at 43.5 GHz (720 m, against 500 m at 66 GHz), the cases of interest occurring in the absence of rain in both bands.

For both the linear and the planar regular geometries, there is no significant difference between the values of the co-channel re-use factor for the linear and the planar regular geometries, because the presence of obstructions decreases considerably the degree of interference between cells. Different values for r_{cc} result at 43.5 and 66 GHz, being slightly higher for the former frequency. However, for these regular geometries, as the co-channel re-use factor needs to be even, no practical difference exist on the co-channel re-use factor and on the re-use pattern between both bands, it being $r_{cc} = 6$ and $K = 3$. The values of the interference-to-noise ratio decrease approximately 3 dB from the pair of cell geometry to the linear one, and also from the latter to the planar regular (Manhattan) geometry, leading to the need of achieving a higher carrier-to-interference threshold, according to (3.6).

However, a difference exists in the achievable maximum coverage distances, values at 43.5 GHz being more than 20 % larger than at 66 GHz, despite, for the planar regular geometry, $r_{cc} \leq 6$ being only obtained for maximum coverage distances up to 240 m, whereas in the other cases it is obtained for distances up to values near the asymptotic ones (in the presence of rain).

Considering the 39.5 GHz and the 62 GHz frequencies, one obtains $r_{cc} = 6$ for the former and $r_{cc} = 4$ for the later, which means that operation near the 62 GHz frequency leads to a higher system capacity.

Results for irregular urban geometries were obtained using a cellular planning tool, which allows the placement of base stations over a 2-D representation of an area to be covered, computes the associated coverage and interference between cells, and inputs these results into frequency assignment algorithms to determine achievable values of frequency re-use and system capacity. For interference limited scenarios, the minimum value obtained for the re-use pattern is $K = 5$, and the number of cells, N_c, to cover an area of 2.54 km^2 is 115±2. Again, larger coverage *lengths* can be achieved at 40 GHz, although with a higher associated K.

Because of the difference in K between the two urban geometries, the one-way bandwidth per cell is higher for the planar regular geometries. However, there is no practical difference between the bands of 40 and 60 GHz. For a total bandwidth assigned to the system of 2 GHz, the one-way bandwidth per cell is 333 MHz for the regular geometry and 200 MHz for the irregular urban geometry. The comparison between geometries is, of course, an approximated one, because different antenna gains are considered for each cell in the irregular urban geometry – although this does not affect the computation of C/I. With a gain for the BS antennas of 12 dBi, cells have a coverage distance of R = 84 m (the lowest of the coverage distances considered). For the planar regular geometry, considering also this maximum coverage distance, and a 'net' street area of 22.4 %, 90 cells are needed to cover an area similar to the one of the irregular urban geometry.

The highest values for N_c and K in the irregular geometry result from the highest complexity of the urban environment, and a higher number of cells is needed to overcome the difficulties in coverage resulting from urban obstacles. This originates a higher number of interference sources, coming from different directions – although obstructions from buildings to the interference exist. Therefore, the highest system capacity values for the planar regular geometry are explained by the lowest values of the re-use pattern.

Chapter 4

Traffic from Mobility

4.1. Introduction

The deployment of MBS in urban scenarios will be based on a micro-cellular structure (with cells confined to streets), having dimensions of the order of a few hundreds of metre; for main road scenarios, the use of micro-cells is also foreseen. This micro-cellular structure, in conjunction with high mobility, yields a tele-traffic analysis, where both new connections and handover traffics should be considered simultaneously. For systems where guard channels are used for handover, this analysis is made assuming that handover traffic is Poisson distributed [ChLu95], and that there is independence among the number of connections being served at each cell [Jabb96].

One of the goals of system planning may be the maximization of the new connections traffic in terms of cells dimension, i.e., one is interested in obtaining the cell coverage range that leads to a maximum new connections traffic density supported by the system. For the case of linear geometries, where mobiles travel randomly through cells with total length $L_c = 2R$, and BSs located in the centre, located end-to-end, a new connections traffic per unit length (or new connections traffic linear density) is considered, ξ_n. To have an insight into the trade-offs involved in the optimisation procedure for MBS, the behaviour of ξ_n in terms of R, needs to be studied for various mobility scenarios: static, pedestrian, urban, main roads and highways.

At first glance, one could consider that the new connections traffic linear density is proportional to $(1/R)$; however, this is only valid for the static scenario, where there are no handovers. In scenarios with considerable mobility, the number of connections generated by handover increases as L decreases and the velocity increases, implying that ξ_n does not increase linearly with $(1/R)$. For a given supported traffic, the increasing behaviour of ξ_n, associated with the decrease of the coverage distance, corresponds to an increase of the cross-over rate η (number of handovers per unit length)

[Jabb96]. These facts originate higher probabilities of handover failure P_{hf} (which is the probability of a user not succeeding in transferring its connection from a cell to another) with the decrease of R. The resulting connection-dropping probability, P_d (the probability of forced termination of the connection during its duration), also decreases with R.

The simple situation of homogeneous traffic (constant value of new connections traffic in the whole service area) and linear coverage geometry (where mobiles handover between the first and the last cells, a typical geometry for roundabouts [SiSt97]) will be considered here as first step to a more complicated (and closer to reality) analysis. The objective of the design is to obtain values for R that verify the requirements of system quality. These requirements consist of values lower than 1-2% for the customer or connection blocking probability, P_b, the probability that an arriving customer is blocked [CBMF94], and lower than 0.1-0.5% for the connection dropping probability [ITUT96].

When no guard channels for handover are used, the blocking and the handover failure probabilities are equal [Jabb96], which strongly limits system capacity for high handover failure probabilities, i.e., corresponding to lower coverage distances. If guard channels for handover were used, the equations for blocking and handover failure probabilities would be decoupled, and the arising trade-offs allow to improve system performance for systems with the smallest cells.

Although MBS will be a multi-service system, providing multimedia mobile communications handling both bursty and constant-bit-rate traffic, in this chapter only two types of applications will be taken into account, in order to simplify this first analysis of the problem: short duration ones, with an average duration of 3 min (e.g., video-telephony or freight fleet management), and long duration ones, with an average duration of 20 min (e.g., emergency services, repair assistance, assistance in travel, TV outside broadcast, interactive games and video on demand) [CBMF94], [ZuAs94]. Anyway, this analysis will be very useful in the computation of multi-service aggregated traffic, because the knowledge about individual applications can be fed into the multi-service traffic analysis, this being the first step of the more general problem [RoTs90]. In some approaches, it consists of computing, for each type of traffic, the state probability as if it were the only kind of traffic in the system.

Generally, models assume that handover connections follow a Poisson distribution [ChLu95], which, in conjunction with new connections traffic being Poisson distributed, allows considering the aggregate traffic as Poisson distributed, and justifies the independence of total traffic among cells [Jabb96]. However, it will be shown that for configurations that do not use guard channels for handover, the assumption of handover traffic being Poisson distributed is not necessary.

In Section 4.2, the validity of models for traffic from mobility in such micro-cellular systems is studied. The Markov chain associated with the system without guard channels for handover is presented, and an approximate solution, which agrees with the usual solutions available in literature, is proposed. This analysis is based on migration processes/Jackson networks theory, its conditions of validity and the error associated with the approximation being discussed and examined. The use of guard channels for handover leads to a more complex multi-dimensional Markov chain, whose solution is not straightforward, and which is presented as a topic for further research. Because of that, in this case, the assumption of handover traffic being Poissonean should still be used.

In Section 4.3, the influence of traffic from mobility on the micro-cellular coverage distance is examined. Time parameters are described and the handover probability is introduced. The characteristics of some main mobility scenarios are introduced, and formulas for the cross-over rate are then obtained, from which values for the average cross-over velocity are calculated. In systems without guard channels for handover, for given values of the number of channels in each cell and of P_b, one can calculate the corresponding supported traffic, by using the models developed in Section 4.2. Equations for the new connections traffic and the traffic coming from handover are also obtained. Models for the computation of new connections traffic linear density are presented, its dependence on R is highlighted, and the resulting limitations in system capacity (which are imposed because of the high mobility of terminals) are discussed. Finally, using these values of the supported traffic, some numerical results for the approximation error of the models presented in Section 4.2 are obtained for the actual environments involved in terrestrial systems.

In Section 4.4, the use of guard channels for handover is proposed as a prospective solution to overtake the limitations discussed in Section 4.3 for the new connections traffic linear density. First, the assumptions made in the traffic analysis are described. Finally, the trade-offs involved in the design are described, and results are obtained for the supported traffic, the new connections traffic linear density and coverage distances that maximise it. A comparison between the results for short and long duration connections is addressed.

Finally, in Section 4.5, some conclusions are drawn on the influence of mobility on new connections traffic linear density, and its consequences on the optimisation of MBS capacity.

4.2. Models

4.2.1. Scope of the Problem

As it has been already presented in Chapter 3, micro-cellular mobile communication systems with a linear coverage geometry are formed by contiguous cigar shaped cells, with a maximum coverage distance R and a total length $L_c = 2R$, Fig. 4.1. Base stations are located at the centre of cells, where mobile terminals travel randomly with a given velocity. The tele-traffic analysis for systems of this kind is straightforward assuming that some conditions, related to the mobility of terminals and to the maximum coverage distance of cells, are fulfilled. This is mainly true for homogeneous, or locally homogeneous, traffic over the whole system; the locally homogeneous traffic hypothesis is made in order to allow the generalisation of the models for systems with spatial traffic variation as, e.g., in urban areas, where there are hot spots at the centre of cities, mainly in rush hours.

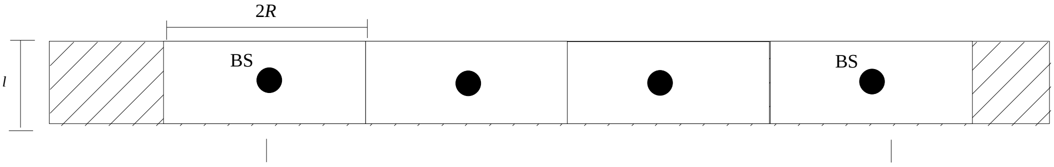


Fig. 4.1 – Linear coverage geometry.

The new connection generation rate per cell and the service rate are denoted by λ and μ, respectively. Fig. 4.2 shows two adjacent cells (N_c = 2), with m available channels in each cell. The transition rate between a cell j and a cell k is η_{jk}. For N_c = 2, one has $\eta_{jk}(n_j) = n_j \cdot \eta$ because the dwell time in a cell is exponentially distributed with mean $1/\eta$, η being the cross-over rate [Jabb96], and n_j being the number of active users at cell j. For such conditions the Markov chain used to model its tele-traffic behaviour is the one presented in Fig. 4.3, where m = 3 channels are used.

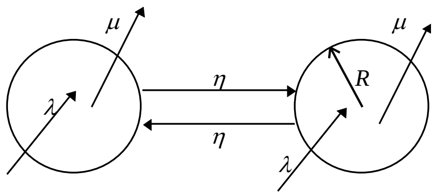


Fig. 4.2 – Transition rates for N_c = 2 cells.

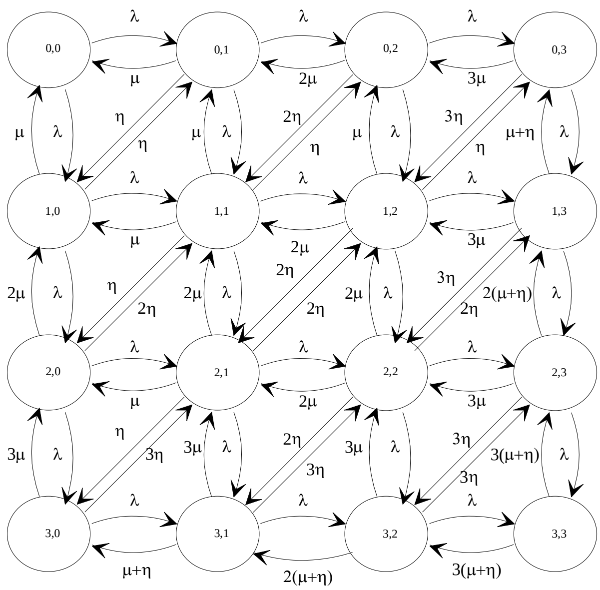


Fig. 4.3 – Markov chain for N_c = 2 and m = 3 (from [SiSt97]).

For a more general geometry with $N_c > 2$ cells, Fig. 4.4 (example given for $N_c = 10$), the associated Markov chain will be N_c-dimensional, with a cross-over rate between each pair of cells given by $\eta_{jk}(n_j) = n_j \cdot \eta/2$, where η is the total cross-over rate. The division by 2 comes from the assumption that mobiles move random velocity, thus, in a given cell, mobiles in handover will be divided by half to each one of the two neighbour cells (on average). For design purposes one wishes to obtain equations for the blocking and for the handover failure probabilities [SiSt97]. Instead of a linear geometry with an infinite number of cells the example of a circular geometry is presented, because it directly validates the hypotheses of homogeneous traffic without any further considerations.

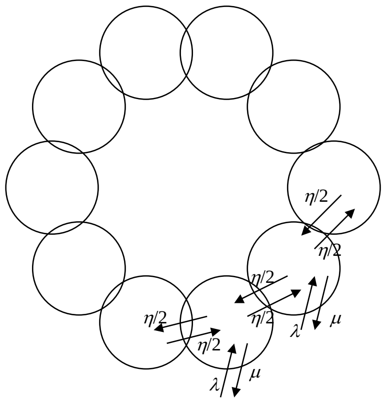


Fig. 4.4 – Transition rates for N_c = 10 cells (from [SiSt97]).

If guard channels for handover are considered, from the total *m* channels, *g* guard channels are used for handover and the remaining *c* channels are available for both new and handover connections, Fig. 4.5 (λ_i denotes the new connection generation rate at cell *i* and λ_h denotes the handover connection generation rate); in this situation, the Markov chain will be different from the previous one because the new connections generation rate will be zero for the transitions to the guard channels for handover.

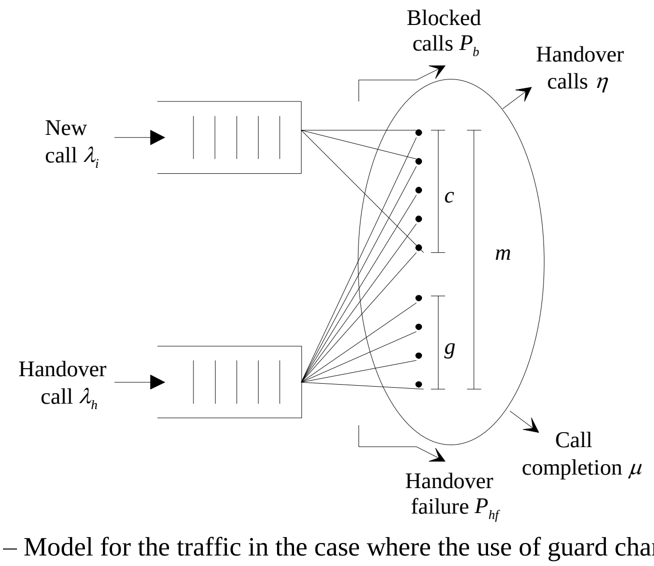


Fig. 4.5 – Model for the traffic in the case where the use of guard channels for handover is considered (from [Jabb96]).

It is possible to obtain formulas for the blocking and handover failure probabilities by solving the resulting system of equations for the steady-state probabilities, particularly if the steady-state probabilities have a product form, which occurs in the approximation considered for the case without guard channels for handover.

4.2.2. Approximate Solution

4.2.2.1 Model

Let $n_i(t)$ be the number of users in cell i, $i \in \{1, ..., N_c\}$, at every time $t \geq 0$, and $\boldsymbol{n}(t) = (n_1(t), ..., n_{Nc}(t))$, then, $\{\boldsymbol{n}(t)\}$ is a continuous time Markov chain with special structure, where state $\boldsymbol{n} = (n_1, n_2, ..., n_{Nc})$ means that there are n_i active users at cell i, $i \in \{1, ..., N_c\}$. Denoting the solution for the steady-state probabilities in the exact model by $p(\boldsymbol{n})$, based on the definitions of [SiSt97], the probability that a new connection arriving at a cell i will be blocked is equal to the sum of all steady-sate probabilities $p(\boldsymbol{n})$, where $n_i = m$

$$P_{B_i} = \sum_{n_1,...,n_{i-1},n_{i+1},...,n_{N_c}} p\left(n_1, n_2, ..., n_{i-1}, m, n_{i+1}, ..., n_{N_c}\right). \tag{4.1}$$

When a mobile being initially served in cell k suffers an handover to a cell i, the handover failure probability is the ratio between the rate of unsuccessful handover attempts from cell k to i and the total rate of handover attempts between those cells [SiSt97]

$$P_{hf_{ki}} = \frac{\sum_{n_1,...,n_{i-1},n_{i+1},...,n_{N_c}} n_k \; p\left(n_1, n_2, ..., n_{i-1}, m, n_{i+1}, ..., n_{N_c}\right)}{\sum_{n_1,n_2,...,n_{N_c}} n_k \; p\left(n_1, n_2, ..., n_{N_c}\right)}. \tag{4.2}$$

As there is no simple analytical solution for the steady-state probabilities of the exact Markov chain, it is necessary to use approximate solutions. Typical ones available in the literature for this problem correspond to obtain the state probabilities for a similar, but slightly different, chain where rates η, 2η, 3η are not considered for the transitions from state (3, 1) to state (3, 0), from (3, 2) to (3, 1), and (3, 3) to (3, 2), respectively, and also from states (3, i) to (3, i-1), with i = 1, ...,3. For this modified Markov chain, the steady-state probabilities have a product form. Thus, as results arising from this property are very powerful and elegant, one intends to check the validity of the approximation, comparing results for blocking and handover failure probabilities between the approximate chain, where the boundary conditions were changed in this way, with the numerical results for the exact one.

For configurations with $N_c > 2$ cells, Fig. 4.4, η is replaced by $\eta/2$ and the transition rates between cells j and k are only different from zero for contiguous cells $k = j\pm1$, $1 \leq j, k \leq N_c$. If an infinite number of available channels existed, this Markov chain would correspond to an open migration process [Kell79], which is then an open Jackson network [Wolf89]. Therefore, for the range of coverage distances where this approximation is valid, the theory of open migration processes is an elegant solution to obtain the steady-state probabilities. Equations for the computation of blocking and handover failure probabilities can then be easily derived, and formulas to compute the total service rate, and mainly an equilibrium equation for the rate of generation of both new and handover connections are directly obtained. This equilibrium equation allows to sum traffics resulting from the dynamic of mobiles, it being a simple way to compute the overall traffic. Besides, the reversibility of this migration process automatically provides a validity condition for the model [Kell79] for homogeneous or locally homogeneous traffic, i.e., traffic is approximately equal among neighbour cells.

The state space for such open network (where arrivals and departures of users to/from the system are allowed, at least, at one cell) is S = {$\boldsymbol{n}$: $n_i \geq 0$, $i = 1, ..., N_c$}, and the assumptions that follow ensure that the chain {$\boldsymbol{n}(t)$} is irreducible. Defining state N_c+1 as the 'outside world' relatively to the system, the transition rates are given by [Wolf89]:

- Arrival to the system at cell i: $\eta_{Nc+1,i}(\boldsymbol{n}) = \lambda_i$
- Departure from the system at cell i: $\eta_{i,Nc+1}(\boldsymbol{n}) = n_i\mu$
- Transition from cell i to cell j: $\eta_{ij}(\boldsymbol{n}) = \eta_{ij}(n_i)$

This definition of the transition rates means the following:

- The arrival rate at each cell is independent of the state of the system, i.e., the arrival processes at each cell are independent Poisson processes.
- The service rate at each cell may depend on the number of customers at the cell, but is otherwise independent of $\boldsymbol{n}$.
- Together with the last conclusion, the definition of the transition rate from cell i to cell j means that the cell visited next by a departure from cell i may depend on i, but is otherwise independent of $\boldsymbol{n}$. Because {$\boldsymbol{n}(t)$} is a Markov process, the last equality is equivalent to assuming that given the cell the customer is departing from, and the past history of cells visited by that customer, the next visited cell is independent of this past history.

Defining $\mathrm{H}_i(\boldsymbol{n})$ as the total service rate at cell i multiplied by n_i, one has

$$\mathrm{H}_i(\boldsymbol{n}) = \sum_{j=1}^{N_c+1} \eta_{ij}(\boldsymbol{n}). \tag{4.3}$$

The transition rates can be denoted by $\eta_{ij}(\boldsymbol{n})=\mathrm{H}_i(n_i)\, p_{ij}$, $n_i \in$ IN, with the following transition probabilities

$$p_{ij} = \frac{\eta_{ij}(\mathbf{n})}{\mathrm{H}_i(\mathbf{n})} = \frac{\eta_{ij}(n_i)}{\mathrm{H}_i(n_i)} = \begin{cases} \dfrac{\eta}{2(\eta+\mu)}, & j = i \pm 1 \\ \dfrac{\mu}{\eta+\mu}, & j = N_c + 1 \\ 0, & \text{otherwise} \end{cases} \tag{4.4}$$

for $1 \leq i, j \leq N_c$ (the right member is the particularisation of p_{ij} for the linear geometry); in these conditions $\mathrm{H}_i(\boldsymbol{n}) > 0$ if and only if $n_i > 0$. Note that $\sum_{j=1}^{N_c+1} p_{ij} = 1$ for all i. Although these models are quite general, the analysis presented below will be done for the linear coverage geometry; its generalisation can be done via the appropriate changes, mainly for regular geometries, as urban grids. For the linear geometry particular case one obtains

$$\eta_{ij}(\boldsymbol{n}) = \eta_{ij}(n_i) = \begin{cases} n_i \cdot \eta/2 & , j = i \pm 1 \\ 0 & , \text{otherwise} \end{cases} \tag{4.5}$$

which leads to

$$\mathrm{H}_i(\boldsymbol{n}) = n_i \cdot (\eta + \mu) = \mathrm{H}_i(n_i) \tag{4.6}$$

meaning that the total service rate is the sum of the service rate μ and the cross-over rate η. Note that the assumption that handover traffic is Poisson distributed is not being used.

4.2.2.2. Solution

Let Λ_i be the composite (external or internal) arrival rate (departure rate) at cell i, $i \in \{1, ..., N_c\}$. It is referred to both arrival/departure of connections because, in an equilibrium situation, the arrival rate at a cell is equal to the departure one (both due to service termination or transition of the connection to another cell). In a stable network, every arrival is served, and Λ_i can be computed in advance by equating departure rates (on the left-hand side in (4.7)) and arrival rates at every cell by the following flow equilibrium equation:

$$\Lambda_i = \lambda_i + \sum_{j=1}^{N_c} \Lambda_j p_{ji}, i = \{1, ..., N_c\}. \tag{4.7}$$

According to the approach presented in [Wolf89] the solution for state probabilities for such Jackson networks has a product form, it being given by

$$p(\mathbf{n}) = \prod_{i=1}^{N_c} p_i(n_i) \tag{4.8}$$

where the probability of n_i channels being occupied at cell i is

$$p_i(n_i) = \frac{k_i \Lambda_i^{n_i}}{\prod_{j=0}^{n_i} \mathrm{H}_i(j)}, \tag{4.9}$$

for every $n_i \geq 0$, $i = \{1, ..., N_c\}$, which are independent among each other, and the normalisation constant is defined as

$$k_i^{-1} = \sum_{n=0}^{\infty} \frac{\Lambda_i^{n}}{\prod_{j=0}^{n} \mathrm{H}_i(j)}, \tag{4.10}$$

where the first term of the sum (n = 0) is set equal to 1. This solution for the approximate chain would correspond to having an infinite number of channels in each cell. Nevertheless, the solution for a finite number of m available channels can be obtained via truncation of the above one, on the condition that the chain should be reversible. It is worthwhile to note that the equilibrium distribution at cell i is just what it would be if it were the only cell in the system, with connections arriving with a Poisson distribution with rate $\rho_i \mathrm{H}_i(n_i)/n_i$ (where ρ_i is the overall traffic at cell i), and leaving the system with rate $\mathrm{H}_i(n_i)$. This is particularly intriguing because the combined arrival process of connections from other cells and new ones is not in general Poisson [Kell79].

4.2.2.3. Application to the Linear Coverage Geometry

Let ρ_j be the overall traffic at cell j

$$\rho_j = \frac{\Lambda_j}{\mu + \eta} \tag{4.11}$$

in order to be reversible, the process should satisfy the following conditions for every pair (j, k)

$$\rho_j \cdot \eta_{jk} = \rho_k \cdot \eta_{kj} \tag{4.12}$$

$$\rho_j \cdot \mu = \lambda_j \, . \tag{4.13}$$

For the linear coverage geometry, (4.12) leads to

$$\rho_j \cdot \eta/2 = \rho_k \cdot \eta/2 \tag{4.14}$$

and so, for homogeneous traffic, both conditions (4.12) and (4.13) are fulfilled, because $\lambda_j = \lambda$; the solution for the system of equations (4.7) leads to

$$\Lambda_1 = ... = \Lambda_J = \lambda \cdot \frac{\eta + \mu}{\mu} \, , \tag{4.15}$$

the overall traffic being given by

$$\rho = \lambda/\mu \, . \tag{4.16}$$

As the handover traffic is proportional to p_{ij}, $j = i \pm 1$, it is given by

$$\rho_h = \frac{\lambda}{\mu} \cdot \frac{\eta}{\eta + \mu} \tag{4.17}$$

and consequently the new traffic connections is

$$\rho_n = \rho - \rho_h = \frac{\lambda}{\eta + \mu} \, . \tag{4.18}$$

Due to the reversibility, the solution for the approximated chain is obtained by truncating the solution for an infinite number of channels. For such conditions, the blocking and handover failure probabilities at each cell are equal, because of the independence stated above. They can then be obtained by computing $p_i(m)$, which corresponds to the well-known Erlang-B formula. Results for these probabilities, as a function of the traffic, with m as a parameter, or as a function of m, with ρ as a parameter, can be found in almost every book on tele-traffic.

It is worthwhile to note that the models developed here for homogeneous traffic can be further generalised in order to take into account more general spatial distributions of traffic, by solving a system of flow equilibrium equations, regarding that the overall traffic must be locally homogeneous, i.e., approximately equal among neighbour cells.

4.3. Influence on the Optimum Micro-cellular Coverage Distance

4.3.1. Traffic Requirements

In a linear coverage geometry, cells are placed end-to-end and mobiles can handover from a cell only to one of the two adjacent ones, Fig. 4.6; a connection comprises successive sessions τ_1, τ_2, τ_3, ... in cells traversed by a mobile terminal, and its duration τ follows an exponential distribution whose mean is $\bar{\tau} = 1/\mu$ [Jabb96], where μ is the service rate. The channel occupancy time τ_c is the time spent by a user in communication prior to handover (or subsequent to handover) or connection completion, which can also be modelled by an exponential distribution with reasonable accuracy [Guér87].

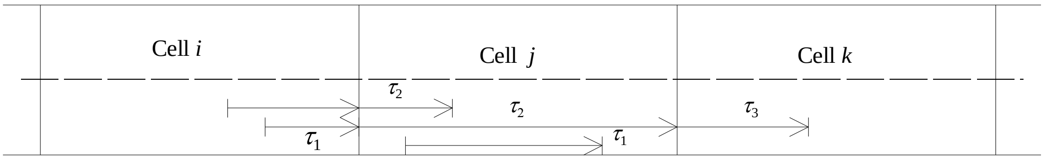


Fig. 4.6 – Dwell time and channel occupancy time.

The cell dwell time τ_h is the residing time of a mobile within a cell. Further assuming that the dwell time is exponentially distributed with mean $\bar{\tau}_h = 1/\eta$, then the channel occupancy time is $\tau_c = \min\{\tau, \tau_h\}$, i.e., it is either the time spent in a cell before crossing the cell boundary if the connection continues, or the time until the channel is relinquished [Jabb96]. As the minimum of two exponentially distributed random variables is also exponentially distributed with parameter $\mu_c = \mu + \eta$, the mean channel occupancy time is given by

$$\bar{\tau}_c = \frac{1}{\mu_c} = \frac{1}{\mu + \eta} \tag{4.19}$$

the probability of handover being given by

$$P_h = \text{Prob}\{\tau > \tau_h\} = \frac{\eta}{\mu + \eta} = \frac{\bar{\tau}_c}{\bar{\tau}_h}. \tag{4.20}$$

Usually the service rate is assumed to be known for the service or application under analysis, and the cross-over rate can be calculated taking into account the distribution for velocities [ChLu95]

$$\eta = \frac{1}{\int_0^{V_{\max}} \left(\frac{2R}{v}\right) \cdot f(v)dv} \tag{4.21}$$

where v is the velocity and $f(v)$ is the velocity probability density function (note that in a linear geometry the total length of the cells is $2R$).

For a properly designed system, the new connections traffic density increases as the coverage distance decreases, together with the increase of the handover rate (mean number of handovers per connection when the probability of the handover failure is negligible) [Jabb96]; this also causes the increase of handover failure and connection dropping probabilities. The desired maximisation of the new connections traffic linear density obeys to requirements of system quality, which consist of values lower than 1-2% [CBMF94] for the blocking probability and lower than 0.1-0.5% for the connection dropping probability [ITUT96]. In some cases, an improvement in system performance can be achieved if guard channels are used for handover, but different solutions are obtained depending on mobility scenarios and on the number of guard channels for handover, Fig. 4.5.

The connection dropping probability P_d is given by [Jabb96]

$$P_d = P_h P_{hf} \sum_{i=0}^{\infty} P_h^{\,i} \left(1 - P_{hf}\right)^i , \tag{4.22}$$

where i denotes the order of the handover and P_{hf} is the handover failure probability; for small values of P_{hf}, it can be approximated by

$$P_d = (\eta/\mu) \cdot P_{hf} \, . \tag{4.23}$$

The ratio η over μ is the handover rate, γ.

If guard channels for handover were not used P_{hf} would be equal to the blocking probability P_b [HoRa86], which imposes a strong limitation, because P_b would be as low as P_d determines. The use of guard channels for handover allows to overtake this limitation, because P_b and P_{hf} will be decoupled; in this case, depending on the coverage distance, the design is made by considering the traffic supported by m channels, from which g are guard channels [Jabb96].

The parameters involved in the design depend on the connection generation rate λ, the number of channels at each cell m, besides v and μ. The simple situation of homogeneous traffic (constant value of new connections traffic in the whole service area) and linear coverage geometry (where mobiles handover between the first and the last cells, typical for circular geometries [SiSt97]) will be considered here as first step to a more complicated (and closer to reality) analysis.

4.3.2. Mobility Scenarios

The scenarios examined in the analysis are presented in Table 4.1, where a triangular distribution, with average $V_{av} = (V_{max}+V_{min})/2$ and deviation $\Delta = (V_{max}-V_{min})/2$, is considered for the velocity [ChLu95], Fig. 4.7.

Table 4.1 – Scenarios of Mobility Characteristics.

Scenario	V_{av}[m·s^{-1}]	Δ [m·s^{-1}]
Static	0	0
Pedestrian	1	1
Urban	10	10
Main roads	15	15
Highways	22.5	12.5

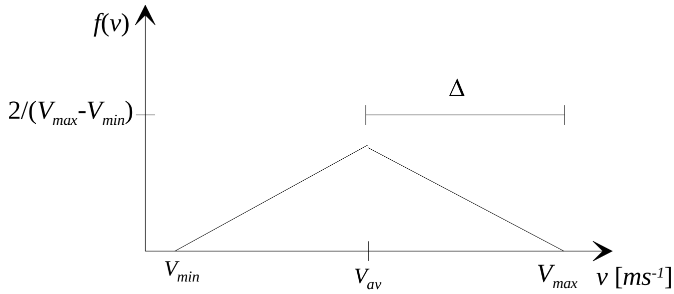


Fig. 4.7 – Velocity probability density function.

The probability density function is given by

$$f(v)=\begin{cases}\frac{1}{\Delta^2}\cdot\left[v-\left(V_{av}-\Delta\right)\right], & V_{av}-\Delta\leq v\leq V_{av}\\ -\frac{1}{\Delta^2}\cdot\left[v-\left(V_{av}+\Delta\right)\right], & V_{av}\leq v\leq V_{av}+\Delta\\ 0 & \text{, otherwise}\end{cases} \tag{4.24}$$

which leads, when V_{min}, $\Delta > 0$, to the following cross-over rate

$$\eta=\left\{\frac{2R}{\Delta^2}\left[\left(V_{av}+\Delta\right)\cdot ln\left(\frac{V_{av}+\Delta}{V_{av}}\right)-\left(V_{av}-\Delta\right)\cdot ln\left(\frac{V_{av}}{V_{av}-\Delta}\right)\right]\right\}^{-1} \tag{4.25}$$

and, when $V_{min} = 0$ ($\Delta = V_{av}$), to the limit

$$\eta=\frac{V_{av}}{2\cdot ln(2)}\cdot\frac{1}{(2R)}\,. \tag{4.26}$$

Defining the average cross-over velocity η^* as

$$\eta^* = \eta\cdot(2R) \tag{4.27}$$

(η normalised to the cell length $2R$) one obtains, for the scenarios from Table 4.1, the values of Table 4.2.

Table 4.2 – Average Cross-over Velocity.

Scenario	η^*[m·s^{-1}]
Pedestrian	0.72
Urban	7.21
Main roads	10.82
Highways	21.21

It is interesting to define η^*, because it enables to make explicit the dependence on R of some parameters to be defined later on. One example is the dependence of the handover probability on R. It can be computed by

$$P_h=\frac{\eta^*}{\eta^*+2\mu R}\,. \tag{4.28}$$

For the considered four mobility scenarios, P_h has been plotted as a function of R, for the two previously mentioned types of service duration (short and long duration ones), with respective service rates, $\mu = 1/3$, 1/20 min^{-1}, Figs. 4.8-4.9. Coverage distances up to 1000 m were considered, a value that is clearly larger than the coverage distances foreseen for MBS, typically 100-350 m. As P_h gives the percentage of connections coming from handover (both entering or quitting a cell), (1-P_h) gives the percentage of new connections (or connections terminated in a given cell) – the case for new connections derived using the flow equilibrium equation presented in [Jabb96]. Therefore, in high mobility scenarios, and for short duration connections, more than 70% of connections in each cell come from handover. This value rises up to 95% for long duration connections, Table 4.3.

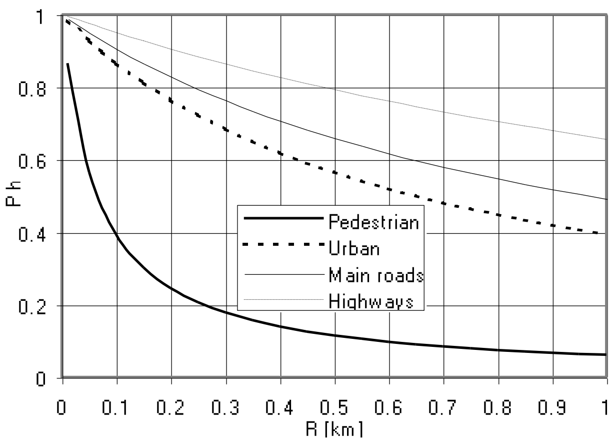


Fig. 4.8 – Handover probability for short duration connections, $\mu = 1/3$ min^{-1}.

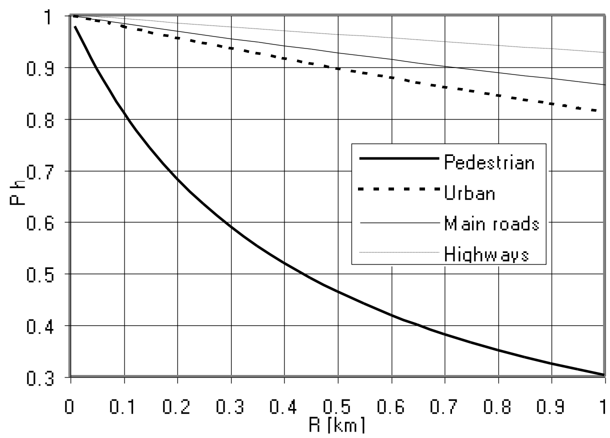


Fig. 4.9 – Handover probability for long duration connections, $\mu = 1/20$ min^{-1}.

Table 4.3 – Handover Probability for High Mobility Scenarios.

P_h [%]	$\mu = 1/3$ min^{-1}			$\mu = 1/20$ min^{-1}		
Scenario	R = 100 m	R = 200 m	R = 350 m	R = 100 m	R = 200 m	R = 350 m
Urban	86.6	76.4	65.0	97.7	95.5	92.5
Main roads	90.7	83.0	73.6	98.4	97.0	94.9
Highways	95.0	90.5	84.5	99.2	98.5	97.3

As it would be expected, handover is more likely to occur in long duration connections, because mobiles will traverse more cells on average. These results motivate the inspection of using guard channels for handover as a possible solution to avoid system capacity degradation.

4.3.3. New Connections Traffic Linear Density without Guard Channels for Handover

For given values of m and P_b, and for a configuration that does not use guard channels for handover connections, one can calculate the corresponding supported traffic ρ_m, by using the well known Erlang-B model [Yaco93], which is coincident with the model from Section 4.2. Having the value of the supported traffic for a given threshold blocking probability, $(P_b)_{max}$, the new connections traffic, ρ_n, and the traffic coming from handover, ρ_h, can then be obtained as follows [ChLu95]

$$\rho_n = \frac{\mu}{\eta+\mu}\cdot\rho_m = \frac{2\mu R}{\eta^* + 2\mu R}\cdot\rho_m \tag{4.29}$$

$$\rho_h = \frac{\eta}{\eta+\mu}\cdot\rho_m = \frac{\eta^*}{\eta^* + 2\mu R}\cdot\rho_m, \tag{4.30}$$

where the dependence on the cell length has been made explicit by introducing the cross-over average velocity. Note that $\rho_m = \rho_n + \rho_h$.

Dividing (4.29) by ($2R$) one obtains a new connections traffic linear density

$$\xi_n = \frac{\rho_n}{2R} = \frac{\mu}{\eta^* + 2\mu R}\cdot\rho_m, \tag{4.31}$$

which can be normalised as follows

$$y = \frac{\xi_n}{\rho_m\cdot\mu/\eta^*} = \frac{1}{1+\left(\mu(2R)/\eta^*\right)} = \frac{1}{1+x}, \tag{4.32}$$

with $x = \mu(2R)/\eta^* = \mu/\eta = 1/\gamma$.

For the static scenario the new connections traffic linear density is $\xi_n = \rho_m/(2R)$ because $v = 0$ and $\eta^* = 0$; consequently, in a non-static scenario, if the contribution of mobility was not considered, one would obtain $y = 1/x$.

From the operator's point of view, the objective is to maximise ξ_n, thus, the dependence of this parameter on R should be analysed. Given constant values of the blocking probability, one obtains the graphs from Fig. 4.10 for both situations (with and without mobility). Then, one could conclude that ξ_n is upper limited by $(\rho_m\mu/\eta^*)$ [Erlang[+]/m], which decreases with velocity; but, one should note as well that, for a given R, x will be lower for higher velocities, and so y will be larger, which partly compensates the lower values of $(\rho_m\mu/\eta^*)$ in (4.32).

[+] The unit 'Erlang' is referred as 'Erl' in some of the charts with results for ρ_m and ξ_n.

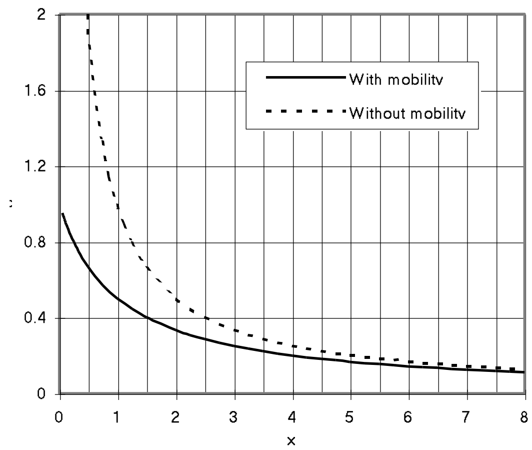
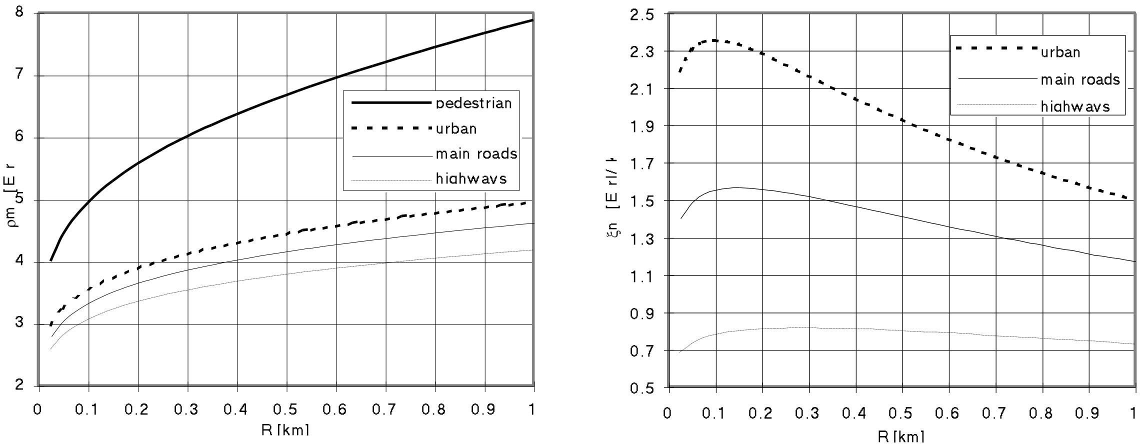


Fig. 4.10 – Normalised new connections linear traffic density *y* as a function of *x*.

However, it is worthwhile to note that connection dropping probability restrictions also need to be fulfilled. Because, with no guard channels for handover, $P_b = P_{hf}$, the maximum handover failure probability, $(P_{hf})_{max}$, should be computed according to (4.23) [Jabb96], and, because of that, it will be a linear function of *R* with slope $2\mu(P_d)_{max}/\eta^*$.

So, the traffic supported by *m* channels will depend on *R*; for the considered scenarios an example is given in Fig. 4.11, where: $m = 11$, $P_b = 2$ %, $P_d = 0.5$ %, $\mu = 1/3$ min^{-1}, and the values for the average velocity V_{av} and the velocity deviation Δ are the ones presented in Table 4.1. The supported traffic is obtained as the minimum ρ_m between the case $P_b = 2$ % and $P_{hf} = P_b = (P_{hf})_{max}$. However, from the results, one has actually verified that for this maximum coverage distances the supported traffic only corresponds to the restriction associated with $(P_{hf})_{max}$. As it can be seen, the supported traffic will not be constant, rather having a decreasing behaviour with the decrease of *R*.



a) Supported Traffic b) New connections traffic linear density

Fig. 4.11 – Traffic for *m* = 11 channels and the design made according to connection dropping probability restrictions.

In this case, the dependence of ξ_n on R will be as presented in Fig. 4.11.b) for the three scenarios with higher mobility, i.e., for each scenario, there is an optimum value for the coverage distance which maximizes ξ_n. These maxima correspond to lower values of R for the scenarios with lower mobility, it being lower for the scenarios with higher mobility. For coverage distances lower than this optimum value, ξ_n decreases with the decrease of R. This is due to connection dropping probability restrictions, which contradicts the behaviour expected from the simple analysis without considering it. It is also worthwhile to note that the new connections traffic linear density is much more sensitive to the mobility scenario than the supported traffic, because, the former, besides the dependence on ρ_m, also depends on P_h.

4.3.4. Numerical Results for Models Validation

It is now important to numerically compare the solutions for the blocking and handover failure probabilities between the exact and approximate models presented in Section 4.2, and to compute the approximation error for typical scenarios in MBS. Here, one has used a limited number of available results for the exact chain available in literature [SiSt97]; because of that, the case of a small network, with four cells and four channels, was considered. It is worthwhile to stress that one considered the case with m = 4 channels, instead of m = 11, only in order to use the results for the exact chain available in literature, up to the moment. The new connections generation rate is $\lambda = 0.5$ min^{-1} and the service rate is $\mu = 1$ min^{-1}, thus $\rho = 0.5$ Erlang. The exact results for the blocking and handover failure probabilities, as a function of the handover rate, i.e., the ratio $\gamma = \eta/\mu$, are presented in Fig. 4.12, as well as their values for the approximate chain, $P_b = P_{hf} = 0.00158$. The error associated with the blocking probability is given by

$$\varepsilon_{Pb} = \frac{P_b - (P_b)_{ex}}{(P_b)_{ex}} \tag{4.33}$$

as well as the error for the handover failure probability, ε_{Phf}, substituting P_b by P_{hf}. In Table 4.4 one presents values for ε_{Pb} and ε_{Phf} for several values of γ. For values of γ up to 1, the approximation errors, for the blocking and handover failure probabilities are lower than 1.44 and 7.77 %, respectively.

Table 4.4 – Approximation Errors for P_b and P_{hf}.

γ	ε_{Pb} [%]	ε_{Phf} [%]
0.01	0	~ 0
0.1	0.08	1.44
1	1.44	7.77
3.5	6.95	19.61
10	12.29	31.73

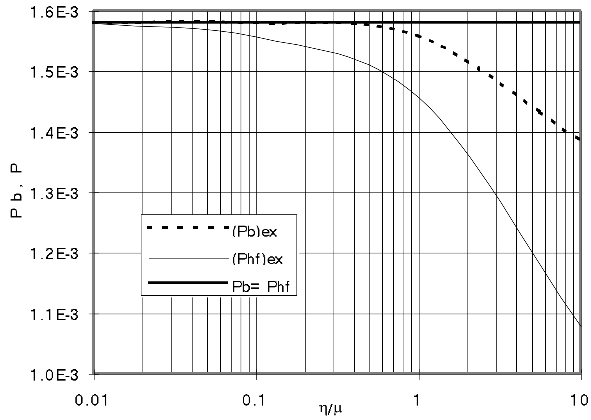


Fig. 4.12 – Blocking and handover failure probabilities, as a function of γ for m = 4 (partly from [Kell79]).

In order to obtain the range of maximum coverage distances that validate the approximation for the typical MBS mobility scenarios, Fig. 4.13 presents the variation of the parameter γ as a function of R. It decreases with R for all MBS scenarios, it being higher for higher mobility scenarios.

For design purposes, the traffic supported by m = 4 channels should be obtained following the approach presented in Section 4.3.3, where P_b is computed according to connection-dropping probability requirements, P_d = 0.5 %, Fig. 4.14. This approach allows simultaneously fulfil the requirements for blocking and handover failure probabilities. From Fig. 4.14, the supported traffic is ρ = 0.5 Erlang for R = (< 25),180, 280 and 550 m, for pedestrian, urban, main roads and highways scenarios, respectively. These values correspond to $\gamma \sim 3.5$. In this case, approximation errors for the blocking and handover failure probabilities are 6.95 % and 19.61%, respectively. Therefore, despite it is accurate for the computation of the blocking probability, the approximate model should be carefully applied for the computation of the handover failure probability. It is also worthwhile to note that, for the respective scenarios, γ = 1 for R = 75, 625, 975 and 1900 m.

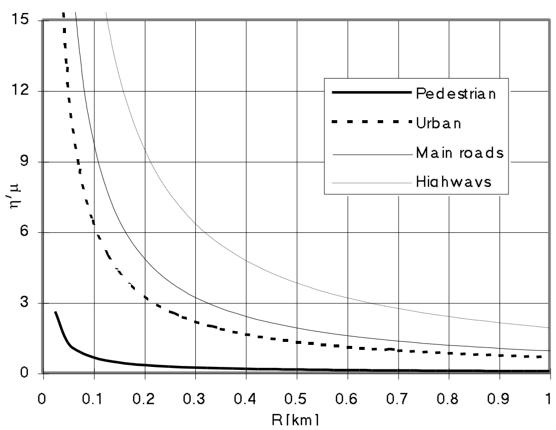


Fig. 4.13 – Parameter γ as a function of R.

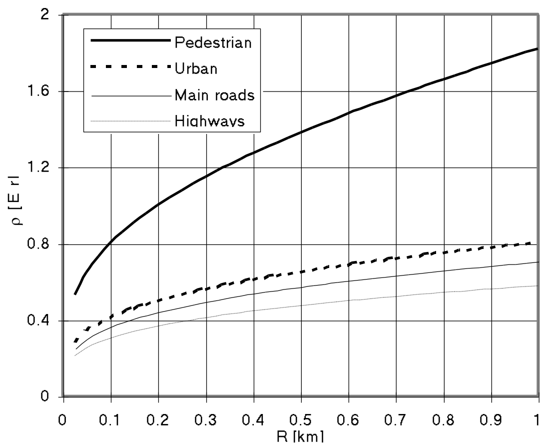


Fig. 4.14 – Supported traffic according to the connection-dropping probability requirements (P_d = 0.5%), m = 4.

For coverage distances larger than these minimum values, the approximation is valid for both P_b and P_{hf} because the approximation errors are always lower than the values given in Table 4.4; however, in this case, ρ is larger than 0.5 Erlang and one is not in the conditions related to Fig. 4.14. Anyway, it is possible that an improved accuracy of the approximate model can also occur for the handover failure probability for other set of values of ρ and m. Further work should be done in order to study the sensitivity of the results to these parameters. In the range of validity of the approximation, the models agree with the ones usually presented in literature, but the hypotheses that handover traffic should be Poisson distributed did not need to be used. In this case, the independence of the number of connections, n_i, among cells was also validated.

For the case where guard channels for handover are used, as the corresponding Markov chain is not irreducible, that theory cannot be applied and further research is needed to properly solve the problem. By now, one only can continue to solve such kind of problems assuming that the handover traffic is Poisson, which cannot be generally true.

4.4. Traffic from Mobility with Guard Channels for Handover

4.4.1. Blocking and Handover Failure Probabilities

Considering the use of guard channels for handover, assuming that the handover traffic can be approximate by a Poisson process [RoTs90], and that the new connections traffic is also Poisson distributed, which is valid for a number of users in a cell much larger than the supported traffic, when no queuing of new or handover connections is performed, the blocking and handover failure probabilities are given by [Jabb96]

$$P_b = \frac{(\rho_n + \rho_h)^c \sum_{k=c}^{c+g} \frac{\rho_h{}^k}{k!}}{\sum_{k=0}^{c-1} \frac{(\rho_n + \rho_h)^k}{k!} + (\rho_n + \rho_h)^c \sum_{k=c}^{c+g} \frac{\rho_h{}^k}{k!}} \tag{4.34}$$

$$P_{hf} = \frac{(\rho_n + \rho_h)^c \frac{\rho_h{}^g}{(c+g)!}}{\sum_{k=0}^{c-1} \frac{(\rho_n + \rho_h)^k}{k!} + (\rho_n + \rho_h)^c \sum_{k=c}^{c+g} \frac{\rho_h{}^k}{k!}} . \tag{4.35}$$

The total traffic supported by m channels is then $\rho_{m,g} = \rho_n + \rho_h$, when guard channels for handover are considered. The new connections traffic and the traffic coming from handover can then be easily obtained as in Section 4.3.3, replacing ρ_m by $\rho_{m,g}$ [Jabb96]. This approach allows simultaneously fulfil the requirements for both blocking and connection dropping probabilities. These requirements are stringent, typically P_b = 2% and P_d = 0.5 %, distinctly limiting system performance in a way that depends on the average velocity of mobile terminals and on R.

4.4.2. Supported Traffic

The examples given here were obtained for the conditions mentioned in Section 4.3.3.

For g = 0, using the supported traffic $\rho_{m,g}$ that verifies P_b = 2%, which does not depend on R, one obtains values for the new connections traffic linear density that increase with the decrease of the coverage distance. However, the corresponding connection-dropping probability constraints associated with (4.23) and with $P_b = P_{hf}$ (and in this case also equal to 2 %), Fig. 4.15, are only fulfilled in the pedestrian scenario, and only for $R > 300$ m; a way to resolve this limitation, without drastically decreasing the new connections traffic linear density, is the use of guard channels for handover.

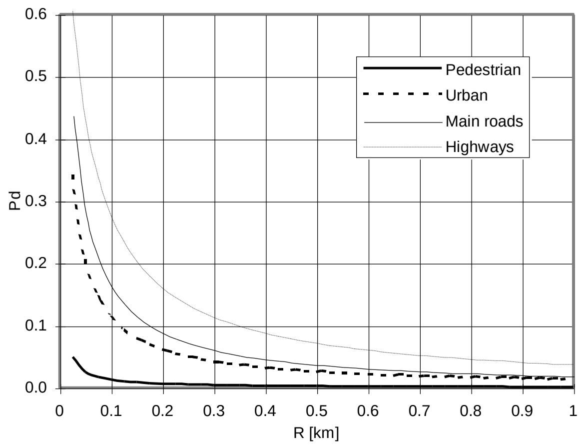


Fig. 4.15 – Connection-dropping probability for g = 0.

From an operator's point of view, in order to achieve MBS provisional coverage distances, approximately in the range 100-350 m [VeCo97], one intends to increase ξ_n while R decreases. In order to obtain results for the supported traffic the procedure was the following: taking P_d = 0.5%, (4.23) was used to get a value for P_{hf}; with this P_{hf} value and with P_b = 2%, (4.34) and (4.35) were solved separately for the supported traffic $\rho_{m,g}$ (using (4.29) and (4.30)), and the respective values, ρ_{Pb} and ρ_{Phf}, were obtained; in order to cope with both probability requirements, the minimum of these two was taken.

First, one considered the case without guard channels for handover (g = 0). Assuming a total of m = 11 channels, although the curves are not presented, the supported traffic increases with the increase of the coverage distance, being higher for the short duration connections, Table 4.5.

Table 4.5 – Supported Traffic without Guard Channels for Handover.

$\rho_{m,g}$ [Erlang]	μ = 1/3 min^{-1}			μ = 1/20 min^{-1}		
Scenario	R = 100 m	R = 200 m	R = 350 m	R = 100 m	R = 200 m	R = 350 m
Pedestrian	5.0	5.6	6.2	4.1	4.6	5.0
Urban	3.5	3.9	4.2	3.0	3.3	3.5
Main roads	3.3	3.7	3.9	2.9	3.1	3.3
Highways	3.1	3.3	3.6	2.6	2.9	3.1

For long duration connections, one observed that the supported traffic is approximately 85 % of the one for short duration connections. Nevertheless, system capacity should be measured using the new connections traffic linear density, which is being done in the next section. Considering the use of guard channels for handover, while $\rho_{P_b}(R)$ is almost constant with R, right part of the curves in Fig. 4.16 (example for g = 1), $\rho_{P_{hf}}(R)$ increases with R (since it was obtained according to (4.23), and η depends on R, as in (4.26) and (4.27)), left-hand side of the curves. Thus, a breakpoint exists at the intersection of both curves, where $\rho_{Phf}(R) = \rho_{Pb}(R)$, and for values of R lower than this breakpoint the curves have an appreciable slope.

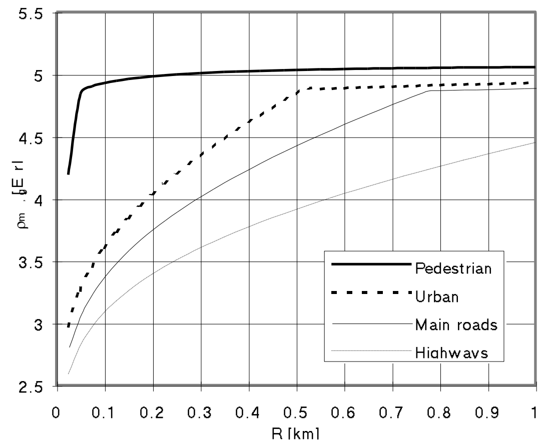


Fig. 4.16 – Traffic supported by m = 11 channels with g = 1.

One can observe that the supported traffic decreases as the velocity of the associated scenario increases, mainly in the zone of the curves limited by handover failure; it can be seen as well that the breakpoint occurs for increasing values of *R* for faster and faster mobiles. As it could be expected, when *g* increases, $\rho_{P_b}(R)$ decreases; however, as $\rho_{m,g}(R)$ is the minimum between $\rho_{P_b}(R)$ and $\rho_{P_{hf}}(R)$, this decrease is only effective for the part of the curves where $\rho_{P_b}(R)$ is lower than $\rho_{P_{hf}}(R)$. The challenge in the design for low values of *R* is finding values for *g* that, for a given *m*, both maximise ρ_{Phf} and keep it lower than ρ_{Pb}, mainly for the scenarios with high mobility (urban, main roads and highways).

4.4.3. New Connections Traffic Linear Density

4.4.3.1. Short Duration Connections

For given values of *m* and *g*, one can then obtain the curves for the new connections traffic linear density $\xi_n(R)$ according to (4.31); Figs. 4.17 and 4.18 show these curves for μ = 1/3 min^{-1} and *g* = 1, 2 (the latter only for the highest mobility scenarios).

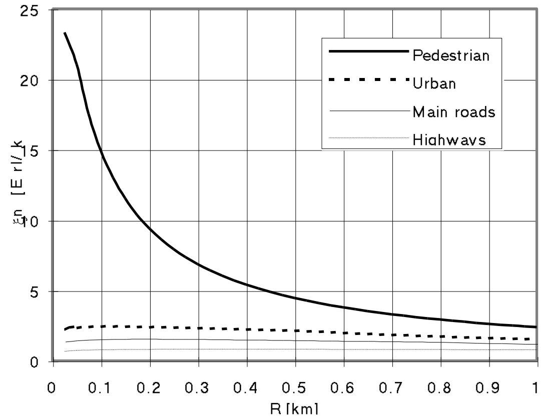


Fig. 4.17 – New connections traffic linear density, for *m* = 11 and *g* = 1, μ = 1/3 min^{-1}.

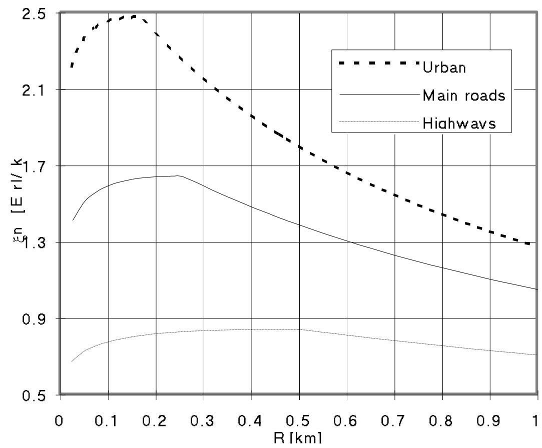


Fig. 4.18 – New connections traffic linear density, for *m* = 11 and *g* = 2, μ = 1/3 min^{-1}.

For the pedestrian case, as $\rho_{m,g}$ is almost constant for all the range of R, one basically observes that it follows the behaviour of the ratio at the right member from (4.31). For the three scenarios with higher mobility, $\xi_n(R)$ presents maxima, depending on the velocity and on g; these maxima occur for distances lower than the breakpoints, corresponding, for design purposes, to optimum values of R, R_{opt}, Table 4.6. They agree with the provisional values for MBS, and also with the need to use larger cell lengths for high mobility scenarios, owing to the cost associated with signalling [SiBr96]. One can also see that breakpoints occur for lower coverage distances as g increases.

Table 4.6 –Approximate Values for R_{opt} and Maximum Values for ξ_n with m = 11, μ = 1/3 min^{-1}.

Scenarios	R_{opt} [m]		ξ_n [Erl/km]	
	g = 1	g = 2	g = 1	g = 2
Urban	125	150	2.40	2.47
Main roads	175	250	1.60	1.65
Highways	375	475	0.82	0.84

Fig. 4.19 presents $\xi_n(R)$ for the highway scenario for several values of g. One observes an improved new connections traffic linear density for g = 2 for 160 < R < 610 m, the maximum ξ_n = 0.84 Erlang/km being obtained for R_{opt} = 475 m.

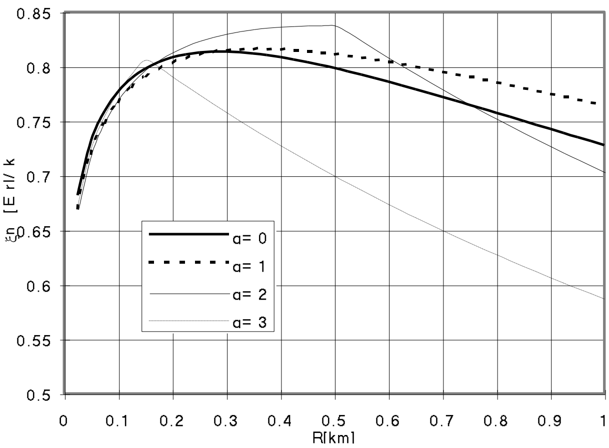


Fig. 4.19 – New connections traffic linear density, for m = 11 and g = 0, 1, 2 and 3, in the highway scenario.

When g = 3, an improvement of the new connections traffic linear density only exists for $130 < R < 160$ m, the maximum being obtained for $R_{opt} = 130$ m, ξ_n = 0.81 Erlang/km. It is noticeable that the use of guard channels makes a difference in system performance, specially for high speed scenarios, where it allows to overcome the problems associated with handover failure constraints. For these scenarios, and for the typical coverage distances in MBS, the new connections traffic linear density is one order of magnitude below the values obtained for the pedestrian scenario (where it is approximately 10-15 Erlang/km), decreasing from 2.47 Erlang/km, in the urban scenario, down to 0.84 Erlang/km, in the highway scenario.

4.4.3.2. Comparison between the Long and Short Duration Connections

Depending on the maximum coverage distance of the cells, the curves for the supported traffic and new connections traffic linear density are different. Although traffic increases with *R* and the (total) traffic linear density, $\rho_{m,g}/(2R)$, decreases with it, the new connections traffic linear density increases up to an optimum value of *R*, after which it starts to decrease, except for case of the pedestrian scenario with short duration services. In the following examples, the values for the coverage distance where $\xi_n(R)$ has a maximum are sought for short and long duration connections and for the various mobility scenarios, such that system capacity is maximised, Figs. 4.20-4.24.

For higher mobility scenarios, and long duration services, maxima occur for larger values of *R*; one presents results for coverage distances up to 2 km, although they will not be reached in actual cells. The cases with g = 3 channels for handover were only considered for the cases (mobility scenario/type of application) where an improvement occurs relatively to the case g = 2.

For short duration services, higher optimum values for ξ_n were obtained with g = 2 and R = 175, 250 and 475 m (ξ_n = 2.47, 1.65 and 0.84 Erlang/km), for the urban, main roads and highways scenarios, respectively.

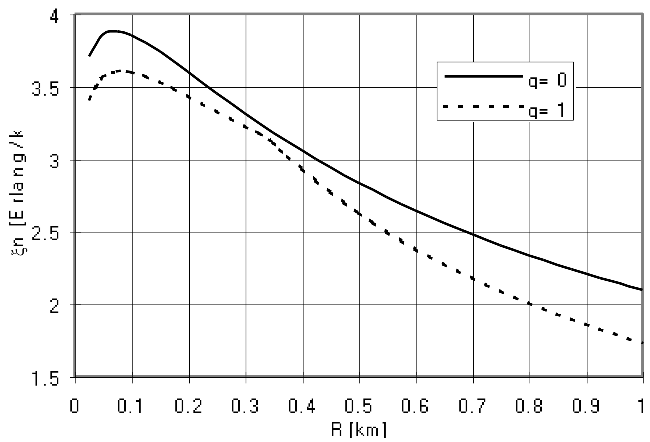


Fig. 4.20 – ξ_n for the pedestrian scenario and long duration services.

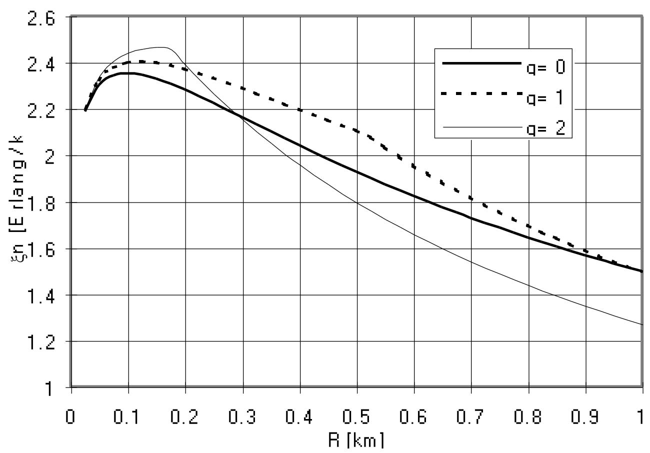


Fig. 4.21 – ξ_n for the urban scenario and short duration services.

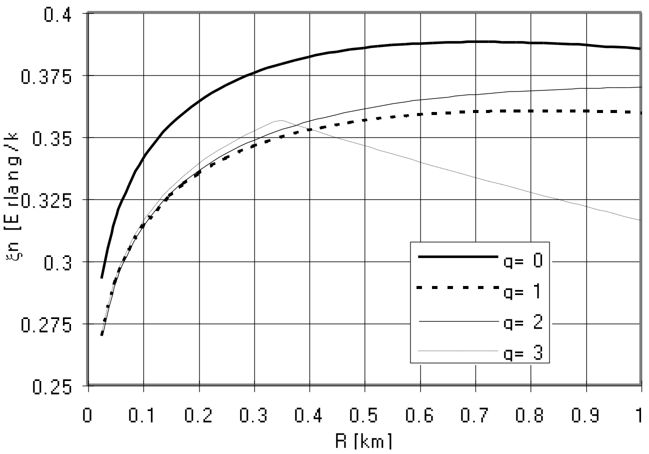


Fig. 4.22 – ξ_n for the urban scenario and long duration services.

For long duration services, lower optimum values for ξ_n were obtained for g = 0 and R = 75, 700, 1000 and 2000 m (ξ_n = 3.9, 0.39, 0.26 and 0.13 Erlang/km), approximately, for the four respective scenarios.

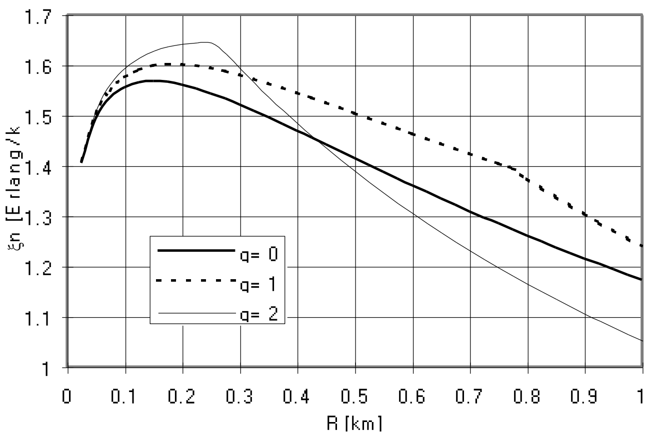


Fig. 4.23 – ξ_n for the main roads scenario and short duration services.

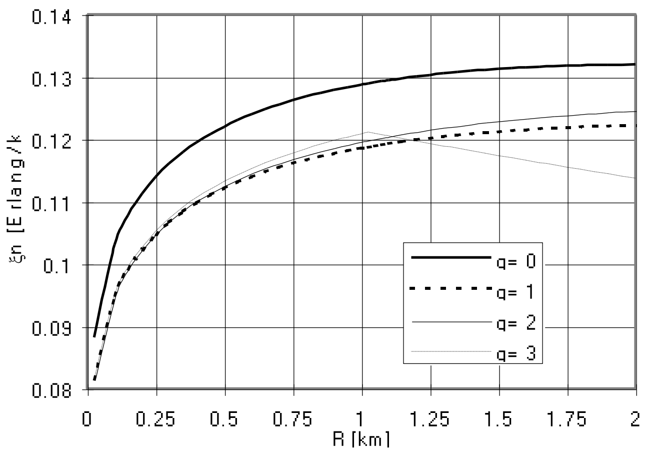


Fig. 4.24 – ξ_n for the highways scenario and long duration services.

It is worthwhile to verify that, in this case, the utilisation of guard channels for handover does not improve system performance. One could suppose that the increasing of g would improve it, but the consequent degradation of blocking probability performance imposes a limitation that is not possible to solve. From long duration services to short duration ones there is a ratio of approximately 1/6 between the values of new connections traffic linear density, while the corresponding coverage distances are four times larger. As the optimum coverage distances, for the former, are near the feasible ones, this implies that long duration services will operate in systems with coverage distances lower than the optimum values, the feasible values for, e.g., R = 150 m, being ξ_n = 3.4, 0.36, 0.23 and 0.11 Erlang/km (respectively 87, 91, 88 and 82 % lower than the optimum ones). Note that although R = 150 m is higher than the optimum coverage distance in the pedestrian scenario, it is lower than it in the remaining cases. For the envisaged coverage distances, although the use of guard channels for handover leads to benefits in system performance for short duration services, it causes some degradation when long duration ones are considered.

4.4.3.3. Variation of the New Connection Traffic Linear Density

Considering m fixed, and g as a parameter, one can observe that there are values of R that maximise ξ_n for each pair (m, g). The variation of new connections traffic linear density for $g \neq 0$ relatively to the case $g = 0$ is defined as

$$\chi_{n[\%]} = (\xi_{n[g\neq0]} / \xi_{n[g=0]}) \cdot 100. \qquad (4.36)$$

As one has already seen for short duration services, it is important to quantify how much the improvement is. For the pedestrian scenario, although the graph is not presented, there is only a slight improvement for R < 100 m. In the urban scenario, the improvement is relevant for 0 < R < 1000 m with g = 1 (10 % maximum), and for 0 < R < 280 m with g = 2 (7 % maximum), Fig. 4.25. The use of two guard channels for handover in the main roads scenario leads to an improvement in performance exactly for the range of coverage distances foreseen for MBS, i.e., 100 < R < 350 m (7 % maximum).

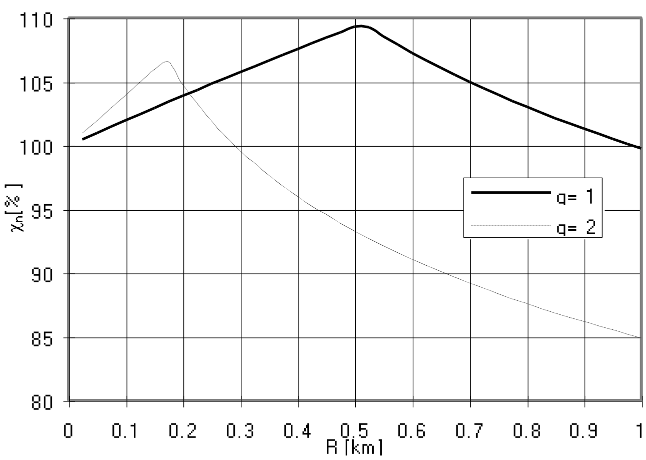


Fig. 4.25 – $\chi_{n[\%]}$ for the urban scenario.

In the case of the highways scenario, g = 2 is recommended for coverage distances up to 500 m, a maximum improvement of 5 % being achieved; however $g = 3$ also leads to a little improvement in a small range of coverage distances, 0 < R < 150 m, Fig. 4.26.

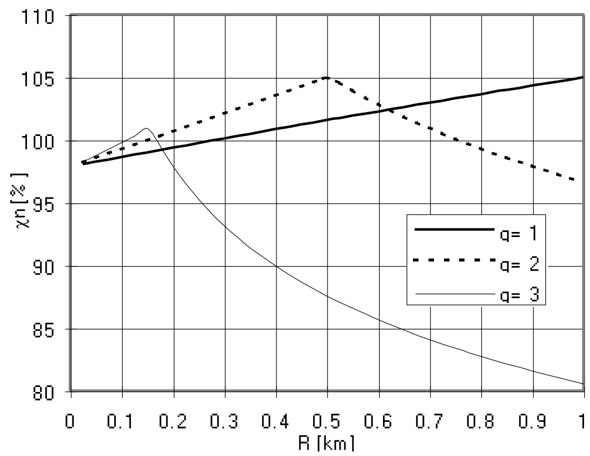


Fig. 4.26 – Variation of new connections traffic linear density, highways.

Results for the fixed *g/m* case are presented in Figs. 4.27-4.28.

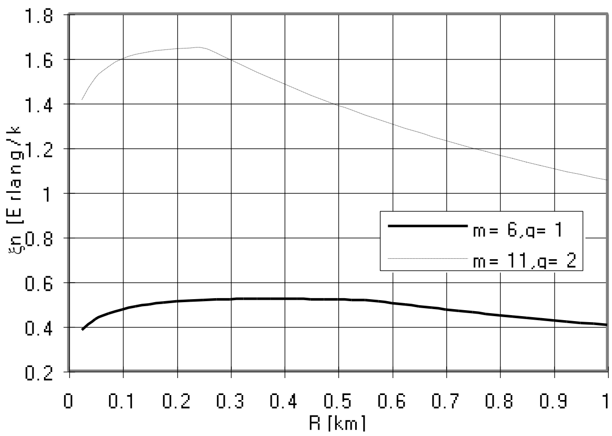


Fig. 4.27 – ξ_n for the main roads scenario, g/m ~17-18%.

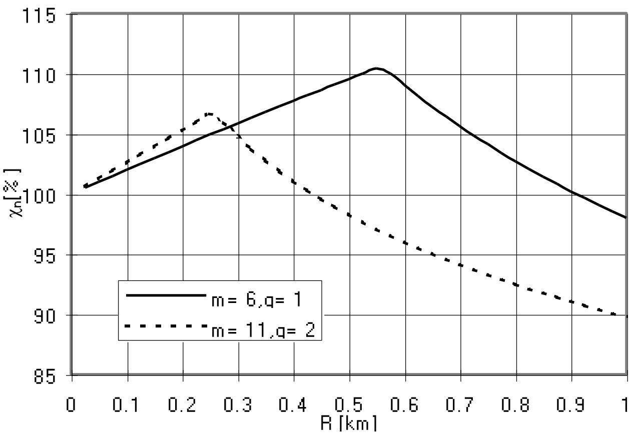


Fig. 4.28 – $\chi_{n[\%]}$ for the main roads scenario, g/m ~17-18%.

The use of guard channels results on a slightly better performance for $100 < R < 900$ m, with $m = 6$ (10 % maximum), while for $m = 11$ a little extra improvement exists for low values of R, i.e., $100 < R < 300$ m (7 % maximum). Therefore, for fixed values of g/m, and the coverage distances of interest, the improvement in system capacity is similar for different values of g. However, it is slightly higher when larger m and g are used.

4.5. Conclusions

An approximate traffic model for systems without guard channels for handover, which takes into account both handover and new traffic connections, was presented, and its validity was shown based on the theory of Jackson networks, the reversibility of its associated Markov process. These conclusions agree with the models usually presented in literature, but the hypothesis that handover traffic should be Poisson distributed was not needed. The independence of the number of connections among the cells was also validated. Numerical values were presented that validate the approximation for a small micro-cellular network, with linear coverage geometry. For typical coverage distances foreseen for MBS, this approximate model should be carefully applied for the handover failure probability, because of its high approximation error (at least in the situation presented here).

Models to compute the supported traffic and the new connections traffic linear density, as a function of velocity and cell length, were examined. For a fixed blocking probability, one verifies that the new connections traffic linear density, which was used as a measure of system capacity, is upper limited by the average cross-over velocity of the associated scenario, having lower values for scenarios with high mobility, varying differently depending on the average cross-over velocity. However, for actual scenarios connection-dropping probability constraints are not fulfilled in such conditions. Thus, in order to simultaneously verify the constraints for the blocking and the handover failure probabilities, it is necessary to consider lower blocking probability thresholds, which leads to a decrease of the new connections traffic linear density proportional to R for such configurations. Feasible values for the new connections traffic linear density were obtained, where there are optimum values for the coverage distance that maximise it. These maxima correspond to lower values of the coverage distance for scenarios with lower mobility. They are however lower for scenarios with higher mobility.

In order to overtake the limitation associated with high mobility scenarios, configurations that use guard channels for handover were analysed for both short and long duration connections. Results were obtained for different values of the number of guard channels, g. In the case of short duration connections, for the coverage distances foreseen for MBS, higher optimum values for the new connections traffic linear density are obtained for $g = 2$; however, for the highways scenario, the corresponding coverage distances are larger than the foreseen cell lengths. It has also been verified that there is degradation in system capacity, measured in Erlang/km, for higher and higher mobility scenarios.

The distinction between short and long duration connections services was done and one has concluded that the use of guard channels for handover has only to be considered for the former, allowing to increase system capacity of about 10% with $g = 2$, mainly for lower values of R, where these limitations are more demanding. For long duration connections, the use of guard channels for handover has not shown to be advantageous. From long duration to short duration connections, the new connections traffic linear density is 1/6 less (which is approximately the ratio between the service rates), and the optimal coverage distances are four times larger. For fixed values of g/m, and the coverage distances of interest, the improvement in new connections traffic linear density is similar for different values of m and g. However, it is slightly higher for larger values of m.

One can use the conclusion obtained for long duration connections to justify not using guard channels for handover in the multi-service traffic analysis (as the mixture of applications is mostly made of long duration connections). These results can be generalized to other cellular geometries, at least approximately, if the actual distance the mobile has to travel to completely traverse a cell is also $2R$.

Chapter 5

Multi-service Traffic

5.1. Introduction

Nowadays analysts are frequently faced with incomplete knowledge of user demands, as well as uncertainty about future evolution of MBS; this problem was also faced with the same difficulties. Although it is not necessary that future MBS will be based in ATM technology, the work from RACE-MBS and ACTS-SAMBA projects considered so, this being the approach one follows here. In ATM networks, the available resources are shared in a way that allows for multiplexing of different traffic sources. As far as different sources do not take this peak values simultaneously, for a fixed number of users, the network can use less resources than would be required if resources were assigned according to the peak amounts required by each user, or alternatively, the number of users accommodate by a fixed amount of resources can be increased, and a gain from this statistical multiplexing occurs [Sait94].

In order to model multi-service in MBS, one needs first to model the air interface access of MSs to BS resources, as well as the slot arrival process. Because traffic can be generated from different mixtures of voice, data or video sources, it is important to obtain performance measures for resource usage, given the slot arrival process(es). One analyses the associate models, making use of some interesting characteristics of the frame structures [PrSv99], and of the MAC protocols [ALMH98] as well. The DSA++ MAC protocol [ALMH98], which was being under consideration in the wireless ATM standardisation process of the Wireless ATM Group (WAG) of the ATM Forum and the Broadband Radio Access Networks (BRAN) project of ETSI [ALMH98], allows for considering connection oriented communications [KrSL98], [KrSc98]. By allocating a so-called container, formed by a certain number of slots, a BS defines channels like in circuit-switched connections. Thus, the methodologies for circuit-switched network analysis supporting heterogeneous traffic can be applied, while the MAC protocol guarantees that the maximum delay is kept under values that do not affect the performance of applications [ALMH98], namely real-time ones. Following this approach, for non-real time applications, one assumes that a minimum data rate is guaranteed by the system, e.g., in ABR (Available Bit Rate) applications, only this minimum being considered in traffic computations. The access to supplementary resources (if needed) is only possible if they are available, but it has not to be taken into account in the computations of the blocking probability, because it does not correspond to the worst-case situation.

Therefore, one needs to identify relevant models for the characterisation of voice, data and video traffic sources, and choose the appropriate one(s), in view of the need of finding a unified model to evaluate the QoS as a fraction of the aggregate traffic. Hence, from the point of view of traffic engineering, keeping in mind that these models are needed to obtain a merit function for cellular MBS planning and optimisation purposes, the implementation feasibility of the aggregate traffic model is crucial in the choice of the basic model(s) for the sources. It is also worthwhile noting, at least in this phase, that an analytical approach is sought, instead of a simulation one. Examples are worked out for sets of applications in actual deployment scenarios either considering or not terminal mobility.

In Section 5.2, the characteristics and limitations of traffic sources models are presented, i.e., the models that characterise the bursty characteristics of traffic in a way that is suitable for cellular planning and dimensioning purposes. General models are presented and the choice of an approximated one is justified.

In Section 5.3, the Bernoulli-Poisson-Pascal model is proposed for the computation of the blocking probability in such mobile multi-service systems. After presenting the basis of this model, one describes the way how the occupancy *pmf* (probability marginal function) is computed, and the different solutions are described for each of the cases: Bernoulli, Poisson and Pascal. Then, the algorithm for the computation of the blocking probability is described. Finally, the user model for application and service components activation is presented, and the way an equivalent user of an application generates an actual service component user is described.

In Section 5.4, the parameters for the characterisation of service components are presented. The correspondence between applications and service components is described, and the service component parameters are addressed. The application data rates and the asymmetry factors are determined, and an approximated approach to take terminal mobility into account is presented.

In Section 5.5, some of the dimensioning assumptions regarding the frame, container and slot structures are presented, and the assumptions made on the upper bounds for system capacity, in terms of user available kb/s per operator or per cell, are described, where a staircase shaped upper boundary for user data rates, in terms of terminal mobility, is identified.

In Section 5.6, results for the blocking probability as a function of the fraction of active users, and for the supported fraction of active users (for a given threshold of the blocking probability) are presented. The assumptions considered for the number of potential users in a cell and for the number of up- and downlink available resources are first presented. Then, the results for supported fraction of active users, the number of supported users and the spectral efficiency are presented for the cases of absence and presence of mobility, for a fixed *R*. Finally, in order to provide results to be fed into the cost/revenue analysis of Chapter 6, the dependence of these variables on *R* is analysed. This allows for distributing the available resources between the links, according to handover failure probability constraints, for a given value of the reuse pattern (which depends on the band, and on the re-use geometry).

Conclusions are drawn at the end of the Chapter.

5.2. Characterisation and Limitations of the Source Traffic Models

5.2.1. Bursty Behaviour

Multi-service traffic models can be divided into two families, one more suitable for discrete-event simulation purposes, and another that is more appropriate for analysis [FrMe94]. Burstiness is present in traffic if the process formed by the arrival instants T_1, T_2, .., T_n appears to form a visual cluster, i.e., periods when the inter-arrival times (A_1, A_2, …, A_n) between discrete entities (e.g., packets, cells or slots) are short are followed by periods when inter-arrival times are long. However, the mathematical modelling of burstiness is complex, and different notions arise.

The simplest ones take into account the first order properties of traffic, i.e., the peak to mean ratio and the coefficient of variation, defined as the ratio of the standard deviation to mean inter-arrival time. In contrast, according to [FrMe94], the peakdness measure and the index-of-dispersion measure do take into account the temporal dependence of traffic (second order properties). Finally, also according to [FrMe94], the Hurst-parameter can also be used as a measure of burstiness via the concept of self-similarity.

The next Sections give an overview of different bursty traffic sources models for audio, data and video.

5.2.2. Models for the Characterisation of Traffic Sources

5.2.2.1. Renewal Processes

The difficulty in the multi-service traffic analysis comes from modelling the arrival process that results from superimposing a number of independent sources. An analytical approach is sought instead of a simulation one. This Section introduces renewal traffic processes and the important special cases of Poisson and Bernoulli ones. Renewal models have a long history owing to their relative mathematical simplicity [Ross83]. In a renewal traffic process, the inter-arrival times, A_n, are independent and identically distributes (i.i.d.), but their distribution is allowed to be general. However, with few exceptions, the superimposing of independent renewal processes does not yield a renewal process. This is because the superimposed traffic has a strong auto-correlation, which is not modelled by renewal processes [FrMe94]. The importance of capturing auto-correlation comes from the role of auto-correlation functions as a statistical proxy for temporal dependence [FrMe94], and also because a positive auto-correlation among inter-arrival times can explain, to a large extent, the phenomenon of traffic burstiness. As bursty traffic is expected to be dominant in mobile broadband networks, models that capture the auto-correlated nature of traffic are essential for predicting their performance. Furthermore, traffic that is bursty in nature gives rise to much worse performance (such as mean waiting times) than renewal traffic, which lacks temporal dependence.

One of the most important examples of renewal is the Poisson process, the oldest traffic model [FrMe94]. In fact, a Poisson process can be characterised by a renewal process whose inter-arrival times A_n are exponentially distributed with rate parameter λ,

$$\text{Prob}\{A_n \le t\} = 1 - e^{-\lambda t}. \tag{5.1}$$

It also corresponds to a counting process $N(t)$ satisfying

$$\text{Prob}\{N(t) = n\} = e^{-\lambda t} \frac{(\lambda t)^n}{n!} \tag{5.2}$$

in which the number of arrivals in disjoint intervals is statistically independent (independent increment property).

Poisson processes have three elegant and important properties:

1. The superposition of Poisson processes is still a Poisson process whose generation rate is the sum of the elementary rates
2. Because of the independent increments property, it is a memoryless process
3. They are very common in traffic applications comprising a larger number of independent traffic streams, each of which may be quite general (the basis of this phenomenon being known as Palm' s theorem).

As a consequence, traffic streams on main communication arteries commonly follow a Poisson process. However, traffic aggregation (multiplexing) does not always result in a Poisson stream having, e.g., the self-similarity property.

The discrete-time analogue of Poisson processes are the Bernoulli ones, discrete time referring to the case when time is slotted. As the continuous-time Poisson process, time-dependent and compound (without the axiom of regularity) Bernoulli processes are defined in a natural way. The probability of an arrival in any time slot is p, independent of any other ones. It follows that for slot k the corresponding number of users N_k is binomial distributed,

$$\text{Prob}\{N_k = n\} = \binom{k}{n} \cdot p^n \cdot (1-p)^{k-n},\ n = 0, ..., k \tag{5.3}$$

The inter-arrival time is geometric distributed with parameter p,

$$\text{Prob}\{A_n = j\} = p \cdot (1-p)^j,\ j \in \text{IN}_0 . \tag{5.4}$$

Although there are other types of renewal processes, e.g., phase type ones [FrMe94], the details are not presented here.

5.2.2.2. Markov and Markov-Renewal Traffic Models

According to [FrMe94], contrasting with renewal traffic models, Markov and Markov-renewal traffic models introduce dependence into the random sequence $\{A_n\}$, thus, they can potentially capture traffic burstiness, because of non-zero auto-correlations in $\{A_n\}$.

For a given state space S'=$\{s_1, s_2, .., s_{Ns}\}$, let X_n be a random variable that defines the state at time n. The set of random variables $\{X_n\}$ forms a discrete Markov chain, if the probability of the next value $X_{n+1} = s_j$, $j = 1, 2, \ldots, N_s$, depends only on the current state. This is known as Markov property [Klein75]. If state transitions occur at integer values 0, 1, …, n, …, e.g., for slot arrivals, the Markov chain is discrete. Otherwise, the Markov chain will be a continuous-time one.

Markov property implies that the future depends on the current state, and neither on previous states nor on the time already spent in the current state. This restricts the random variable that describes the time spent in a state to a geometric distribution in the discrete case, and to an exponential distribution in the continuous one, the rate parameters depending on the state from which the jump occurred, and resulting in dependence among inter-arrival times [FrMe94].

Markov-renewal models are more general than discrete-state Markov processes, yet retaining a measure of simplicity and analytical tractability. A Markov renewal process $R_p=\{(M_n, \tau_n)\},\ n \in \text{IN}_0$ is defined by a Markov chain $\{M_n\}$ and its associated jump (transition) times $\{\tau_n\}$, subject to the following constraint: the pair (M_{n+1}, τ_{n+1}) of next-state and inter-jump time depends only on the current state M_n, but not on the previous states nor on the previous inter-jump times. Again, if forward jumps of $\{M_n\}$ are interpreted as arrivals, there is dependence on the arrival process. Also, contrasting with the Markov process case, the inter-arrival times can be arbitrarily distributed, and these distributions depend on both states straddling each inter-arrival interval.

The Markovian Arrival Process (MAP) is a broad and versatile subclass of Markov renewal traffic processes, enjoying analytical tractability [FrMe94], but will not be considered here.

5.2.2.3. Markov-Modulated Traffic Models

Markov-modulated models are an extremely important class of traffic models, where an explicit notion of state is introduced into the description of a traffic stream, i.e., an auxiliary Markov process is evolving in time, and its current state controls (modulates) the probability law of the traffic process. In [FrMe94], it is explained how the probability law for arrivals is modulated by the state of the Markov process *M'*, i.e., traffic is stochastically subordinated to that process such that, in each of the *k* states, the probability law of traffic arrivals is completely determined by *k*, and this holds for every state. Thus, when *M'* undergoes a transition to, say, state s_j, a new probability law for arrivals stands for the duration of state s_j, and so on.

The most commonly used Markov-modulated model is the Markov-Modulated Poisson Process (MMPP) one, which combines the simplicity of the modulating (Markov) process with that of the modulated (Poisson) process. In this case, the modulation mechanism simply stipulates that in state *k* of the process *M'*, arrivals occur according to a Poisson process at rate λ_k. As the state changes, so does the rate. The introduction of MMPP processes allows the modelling of time-varying sources, while keeping the analytical solution of the related queuing performance tractable [FrMe94], [Adas97].

The MMPP parameters, i.e., the elements of the transition matrix $Q = [Q_{ij}]$, can be easily estimated from the empirical data as follows: simply evaluate the empirical data, and then estimate Q_{ij} by calculating the fraction of time when *M* switched from state s_i to state s_j.

For example, MMPP can model a mixture of voice and data, data and video, or even voice, data plus video. For the first, for instance, voice arrivals while in state *k* are assumed to be Poissonean with rate λ_k, while data packets are also Poisson distributed with rate λ_{dk}, the resulting rate at state s_k being $\lambda_{dk}+\lambda_k$. The performance measures, such as queuing distribution and the moments of the delay distribution, are obtained by using the MMPP/G/1 queue analysis [Rebe96]. In [FrMe94], an example is given for voice that considers a two-state MMPP model, where one state is ON with an associated positive Poisson rate, and the other is OFF with associated zero-rate, these models being known as Interrupted Poisson Processes (IPP) for obvious reasons. Also note that an MMPP process with *J*+1 states can be obtained by the superposition of *J* i.i.d. IPP sources.

The ON-OFF source model [Adas97] is the most popular source model for voice [MASK88], Fig. 5.1. In this model, packets are only generated during talk spurts (ON state) with fixed inter-arrival times. The time spent in ON and OFF states is exponentially distributed with means α^{-1} and β^{-1}, respectively.

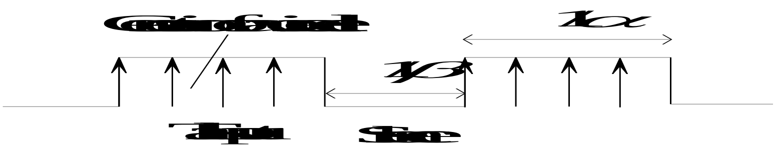


Fig. 5.1 –Voice source behaviour [Sait94].

IPP is also a two-state process, arrivals occurring only in the active state, according to a Poisson distribution with rate λ. Hence, IPP and ON-OFF models differ in inter-arrival times during the active (ON) state ($\alpha = 1$ for the former). MMPP is one of the most well known models, unlike the majority of others, which are normally exclusive for a given traffic source type and not much used. Even though, in those cases, MMPP is used as a reference for comparison purposes.

Transition-modulated processes are a variation of the state modulation idea. Essentially, the modulating agent is a state transition rather than a state per se. A state transition can be however described simply by a pair of states, whose components are the previous and the next transitions, the generalisation of a transition-modulated traffic model to continuous time being straightforward; some work on discrete-time ones is also referred in [FrMe94]. It is also told that Markov-modulated traffic models are a special case of Markovian transition-modulated ones, while, conversely, Markovian transition-modulated processes can be thought as Markov-modulated ones, but on a larger state space. A multiple transition-modulated traffic model can be defined, for each class of interest, the complete traffic model being obtained by superimposing individual traffic ones.

5.2.2.4. Fluid Traffic Models

Fluid models characterise traffic as a continuous stream with a parameterised flow rate, such as b/s, so that a traffic volume replaces a traffic count. These models are appropriate for the cases where individual units of traffic (packets, slots or cells) have little impact on the performance of the network, and where individual units are numerous relative to a chosen time scale. In ATM, the high transmission speeds (say, on the order of a Gigabit per second) render the transmission impact of an individual cell negligible, thus, the analogy of a cell to a fluid molecule being a plausible one [FrMe94]. Fluid models are conceptually simple, and their simulation has an important advantage over other models. For instance, in an event simulation of an ATM multiplex, all models that distinguish between cells, and consider the arrival of each cell as a separate event, consume vast amounts of memory and CPU (Central Processing Unit) resources. In contrast, fluid models characterise the incoming cells by a flow rate, an event being only triggered when the flow rate changes. Since flow rate changes happen much less frequently than cell arrivals, considerable savings in computing and memory resources are achieved. Typically, larger traffic units (such as coded frames) are of greater interest than individual cells. Modelling the larger units as discrete traffic and their transport as fluid flow, would give the best of both worlds: one can measure waiting times and loss probabilities, and enjoy savings on simulation computing resources.

Typical fluid models assume that sources are bursty – of the ON-OFF type. While in the OFF state traffic is switched OFF, in the ON state traffic arrives deterministically at constant rate λ. For analytical tractability, the duration of the ON and OFF periods are assumed to be exponentially distributed and mutually independent, i.e., they form an alternating renewal process [FrMe94]. A Markov model of a set of quantized (fluid) traffic rates is presented in [SMRA89]. Fluid traffic models of this kind can be analysed as Markov-modulated constant rate traffic. The host of generalisations, described above for MMPP, carries over to fluid models as well, including multiple sources and multiple classes of traffic.

5.2.2.5. Auto-Regressive Traffic Models

Auto-Regressive (AR) models [FrMe94] define the next random variable in the sequence as an explicit function of previous ones within a time window stretching from the present into the past. Such models are particularly suitable for modelling VBR-coded video, a foreseen major consumer of bandwidth in emerging high-speed communication networks. The nature of video frames is such that successive frames within a video scene vary very little visually (recall that there are normally 30 frames per second in a high quality video). Only scene changes or other visual discontinuities can cause abrupt changes in frame bit rate, thus, the sequence of bit rates (frame sizes) comprising a video scene may be modelled by an autoregressive scheme, while scene changes can be modelled by some modulating mechanism, such as a Markov chain.

Although it is easy to estimate the AR model parameters, and to generate the sequence recursively, the exponential decay of the auto-correlation function makes the model unable to capture auto-correlation functions that decay at a rate slower than the exponential. The AR model is approximated, in [MASK88], by a Markov modulated fluid model, in order to obtain analytical queuing performance results. AR processes with Gaussian distribution cannot capture VBR video traffic probability distribution, since the latter exhibits heavier tail behaviour than the former. Another example of AR models are the TES (Transform-Expand-Sample) ones, which, according to [FrMe94], can be used to generate synthetic streams realistic traffic to drive simulations of communication networks.

5.2.2.6. Self-similar Traffic Models

Recent studies of high-quality, high-resolution traffic measurements have revealed a new phenomenon with potentially important ramifications to the modelling, design, and control of broadband networks [FrMe94]. These include an analysis of hundreds of millions observed traffic packets over an Ethernet LAN in an R&D environment, and an analysis of a few millions of observed frame data generated by VBR video services. In these studies, referred in [FrMe94], packet traffic appears to be statistically self-similar, mainly traffic aggregation in the main communication streams. A self-similar (or fractal) phenomenon exhibits structural similarities across all (or at least a wide range) of time scales. In the case of packet traffic, self-similarity is manifested in the absence of a natural length of a burst: at every time scale, ranging from a few milliseconds to minutes and hours, similar-looking traffic bursts are evident [LTWW94]. Self-similar stochastic models include fractional Gaussian noise and fractional ARIMA (Auto-Regressive Integrated Moving Average) models. Further details are given in [FrMe94].

5.2.3. Choice of an Approximated Model

In [ARPP98], an intuitive first proposal to define traffic models for the next generations of wireless and mobile networks is to consider a model for ATM networks (e.g., the MMPP one), and to modify it by incorporating the relevant mobility characteristics. This can be done by starting from the MMPP model, which characterises traffic generated from the multiplexing of different traffic sources. In the approach followed there, the mobility can then be modelled by making use of a Markov-additive process of arrivals model. In this work one is going to use a simpler one, consisting of generalising the equilibrium equation for Poisson distributed traffic [Jabb96] to the multi-service traffic case.

5.2.3.1. Voice

In ATM networks there are two alternatives for conveying voice traffic. One method is to convey it as CBR traffic, i.e., coding it at a fixed rate, such as 64 kb/s pulse code modulation (PCM) or 32 kb/s adaptive differential PCM (ADPCM), and using the AAL (ATM Adaptation Layer) type 1 protocol (class-A service). The other method is to use a Speech Activity Detector (SAD) and a Digital Speech Interpolation (DSI) technique. In this case, voice traffic is VBR one, therefore, using the AAL type 2 protocol (class B service). When voice traffic is CBR one, the arrival of cells is periodic if CDV (Cell Delay Variation) can be neglected, and one can use the models of CBR traffic. The process of generating ATM cells where voice signals are coded with VBR is described in [Sait94], which reduces the number of cells transmitted in the network by 35-40%.

These studies assume that the lengths of talkspurts and silence periods in a voice source are exponentially distributed. Field data, however, does not always support these assumptions, although the results depend on the design of a SAD, the language spoken, and the sex of speakers [Sait94] (in particular, a silence period distribution has a tail longer than the tail of an exponential distribution).

Evaluating the performance of voice cell multiplexing requires a new model for the superposed voice arrival processes. As the aggregated arrival process is highly correlated, the simplest approximation (the M/D/1 model) is either too inaccurate for practical use or only acceptable when the number of waiting *positions* is small. Therefore, an approximation is used to analyse statistical multiplexing, e.g., MMPP is used to model voice cell arrival. In particular, it can be modelled by a two-state MMPP, sometimes called the Switched Poisson Process (SPP). In particular, an SPP in which one of the arrivals intensities λ_1 or λ_2 is 0 corresponds to an IPP, details being given in [Sait94], [HeLu86].

5.2.3.2. Video

Promising services of ATM networks are the video based ones, it being important to accurately model the video cell arrival process. The simpler way to model it is as CBR traffic, the AAL type 1 protocol being used in this case. The investigation of video statistics started in 1970s, but little is known about the statistics for the arrival processes of cells containing video information coded at high bit rates or with the recent coding mechanisms, e.g., MPEG-2 or MPEG-4. However, if the resource usage is to be billed by the peak rate, traffic smoothing mechanisms will be sought to being used in the codecs. Hence, keeping this in mind, a CBR traffic approach could be a first accurate way for system planning. Of course, a more complex approach could be followed, where traffic characteristics would depend on the contents of the movie itself [Rose95], but this approach will not be followed here.

Frame-level statistics are important, but, because the output buffer size in an ATM node is small compared with the number of cells in a frame and the length of a frame (ordinarily 1/30 s), it is too difficult to use frame-level statistics to estimate the statistical multiplexing of video traffic in ATM networks.

In [Sait94] an ARMA (Auto-Regressive Moving Average) model linked with a ZMNL (Zero-Memory Non-Linearity) transform is used to model the cell arriving process. The ARMA model is promising, because it is applicable to the number of cells generated during a short interval as well as in a frame, and because it is suitable for simulation. However, the ARMA model is not suitable for queuing analysis. Besides, the video cell arrival process in other codecs and hardware implementations results in different models.

Two other models should then be considered for video arrival processes: the uniform and the ON-OFF ones. In the uniform model, the cell inter-arrival times are either fixed or exponentially distributed, with a fixed intensity within a frame, whereas in the ON-OFF one they are either fixed or exponentially distributed with a fixed intensity during a certain period (the ON one) within a frame (whereas no cells are generated at the in between periods).

The uniform model [MASK88], [YaSu91], represents the system in which cells are stored in buffers in a codec, and sent to the subscribers line at a controlled speed [Sait94], being modelled by an MMPP with J+1 states, and resulting from the superposition of J mini-source models. The ON-

OFF model represents the system where coded cells are stored in codec-buffers and sent to the subscriber line at the full speed of the codec or the line.

One advantage of the uniform approach is that the model for the process of the number of cells generated within a frame, which is easy to calculate, can determine the model for the cell arrival process. In [MASK88], the number of cells generated within a frame is modelled by the first-order AR model and by the discrete finite-level Markovian model [Sait94]. An example of the ON-OFF model is presented in [SaKY91], some details also being given in [Sait94].

In [Sait94], it is also referred that the uniform model is expected to be optimistic and underestimate CLR (Cell Loss Ratio), whereas the ON-OFF model is expected to be pessimistic and overestimate CLR. If one could use both models, one could estimate the range of CLR in the actual cell arrival process, and the effectiveness of smoothing the cell arrival process at the exit of the codecs. If the tariff is sensitive to the peak rate of the actual cell stream, the effort for smoothing the cell stream will be made by each subscriber. This will improve the agreement between the actual CLR and the CLR derived by using the uniform model.

5.2.3.3. Data

In [Sait94], it is referred that actual data packet arrival processes have been investigated, but that the cell arrival process in ATM networks has not yet been precisely identified. Therefore, one should estimate the properties of data cell arrival processes from the statistics of data packets. One characteristic of data packet statistics is that the packet length distribution is bimodal [Guse90]. Because the packet appears as a burst of cells, if data cells are generated from a data packet given as AAL SDU (Service Data Unit) and AAL is fast, this bimodal distribution of packet length suggests that the burst of data cells can bi-modally distributed.

According to [Sait94], when a subscriber generates a long burst (i.e., a long packet), which may correspond to a file transfer, among short bursts (short packets), which may correspond to commands, the source traffic state consists of long-burst and short-burst states. Therefore, although the cell arrival process within a burst depends on the implementation of a higher level protocol (such as the AAL) and cannot yet be identified, the data cell arrival process is likely to be an SPP, which includes the IPP, the Geometrically Modulated Deterministic Process (GMDP), and the Switched Batch Bernoulli Process (SBBP). More details on GMDP and SBBP are presented in [Sait94].

5.2.3.4. Superimposed Traffic

In ATM networks, heterogeneous traffic is multiplexed. Therefore, it is important to superimpose arrival processes easily when evaluating the performance of ATM networks, or to find models for the superposition, alternatively. In order to model superimposed traffic two methods can be considered: statistic superimposition and model superimposition [Sait94].

The statistics superimposition evaluates the statistics (or distribution) of the individual processes, and uses them to compute the statistics of the superimposed process. Because the statistics of the superimposed process must be computed from those of individual processes, the statistics should be suitable for this computation; for example, they should be counting process statistics. In [HeLu86] a typical example is presented for voice sources. The four characteristic parameters used in that method are statistics of the counting process of cell arrivals, hence, if one derives these characteristics for an individual source, one can obtain those for the superposition directly. The statistics superposition has the advantage of not requiring the model for individual processes, the computation being easy, and the state space not growing (unlike the state space in model superposition). In [Sait94] some examples are given.

On the one hand, although statistic superposition is computationally easy, it being useful for large number of cases of superimposed traffic, its accuracy is sometimes poor. This is due to the way of calculating its parameters, which is limited to the moments of the counting process or to their modifications, details being given in [Sait94]. The parameter matching method from such statistics is also limited, and may result in poor accuracy.

On the other, model superimposing first determines models for individual processes and then superimposes them. This method is applicable only when the superimposed model can be obtained directly from individual models such as MMPPs, Phase-type Markov Renewals, MAPs, discrete-time models with a Markov-modulated arrival, or a Discrete-time MAP (DMAP). For instance, if MMPPs are used as individual process models, superimposing can be described by an MMPP with a large state space. An example for the superimposing of video and voice traffic is presented in [Sait94]. As it was already stressed, their parameters can be easily estimated from empirical data, which is an advantage to who wants to follow an approach for cellular planning purposes from the point of view of an operator, who normally has operational data for average duration of calls, and even for service components of each type and their generation rate.

More recent studies also have concluded that superimposed traffic is self-similar, but one will not follow that approach here. Instead, one is going to consider the MMPP model, and consider voice, data and video sources modelled by the IPP model.

5.2.4. Choice of a Model

The MMPP model is used for the analysis of MBS multi-service traffic resulting from the aggregation of CBR and VBR traffic sources. A model for voice sources will not be needed, as the associated data rates are very low, hence, not being relevant in the resource usage analysis and engineering. Data can clearly be modelled by the IPP model, as well as video.

Furthermore, because codec smoothing is recommendable and for the sake of simplicity, the video component is considered as being CBR when it is permanent in an application, which is perfectly true when one deals with pre-saved video, it being compatible with the use of the MMPP model.

In this context, ABR applications are dealt with by considering their minimum value for the data rate. Mobility could be possibly dealt with Markov Additive Processes [ARPP98], although one follows a simpler approach. Note that Markov Additive Processes are not the ones previously referred as MAPs.

Our approach allows for recovering a traditional-like telecommunications operators approach to tele-traffic, generalising it for the multi-service traffic case.

5.3. BPP Model for the Computation of the Blocking Probability

5.3.1. Initial Considerations

MBS resources serve applications via different service components, i.e., the system itself serves the service components, which, in turn, serve the applications. Different applications have different durations, and different associated data rates; each application data rate is obtained by summing the data rates of its different service components (sound, data and video), weighted by the proportion of time they area active during the application, on average. As far as each component can be 'turned' on and off several times during the application, the proportion of time it is active also depends on the number of times it is activated. Thus, one is dealing with a mixture of different service components, whose correspondence with applications has to be completely defined by the user model.

In the general model of a loss system with R_e different types of resources shared by J classes (i.e., service components), a customer arrival at the resources follows a specific random process. Each customer, i.e., service components users, requests a fixed number of resource units, i.e., channels, which are granted if available. If not, the request is cleared and the customer is blocked. The classification of customers is done on the basis of their arrival process, capacity requirement and mean holding time [AwVl97]. In this work, the performance measures that one is interested in are the fraction of time that the system is in a blocking state, i.e., the time blocking probability, P_{tb}, and the probability that an arriving customer is blocked, i.e., the customer or connection blocking probability, P_b. Because of terminal mobility and the resulting handovers, one is also interested in the handover failure probability, whose limitation directly results from the existence of a threshold for the call-dropping probability. When a single service is considered, if one does not use guard channels for handover the handover failure probability is equal to the blocking probability [Jabb96]. Here, one follows this approach for multi-service traffic too.

In [AwVl97], it is referred that the term call blocking is originated in the tele-traffic field, where costumers are calls (connections), resource demand corresponding to bandwidth requirement, and where resources are links capable of supporting a finite bandwidth. The proportion of time (arriving) customers occupy the resources is denominated as traffic. A specific formulation of this model is Erlang's B one, which gives the blocking probability for one class of customers sharing a single trunk of telephone lines, whose requests are unitary, with exponentially distributed inter-arrival times. In fact, the Bernoulli-Poisson-Pascal (BPP) model for the superposition of various types of traffic sources one is using here [AwVl97] can be viewed as a multidimensional generalisation of the classical Erlang B loss model, thus, the state distribution depends on the residency time distributions only through their respective mean, known as the *insensivity property* [Kauf81].

An historical overview of how recursion can be used for the computation of the blocking probability in such systems is presented in [AwVl97], where some previous work from Delbrouk [Delb83], which generalised the recursion for BPP arrival processes, and from Dziong and Roberts [DzRo87], which obtained an algorithm for multiple resources, is highlighted. Other works are referred there, and [AwVl97] is presented as a continuation of those works, as well as a generalisation of some of them to different classes of systems.

5.3.2. Basis of the Model

The formal definition of the system is the following [AwVl97]. The capacity of the resource facilities is partitioned into capacity units. A customer is assumed to need a given number of units of each facility, and the demand is granted on a first come first served basis. If a customer demand cannot be granted, it is cleared and the customer is blocked.

One considers J customer classes, each with different spatial and temporal requirements, and the number of distinct resource facilities $R_e = 1$, i.e., only one-type of channels is considered, c being the total of channels available. The resource capacity vector is defined as $\boldsymbol{c_v} = [c_1, \ldots, c_{R_e}]$, but since $R_e = 1$ one has $c_1 = c$. The class j (the term 'class' referring, in the context of this work, to 'service component') capacity demand of channels per customer, a_j, $j \in \vartheta$, where $\vartheta = \{1, \ldots, J\}$, and $a_j \in$ IN. Besides, the time that these channels, once granted, will be held by the service component (or class) j customer is i.i.d., it being specified by its mean value $\overline{\tau_j}$, whose specific distribution has no influence on the calculations that one is pursuing [Kauf81], [AwVl97]. Thus, given these considerations, the capacity vector, $\mathbf{A}$, is a vector of the following type

$$\mathbf{A} = \lfloor a_j \rfloor, \; j = 1, \ldots, J \; . \tag{5.5}$$

Let the number of class j active customers, i.e., that hold their a_j resources at time t, be represented by the random variable $N_j(t)$. One can then express the state of the system by

$$\boldsymbol{N}(t) = (N_1(t), ..., N_J(t)) \tag{5.6}$$

and $Y(t)$, the current resource occupancy vector as a function of the system state variable

$$Y(t) = \boldsymbol{N}(t) \cdot \mathbf{A}. \tag{5.7}$$

The set of possible states $\mathcal{N}$ is bounded as a result of the finite resource capacity

$$\mathcal{N} = \left\{ \boldsymbol{n} \in \mathrm{IN}^J : [n_1, ..., n_J] \bullet \begin{bmatrix} a_1 \\ ... \\ a_J \end{bmatrix} \le c \right\}. \tag{5.8}$$

where $\boldsymbol{n} = (n_1, n_2, ..., n_J)$ is the state of the system (defining the number of each component active requests). In the limit, if there are more users from an application than from another, the other can use fewer channels. An example for $J = 3$ is given in Fig. 5.2.

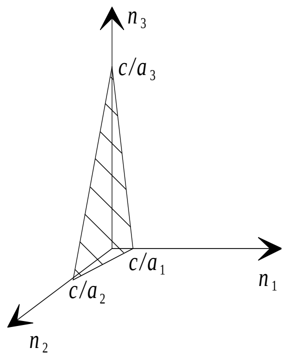


Fig. 5.2 – Boundaries for resource usage for a complete sharing policy, with $J = 3$.

If the state vector $\boldsymbol{N}(t) \in \mathcal{N}$, then the service occupancy vector $Y(t) \in \mathcal{Y}$, where $\mathcal{Y}$ is simply defined by

$$\mathcal{Y} = \{ y \in \mathrm{IN} : y \le c \}. \tag{5.9}$$

The equilibrium *pmf* of the state $\boldsymbol{N}(t)$ and the occupancy $Y(t)$ are defined as follows

$$p(\boldsymbol{n}) = \lim_{t \to \infty} \mathrm{Prob}\{ \boldsymbol{N}(t) = \boldsymbol{n} \} \tag{5.10}$$

$$q(y) = \lim_{t \to \infty} \mathrm{Prob}\{ Y(t) = y \}. \tag{5.11}$$

When the system is in state $\boldsymbol{N}(t) = \boldsymbol{n}$, the time until the next arrival of a class j customer's demand is exponentially distributed with parameter $\lambda_j(n_j)$. This parameter is normalised with respect to the average class j holding time, thus, a different time unit is introduced for each customer class. Blocking takes place if a request cannot be granted entirely, i.e., a class j request arrives when the system is in the set

$$\mathrm{B}_j = \{ \boldsymbol{n} \in \mathcal{N} : \boldsymbol{n} \cdot \mathbf{A} + a_j > c \}. \tag{5.12}$$

In this case, the request will be cleared and the customer blocked, which means that the system remains in the same state.

For exponential holding times, the BPP process can be modelled by the Markov chain of Fig. 5.3, although this model allows for considering more general distributions for the holding times.

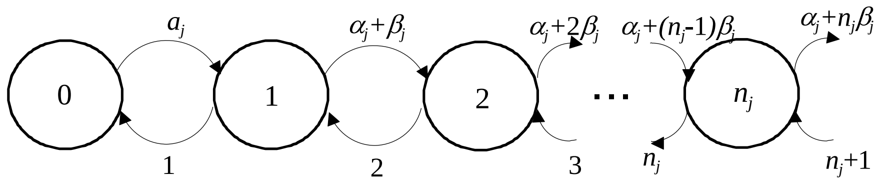


Fig. 5.3 – Markov model of a BPP arrival process for exponential distributed holding times.

5.3.3. Calculation of the Occupancy *pmf*

If one considers independently identically (not necessarily exponentially) distributed holding times for each customer class, the state *pmf* for the number of each class customers having access to the available channels has a product form [AwVl97]

$$p(\boldsymbol{n}) = p(\boldsymbol{0}) \cdot \prod_{j=1}^{J} v_j(n_j), \boldsymbol{n} \in \mathcal{N} \tag{5.13}$$

where the non-normalised marginal probabilities $v_j(\cdot)$ obey to the well known birth-death recursion, which is a direct result of the Markov model directly emanating from assuming exponentially distributed holding times. This is allowed because of the *insensitivity* to the holding time distribution [Kauf81]

$$v_j(n_j+1) = \begin{cases} \dfrac{\lambda_j(n_j)}{n_j+1} v_j(n_j), \text{if } n_j > 0 \\ 1 \qquad\qquad\qquad , \text{if } n_j = 0 \end{cases}. \tag{5.14}$$

In [AwVl97], it is referred that the choice of initial values is arbitrary, although different values for $v_j(0)$ would result in different values for the normalisation $p(\boldsymbol{0})^{-1}$, which is given by

$$p(\boldsymbol{0})^{-1} = \sum_{n \in \mathcal{N}} \prod_{j=1}^{J} v_j(n_j). \tag{5.15}$$

It is widely shown in literature that the computation of $p(\boldsymbol{0})$ with (5.15) is not viable except for relatively small models. If J grows, the probability mass is spread over many dimensions, thus, the state probabilities become too small to be handled by (finite-precision) computers [AwVl97]. Besides, the mere computation time becomes prohibitive, because it is proportional to the number of states.

Noting that the occupancy *pmf* can be expressed as a function of the state *pmf*

$$q(y) = \sum_{\boldsymbol{n} \in \mathcal{N}_y} p(\boldsymbol{n}), \tag{5.16}$$

where $\mathcal{N}_y = \{\boldsymbol{n} \in \mathcal{N} : \boldsymbol{n} \cdot A = y\}$, in the cases where one only wants to find $p(\boldsymbol{n})$ in order to obtain $q(y)$, there is an algorithm that is economic in terms of computation time and storage space – as long as the number of resources is not too high. This algorithm, which assumes a BPP arrival process, is presented in the next Section.

5.3.4. The BPP Arrival Process

One way to measure the characteristics of an arrival process is to pass it through a fictitious infinite resource. The mean traffic specifies the load on the system, whereas the peakdness is defined as the ratio between the variance and the mean of the customer population [AwVl97]. The BPP process, which is a special case of the more general arrival models of Section 5.2, is often used for describing telecommunications traffic [Wilk56], traffic modelled in this way exhibiting almost any combination of mean and peakdness.

Bernoulli-Poisson-Pascal processes are those whose arrival intensity (corresponding to an exponential distribution of the inter-arrival times), conditioned to n_j customers being in the system, is of the form

$$\lambda_j(n_j) = \alpha_j + n_j \cdot \beta_j, \text{ with } \alpha_j > 0 \tag{5.17}$$

where $(-\beta_j)$ is the activation rate and α_j is the arrival rate. The *pmf* of the number of active customers in an infinite resource is [AwVl97]

- **Bernoulli** – if $\beta_j < 0$, where $-\alpha_j/\beta_j$ must be a positive integer, say N_j, for an equilibrium *pmf* to exist; therefore $\lambda_j(n_j) = (N_j - n_j) \cdot (-\beta_j)$.
- **Poisson** – if $\beta_j = 0$, so that $\lambda_j(n_j) = \alpha_j$.
- **Pascal** – if $\beta_j > 0$, provided that $\beta_j < 1$, otherwise no equilibrium *pmf* would exist.

For exponential holding times, a BPP process can be modelled by the Markov chain from Fig. 5.3. Due to the normalisation, already referred to in Section 5.3.2, mean holding times are unitary, thus, death rates are integer values. Note also that, in the Bernoulli case, the number of reachable states is finite, it being equal to N_j+1. By substitution, it can be verified that (5.14) has the following solutions [Wilk56]:

- **Bernoulli**

$$v_j(n_j) = \binom{N_j}{n_j} \cdot (-\beta_j)^{n_j} \tag{5.18}$$

- **Poisson**

$$v_j(n_j) = \frac{\alpha_j^{n_j}}{n_j!} \tag{5.19}$$

- **Pascal**

$$v_j(n_j) = \binom{\alpha_j/\beta_j + n_j - 1}{n_j} \cdot (\beta_j)^{n_j} \tag{5.20}$$

The binomial coefficient is defined as usual, where the factorial of non-integer arguments *x*, arising in the 'Pascal case' is defined in terms of Euler's Gamma function ($x! = \Gamma(x+1)$). All *pmf* can be normalised by dividing them by $(1-\beta_j)^{-\alpha_j/\beta_j}$, which is e^{α_j} for $\beta_j = 0$ [AwVl97].

The mean offered traffic, ρ_j, given in Erlang [Delb83], and the peakdness factor Z_j of the active class *j* customers in an infinite resource are

$$\rho_j = \frac{\alpha_j}{1-\beta_j} \tag{5.21}$$

$$Z_j = \frac{1}{1-\beta_j}\,. \tag{5.22}$$

Assuming that the BPP traffic uses a finite resource of *c* units, the restrictions on the process parameters can be somewhat relaxed [AwVl97]. In particular, β_j may be larger than 1, since the finiteness of the resource prevent the probability mass from diverging to infinite.

Furthermore, for $\beta_j > 0$, $(-\alpha_j/\beta_j)$ does not need to be integer, as long as no negative transition rates exist ($\alpha_j + \left(\min_{r=1,\ldots,R_e} \lfloor c_r / a_{jr} \rfloor - 1\right)\beta_j > 0$). Nevertheless, although $\beta_j \geq 1$ is allowed, the restriction $-\alpha_j/\beta_j \in \mathrm{IN}$ is not lifted.

Therefore, the *pmf* of the customer population of a finite resource is simply a truncated Bernoulli, Poisson or Pascal one. Note that mean and peakdness of traffic on a finite resource (*carried traffic*) will be less than that of the traffic on an infinite resource (*offered traffic*). Some considerations are also made in [AwVl97] on the associated probability generating function.

5.3.5. Algorithms

The first step for the computation of the blocking probability is to compute the occupancy PDF (Probability Distribution Function), $Q(\boldsymbol{y})$, defined as usual as a function of probability marginal function $q(y)$

$$Q(y) = \sum_{\{x \in \Upsilon : x \leq y\}} q(x)\,. \tag{5.23}$$

Delbrouk [Delb83] has proposed the following recursive algorithm for the non-normalised one-dimensional *pmf*

$$q(y) = \frac{1}{y} \cdot \sum_{j=1}^{J} \alpha_j a_j \sum_{k=1}^{\lfloor y/a_j \rfloor} \beta_j^{k-1} q(y - k \cdot a_j) \tag{5.24}$$

which is initialised by $q(0) = 1$.

As this algorithm is computationally heavy, $O(Kc^2)$ in terms of computation time and $O(c)$ in terms of storage space, an alternative algorithm is proposed in [AwVl97]

$$q(y) = \frac{1}{y} \cdot \sum_{j=1}^{J} a_j m_j(y) \tag{5.25}$$

where

$$m_j(y) = \alpha_j q(y - a_j) + \beta_j m_j(y - a_j), \tag{5.26}$$

is an auxiliary variable for the recursive algorithm, such that $m_j(y) = 0$ for $y \leq 0$. This algorithm is only $O(Kc)$ in terms of the time needed to compute $q(y)$, at the extra cost of $O(\sum_j a_j)$ storage space, as only the a_j last computed values of m_j and the $\max_{j \in J} \{a_j\}$ last computed values of q have to be memorised [AwVl97].

In [AwVl97], the numerical stability of the algorithm is also discussed. If μ_j is the class j service rate, its inverse is the average service duration, and $\beta_j^{norm} = \beta_j/\mu_j$ is the normalised β_j resulting from the normalisation of the arrival rate $\lambda_j(n_j)$, referred to at the end of Section 5.3.2, the algorithm can be unstable for $|\beta_j^{norm}| > 1$, which does not apparently occurs for the service components one is considering in this work. Note also that, henceforth, one is going to use α_j^{norm} and β_j^{norm} instead of α_j and β_j where one has previously referred to α_j and β_j, respectively (the definition of α_j^{norm} from α_j is similar to the definition of β_j^{norm}).

The pseudo-code for the algorithm for the computation of time and call blocking probabilities, P_{bt} and P_b, is shown in Fig. 5.4 [AwVl97], [CaBr98]. Further details are given in [AwVl97].

5.3.6. User Model

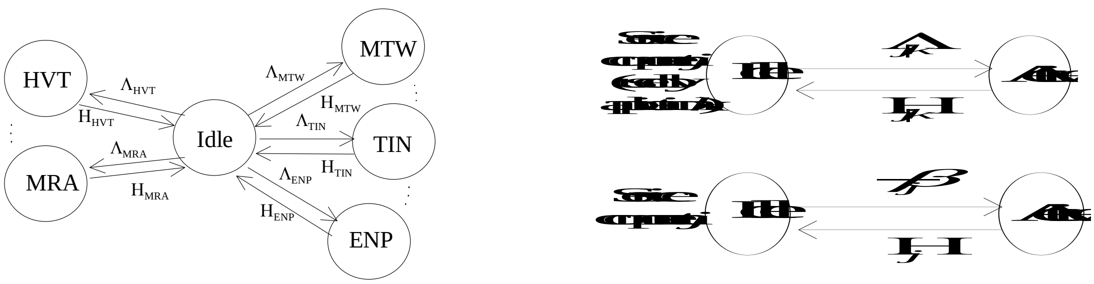
5.3.6.1. Applications Activation

There is a total number of c available resources (or channels) in each cell, being used by a total number of equivalent users, M_T. Furthermore, one is considering the mixture of applications of Table 2.18, i.e., a total of $K_{app} = 21$ applications. The index k, $k = 1, \ldots, K_{app}$, refers to the numbering defined in Table 2.18. Given this traffic mixture, the model for applications activation by users is presented in Fig. 5.5.a). From Table 2.18 one can see that, for example, 1. HVT, 10. MRA, 11. MTW, 16. TIN and 21. ENP are abbreviations for High-definition Video-telephony, Mobile Repair Assistance, Mobile Tele-working, Tourist Information and E-newspaper, respectively. Each user can be either in an idle state or using one of the 21 applications, with generation rate, Λ_k, and total service rate, H_k, respectively.

```
Q <- 0
for j <- 1, ..., J
    {
     i_j <- ⌊c/a_j⌋
     S_j <- 0
     S'_j <- 0
     Q_j <- 0
    }
for y <- 0, ..., c
    {
     Q <- Q + pmf_algorithm(y,a_j,α_j^norm,β_j^norm)
     for j <- 1, ..., J
         if y = (c-i_j a_j) then
            {
             S_j <- Q-Q_j
             Q_j <- Q
             S'_j <- S_j+ β_j^norm S'_j
             i_j <- i_j-1
            }
    }

// Here one has S_j = S_j(0), S'_j = S'_j (0) and Q = Q(c)
for j = 1, ..., J
    {
     P_bt <- S_j/Q
     P_b <- (1-β_j^norm)/(Q/S'_j -β_j^norm)
    }
```

Fig 5.4 – Algorithm to compute time and call blocking probabilities.



a) Applications b) Service Components

Fig. 5.5 – Activation models.

Once application k is active, the six service components are activated with rate $\Lambda_{j|k}$ and extinguished with total service rate $H_{j|k}$, $j = 1, \ldots, J$, Fig. 5.5.b); they can be simultaneously active, or not, and some can even not be activated for a given application.

This is a loss system, whose performance can be measured by the blocking probability of each service component, which simplifies the analysis (because one only needs to consider the service components, and not each application).

5.3.6.2 Average Load and Equivalent User

From Fig. 5.5 it is straightforward to derive the probability of a user having application *k* active

$$p_k = \frac{\Lambda_k / \mathrm{H}_k}{1 + \sum_{i=1}^{K_{app}} \Lambda_i / \mathrm{H}_i} . \quad (5.27)$$

The total traffic is

$$\rho = \sum_{k=1}^{K_{app}} \left(\Lambda_k / \mathrm{H}_k\right), \quad (5.28)$$

hence, the traffic generated by a specific application can be given by

$$\rho_k = \frac{\Lambda_k}{\mathrm{H}_k} = prop_k \cdot \rho . \quad (5.29)$$

where $prop_k$ is the proportion of application *k* active users (numerically given by its usage).

A normalised generation rate is introduced

$$\Lambda_k^* = prop_k \cdot \mathrm{H}_k, \quad (5.30)$$

such that

$$\sum_{k=1}^{K_{app}} \Lambda_k^* / \mathrm{H}_k = 1 \quad (5.31)$$

(one has $\Lambda_k = \rho \cdot \Lambda_k^*$), reducing (5.27) to

$$p_k = \frac{\rho}{1+\rho} \cdot \left(\frac{\Lambda_k^*}{\mathrm{H}_k} \right) = \frac{\rho}{1+\rho} \cdot prop_k . \quad (5.32)$$

The load from each user is obtained by computing the expectation of every application data rate

$$L_u = \sum_{k=1}^{K_{app}} p_k \cdot b_k . \quad (5.33)$$

Multiplying by M_T, the total number of potential users, one obtains the system average load

$$L = \frac{\rho}{1+\rho} \cdot b_1 \cdot M_T , \quad (5.34)$$

where b_1 is the maximum load per user, given by

$$b_1 = \sum_{k=1}^{K_{app}} prop_k \cdot b_k . \quad (5.35)$$

Consequently the fraction of active users is

$$f_a = \frac{\rho}{1+\rho} . \quad (5.36)$$

The product $prop_k \cdot b_k$ gives the maximum load per application.

Because of the independence in activation of each service component, the Bernoulli case of the BPP model is used [AwVl97]. In the context of this model, each equivalent user (of the applications) origins a given number of actual users, one for each service component, using resources with data rates B_{sj}, during a time exponentially distributed with average $1/\mathrm{H}_j$, j = 1, …, J (J is the total number of service components; for the service component j, one has a total service rate $\mathrm{H}_j = \mu_j$ in the static case, and $\mathrm{H}_j = \mu_j+\eta_j$, otherwise, where μ_j is the service rate, η_j being the cross-over rate); so the number of users accessing each individual service component is also M_T.

The activation rate of each component j, given an application k, is defined by [CaBr98]

$$\Lambda_{j|k} = \frac{\mathrm{E}[\text{number of active service component } j \text{ requests}]}{\mathrm{E}[\text{duration of application } k]} = \frac{n_{j|k}}{1/\mu_k} = n_{j|k} \cdot \mu_k \tag{5.37}$$

where $n_{j|k}$ is the number of times the service component j is activated during application k, it being unitary for permanent service components. When the application is static (due to absence of mobility, or because it is not considered), $\mathrm{H}_{j|k}$ is given by $\mu_j = 1/\overline{\tau}$ if the service component is permanent ($\overline{\tau}$ being application k average duration), or by $1/\overline{\tau_s}$ if the application is not permanent, $\overline{\tau_s}$ being the average service component duration. Although the values of $\Lambda_{j|k}$ and $\mathrm{H}_{j|k}$ change when the influence of mobility of terminals is considered (by a factor associated with the service and the cross-over rates of application k), their ratio is maintained constant, and no change will exist for traffic analysis purposes, except for the blocking/ handover failure thresholds.

The number of active users of component j using their resources at time t, a_j, are represented by the random variable $N_j(t)$. As it was already pointed out, when the system is in state $\boldsymbol{N}(t) = \boldsymbol{n}$, the time until next user class j arrival is exponentially distributed with parameter $\lambda_j(n_j)$ (5.17). In the Bernoulli case, it is given by

$$\lambda_j(n_j) = (N_j - n_j) \cdot (-\beta_j) \tag{5.38}$$

where the arrival rate is $\alpha_j = -\beta_j \cdot N_j$, N_j is the number of potential users of service component j, with $N_j = M_T$; n_j is the actual number of active users accessing component j. The respective activation model is illustrated in Fig. 5.5.

The activation and arrival rates are normalised with respect to the total service rate of service component j

$$\beta_j^{norm} = \beta_j / \mathrm{H}_j \tag{5.39}$$

and

$$\alpha_j^{norm} = \beta_j^{norm} \cdot N_j, \tag{5.40}$$

meaning that different time scales are introduced for each service component.

The activation rate of each service component is given by the expectation of $\Lambda_{j|k}$, leading to [CaBr98], [Carv98],

$$(-\beta_j) = \sum_{k=1}^{K_{app}} \Lambda_{j|k} \cdot p_k = \frac{\rho}{1+\rho} \cdot \sum_{k=1}^{K_{app}} \Lambda_{j|k} \cdot prop_k \ . \tag{5.41}$$

If the system is stationary, the average occupancy of component j is given by the following ratio

$$\left(-\beta_j^{norm}\right)=\frac{-\beta_j}{\mathrm{H}_j}=\sum_{k=1}^{K_{app}}\frac{\Lambda_{j|k}}{\mathrm{H}_{j|k}}\cdot p_k \tag{5.42}$$

here called normalised activation rate, meaning that the service rate of service component j is

$$\mathrm{H}_j=\sum_{k=1}^{K_{app}}\Lambda_{j|k}\cdot\frac{\Lambda_k^*}{\mathrm{H}_k}\Bigg/\left(\sum_{k=1}^{K_{app}}\frac{\Lambda_{j|k}}{\mathrm{H}_{j|k}}\cdot\frac{\Lambda_k^*}{\mathrm{H}_k}\right). \tag{5.43}$$

This does depend on mobility, because of the dependence of the numerator on it. If terminal mobility is considered, following an approach similar to the one for the arrival and total service rates in a single service system from Chapter 4, $\Lambda_{j|k}$ has to be replaced by $\Lambda_{j|k}$ times a factor $(\mu_k+\eta_k)/\mu_k$, where μ_k and η_k are the service and the cross-over rates associated with application k. The holding times for every service component should be i.i.d.. An example is the particular case of having exponential distributed holding times.

The data rate associated to each application is

$$b_k=\sum_{j=1}^{J}\frac{n_{j|k}\cdot 1/\mathrm{H}_{j|k}}{1/\mathrm{H}_k}\cdot B_{sj} \tag{5.44}$$

where B_{sj} is the data rate associated to service component j (note that $B_{sj}=a_j{\cdot}B_{s1}$, B_{s1} being the MBS basic data rate). Its value does not change with the consideration of mobility, because when it is considered, $\mathrm{H}_{j|k}$ and H_k are both affected by the factor $(\eta_k+\mu_k)/\mu_k$, the simultaneous change being cancelled by the division.

In order to isolate the dependence of the activation and arrival rates on f_a, one rewrites the activation rate of each service component (5.41) as

$$\left(-\beta_j\right)=f_a\cdot\beta_{j\,max} \tag{5.45}$$

where the maximum activation rate (i.e., the activation rate when $f_a = 1$), $\beta_{j\,max}$, is given by

$$\beta_{j\,max}=\sum_{k=\mathrm{HVT}}^{\mathrm{ENP}}\Lambda_{j|k}\cdot prop_k\ , \tag{5.46}$$

and the arrival rate α_j can be written as

$$\alpha_j=\left(-\beta_j\right)\cdot N_j=f_a\cdot N_j\cdot\beta_{j\,max}\,. \tag{5.47}$$

5.4. Service Components Characterisation Parameters

5.4.1. Correspondence between Applications and Service Components

In what follows one presents the service component characterisation parameters, their average utilisation during the application, the average load, the parameters for the equivalent users (i.e., the users who actually generate the connection, originating the respective service components), and the application data rates. As seen in Section 2.3, the basic components are audio, data and video, a correspondence existing between types of information supporting applications (e.g., moving pictures, sound or multimedia) and service components. Moreover, the sub-divisions from Fig. 2.4 are considered, the envisaged data rates being presented in Table 5.1, except for the audio component, because it will not be relevant for MBS traffic analysis purposes.

Table 5.1 – Sub-division of Basic Components in Actual Service Components.

Basic component	Service component	Data rate [kb/s]
Audio	VOI	-
	HIF	-
Data	LOD	384
	MED	1152, 1536 or 1920
	HID	31872
Video	IVI	384 or 1920
	HDV	8064

In Table 5.2, besides the organisation of services and applications according to the ITU-T I.211 Recommendation [ITUT93a], one presents the main parameters as well and, based on the analysis from Chapter 2, some relevant envisaged values for service components definition, e.g., the envisaged asymmetry factors, the ratio between the maximum loads per user between the down- and uplinks, the average duration of the applications, the foreseen range of variation of the burstiness, and the foreseen usage for different outdoor scenarios. From the deployment scenarios presented in Section 2.5.2, the BCC, URB and ROA ones have been considered.

In Table 5.3, the characteristics of data and video service components are proposed, as well as the actual application k average data rate, b_k, the burstiness being presented for both up- and downlinks. The characteristics of the service components (that model the equivalent user of an application) are: the data rate associated to service component j, B_{sj}, and the number of times it is accessed during application k, if any, $n_{j|k}$ (note that for permanent service components only the bit rate is presented), Fig. 5.6. Since $n_{j|k}$ is an average value, it is not necessarily an integer value.

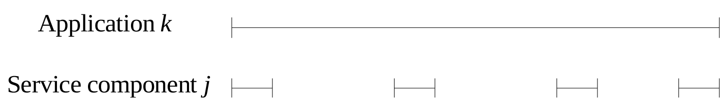


Fig. 5.6 – Illustration of ON and OFF periods of service component j during application k.

If the service component is accessed permanently, only the data rate is presented in Table 5.3. If the access to a service component is not permanent, a pair B_{sj} / $n_{j|k}$ appears in Table 5.3, where the value of $n_{j|k}$ is followed by the symbol ‘x’, meaning ‘times’. In such case, the values of each access duration are the ones presented in Table 5.4 [CaBr98], [Carv98], [AZDS94], [ALMH98].

Table 5.2 – Applications Main Parameters and some Relevant Envisaged Values for Service Components Definition.

Service Hierarchies	Type of Information	Examples of Applications	Abbre-viation	bk [kb/s]		Service parameters				Envisaged relevant values			
						Intrinsic time de-pendency	Delivery require-ments	Direc-tionality	Symmetry / Asymmetry	Average duration [min]	Usage [%]		
				uplink	downlink						BCC	URB	ROA
Interactive Services, Conversational	Moving Pictures and Sound	1. HD Video-telephony	HVT	1 920.0	1 920.0	TB	RT	Bid	Sym/Asy	3	15	11	9.8
		2. ISDN-Videoconference	IVC	384.0	384.0					30	4	4	4
		3. Mobile Video Surveillance	MVS	1 920.0	0.8				Asy	120	0.4	0.5	0.2
		4. HDTV Outside Broadcast	HOB	8 067.8	1 923.8					50	0.1	0.1	0.1
	Data	5. Wireless LAN Interconnection	WLI	145.8	4 031.8		NRT/RT			15	5.4	2.1	5.6
		6. Data File Transfer (FTP)	FTP	19.1	384.0	NTB	RT			0.33	7	7	7
	Document (multimedia)	7. Professional Images	PIM	84.0	8 064.0	TB/NTB	RT			10	2	1	1.5
		8. Desktop Multimedia	DMM	63.4	48.6	TB	RT			5	15	15	15
		9. Mobile Emergency Services	MES	2 731.2	2 731.2				Sym	20	1.8	0.1	1.6
		10. Mobile Repair Assistance	MRA	2 328.0	2 328.0					40	0.2	0.1	0.3
		11. Mobile Tele-working	MTW	1 929.6	1 929.6					20	7.3	2.2	3.3
		12. Freight and Fleet Management	FFM	2 736.0	2 736.0					5	0.7	0.2	2.3
Interactive Ser-vices, Messaging	Mixed Document	13. Electronic Mailbox Service for Multimedia	EMB	63.4	1 536.0	TB	NRT	Bid	Asy	1	3	3	2
Interactive Services, Retrieval	Text, Data, Graphics, Sound, Still Images, Moving Pictures	14. E-commerce	ECO	15.9	48.6	TB	RT	Bid	Asy	5	7	7	7
		15. Multimedia Library	MML	4.8	2 328.0	NTB				40	7.4	4.4	5.6
		16. Tourist Information	TIN	76.5	242.9					15	3.6	1.0	2.1
		16. Remote Procedure Call	RPC	9.6	194.3		NRT/RT			5	3	8	3
		18. Urban Guidance	UGD	1 935.3	1 935.3	TB				5	1.1	3.3	3.3
		19. Assistance in Travel	ATR	1 935.3	1 935.3					20	3.6	11	16.3
Distribution Ser-vices, Broadcast	Video	20. TV Programme Distribution	TVD	0.0	8 064.0	TB	RT	Bid	Asy	90	7.4	9	5
Distribution Ser-vices, Cyclical	Text, Graphics, Sound and Still Images	21. E-newspaper	ENP	0.8	242.9	TB	NRT	Bid	Asy	20	5	10	5

Table 5.3 – Characteristics of Service Components and their Actual Values for Data Rate and Burstiness for both Up- and Downlink.

Application	Abbre-viation	UPLINK: B_{sj} [kb/s] / $n_{j\|k}$					DOWNLINK: B_{sj} [kb/s] / $n_{j\|k}$					b_k [kb/s]		Burstiness	
		Video		Data			Video		Data						
		IV	HDV	LOD	MED	HID	IV	HDV	LOD	MED	HID	UP-LINK	DOWN-LINK	UP-LINK	DOWN-LINK
1. HD Video-telephony	HVT	1920	-	-	-	-	1920	-	-	-	-	1920	1920	1	1
2. ISDN-Videoconference	IVC	384	-	-	-	-	384	-	-	-	-	384	384	1	1
3. Mobile Video Surveillance	MVS	1920	-	-	-	-	-	-	384 / 30x	-	-	1920	0.8	1	480
4. HDTV Outside Broadcast	HOB	-	8064	-	1152 / 20x	-	1920	-	-	1152 / 20x	-	8067.8	1923.8	1.11	1.43
5. Wireless LAN Interconnection	WLI	-	-	-	**1152/34.5x**	-	-	-	-	-	**31872/34.5x**	145.8	4031.8	7.90	7.91
6. Data File Transfer (FTP)	FTP	-	-	384 / 2x	-	-	-	-	**384***	-	-	19.1	384	23.85	1
7. Professional Images	PIM	-	-	384	-	-	-	**8064***	-	-	-	384	8064	1	1
8. Desktop Multimedia	DMM	-	-	**384/15x**	-	-	-	-	**384/11.5x**	-	-	63.4	48.6	6.06	7.90
9. Mobile Emergency Services	MES	1920	8064 / 4x	-	1152 / 10x	-	1920	8064 / 4x	-	1152 / 10x	-	2731.1	2731.2	4.08	4.08
10. Mobile Repair Assistance	MRA	1920	8064 / 4x	-	1152 / 20x	-	1920	8064 / 4x	-	1152 / 20x	-	2328.0	2373.0	4.78	4.69
11. Mobile Tele-working	MTW	1920	-	-	1152 / 20x	-	1920	-	-	1152 / 20x	-	1929.6	1929.6	1.59	1.59
12. Freight & Fleet Management	FFM	1920	8064 / 1x	-	1152 / 5x	-	1920	8064 / 1x	-	1152 / 5x	-	2736.0	2736.0	4.07	4.07
13. Electronic Mailbox Service for Multimedia	EMB	-	-	**384/3x**	-	-	-	-	-	**1536***	-	63.4	1536	6.06	1
14. E-commerce	ECO	-	-	384/25x	-	-	-	-	**384/11.5x**	-	-	15.9	48.6	24.15	7.90
15. Multimedia Library	MML	-	-	-	1152 / 20x	-	1920	-	-	1152 / 20x	-	4.8	2328.0	240	1.32
16. Tourist Information	TIN	-	-	-	1152 / 20x	-	-	-	-	**1920/34.5x**	-	76.5	242.9	15.06	7.90
17. Remote Procedure Call	RPC	-	-	-	1152 / 5x	-	-	-	-	**1536/11.5x**	-	9.6	194.3	120	7.90
18. Urban Guidance	UGD	1920	-	-	1152 / 8x	-	1920	-	-	1152 / 8x	-	1935.3	1935.3	1.59	1.59
19. Assistance in Travel	ATR	1920	-	-	1152 / 30x	-	1920	-	-	1152 / 30x	-	1935.3	1935.3	1.59	1.59
20. TV Programme Distribution	TVD	-	-	-	-	-	-	8064	-	-	-	0	8064	-	1
21. E-newspaper	ENP	-	-	384 / 5x	-	-	-	-	-	**1920 / 46x**	-	0.8	242.9	480	7.90

Table 5.4 – Average duration of service components when they are not permanent.

Service components		$\overline{\tau_s}$ [min]	
		[AZDS94]	[ALMH98]
Video	IVI	-	-
	HDV	0.5	-
Data	LOD	0.0083	0.055
	MED	0.0083	0.055
	HID	-	0.055

In Table 5.3 one considers the following

- the values presented in bold for data components refer to the IPP model for Web Browsing [ALMH98], last column from Table 5.4, i.e., the average duration of service component j given application k is $\overline{\tau_{j|k}} = (\mu_{j|k})^{-1}$ = 0.055 min, corresponding to ON/OFF average durations of 3.3 and 22.8 s, respectively, $n_{j|k}$ being defined accordingly (e.g., it will be used to support the MED component in ENP at the downlink);
- other values refer to the characterisation given in [Carv98]: a duration of 0.0083 min for data, e.g., for the BAS component in Data File Transfer at the uplink, while 0.5 min is used for video, e.g., for the HDV component in MES at the uplink.

Permanent service components are only activated once, and have the same duration of the application they are serving. In this case, only the value of B_{sj} is presented in Table 5.3. From these, the values identified in bold plus an asterisk stand for ABR applications, i.e., they have at least access to the data rate presented in Table 5.3 (8 064, 1 536, or 384 kb/s, depending on the cases), but that can have access to a higher data rate, if needed and when available. Codec smoothing is assumed for video traffic.

After defining the service components characteristics for each application, one can conclude that the actual values for the burstiness (presented in Table 5.3) are always in the range of the foreseen values from Table 5.2, except in links (either up- or downlink) carrying some control data originated from commands, generally in the reverse link (a contra-example of this being the Mobile Video Surveillance Application, whose control commands are in the forward link).

5.4.2. Service Components Parameters

In Chapter 2, one has already assumed a data rate of 384 kb/s for the basic MBS channel. Having said that, the identified service components can be divided into eight different kinds, which can be distinguished in terms of types and data rates, B_{sj}, Table 5.5. This is due to the use of two different values for the data rates of interactive video and three different values for the data rate of the medium data rate type of data (see Table 5.1). The two types of interactive video are identified by IV1 and IV2, at 384 kb/s and 1920 kb/s, respectively, whereas the three types of medium bit rate data are identified by MD1, MD2 and MD3, at 1152, 1536 and 1920 kb/s, respectively. The number of channels requested by each service component, a_j, is shown as well.

Table 5.5 – Service Components: Types and Data Rates.

Service component	j	a_j	B_{sj} [kb/s]
LOD	1	1	384
IV1	2	1	384
MD1	3	3	1152
MD2	4	4	1536
MD3	5	5	1920
IV2	6	5	1920
HDV	7	21	8064
HID	8	83	31872

It is possible to identify two pairs of different service components with the same data rate, B_{sj}, thus, with the same a_j. Although LOD is different from IV1, and MD3 is different from IV2, under the hypothesis from this thesis they have equal characteristics. As a consequence, these pairs will be replaced by unique service components, since the applications one is considering do not use service components of these pairs simultaneously. The definitive ones that are going to be used henceforth, are presented in Table 5.6, the basic service component (BAS) replacing the LOD and IV1 ones, and the MD3 component standing both for the actual MD3 and for the IV2 components.

Table 5.6 – Definition of Actual Service Components Being Used.

Service component	j	a_j	B_{sj} [kb/s]
BAS	1	1	384
MD1	2	3	1 152
MD2	3	4	1 536
MD3	4	5	1 920
HDV	5	21	8 064
HID	6	83	31 872

The usage of service component j, serving application k, is characterised by parameters $n_{j|k}$ and $\overline{\tau_{j|k}} = \mu_{j|k}^{-1}$, both for the uplink, Tables 5.7-5.8 (only the non-null values are presented), and for the downlink, Tables 5.9-5.10. The values for the average duration of each application and their usage in different outdoor deployment scenarios are the ones already presented in Table 5.2, while the resulting values for b_k and for the burstiness are the ones from Table 5.3.

Table 5.7 – Characterisation Parameters for Service Component *j* given Application *k*: $n_{j|k}$ for the Uplink.

Application	$n_{j\|k}$					
	BAS	MD1	MD2	MD3	HDV	HID
1. HVT	-	-	-	1	-	-
2. IVC	1	-	-	-	-	-
3. MVS	-	-	-	1	-	-
4. HOB	-	20	-	-	1	-
5. WLI	-	34.5	-	-	-	-
6. FTP	2	-	-	-	-	-
7. PIM	1	-	-	-	-	-
8. DMM	15	-	-	-	-	-
9. MES	-	10	-	1	4	-
10. MRA	-	20	-	1	4	-
11. MTW	-	20	-	1	-	-
12. FFM	-	5	-	1	1	-
13. EMB	3	-	-	-	-	-
14. ECO	25	-	-	-	-	-
15. MML	-	20	-	-	-	-
16. TIN	-	120	-	-	-	-
17. RPC	-	5	-	-	-	-
18. UGD	-	8	-	1	-	-
19. ATR	-	30	-	1	-	-
20. TVD	-	-	-	-	-	-
21. ENP	5	-	-	-	-	-

Table 5.8 – Characterisation Parameters for Service Component *j* given Application *k*: $\mu_{j|k}^{-1}$ for the Uplink.

Application	$\overline{\tau_{j\|k}}$ [min]					
	BAS	MD1	MD2	MD3	HDV	HID
1. HVT	-	-	-	3	-	-
2. IVC	30	-	-	-	-	-
3. MVS	-	-	-	120	-	-
4. HOB	-	0.0083	-	-	50	-
5. WLI	-	0.0550	-	-	-	-
6. FTP	0.0083	-	-	-	-	-
7. PIM	10	-	-	-	-	-
8. DMM	0.0550	-	-	-	-	-
9. MES	-	0.0083	-	20	0.5	-
10. MRA	-	0.0083	-	40	0.5	-
11. MTW	-	0.0083	-	20	-	-
12. FFM	-	0.0083	-	5	0.5	-
13. EMB	0.0550	-	-	-	-	-
14. ECO	0.0083	-	-	-	-	-
15. MML	-	0.0083	-	-	-	-
16. TIN	-	0.0083	-	-	-	-
17. RPC	-	0.0083	-	-	-	-
18. UGD	-	0.0083	-	5	-	-
19. ATR	-	0.0083	-	20	-	-
20. TVD	-	-	-	-	-	-
21. ENP	0.0083	-	-	-	-	-

Table 5.9 – Characterisation Parameters for Service Component *j* given Application *k*: $n_{j|k}$ for the Downlink.

Application	$n_{j\|k}$					
	BAS	MD1	MD2	MD3	HDV	HID
1. HVT	-	-	-	1	-	-
2. IVC	1	-	-	-	-	-
3. MVS	30	-	-	-	-	-
4. HOB	-	20	-	1	-	-
5. WLI	-	-	-	-	-	34.5
6. FTP	1	-	-	-	-	-
7. PIM	-	-	-	-	1	-
8. DMM	11.5	-	-	-	-	-
9. MES	-	10	-	1	4	-
10. MRA	-	20	-	1	4	-
11. MTW	-	20	-	1	-	-
12. FFM	-	5	-	1	1	-
13. EMB	-	-	1	-	-	-
14. ECO	11.5	-	-	-	-	-
15. MML	-	20	-	1	4	-
16. TIN	-	-	-	34.5	-	-
17. RPC	-	-	11.5	-	-	-
18. UGD	-	8	-	1	-	-
19. ATR	-	30	-	1	-	-
20. TVD	-	-	-	-	1	-
21. ENP	-	-	-	46	-	-

Table 5.10 – Characterisation Parameters for Component *j* given Application *k*: $\mu_{j|k}^{-1}$ for the Downlink.

Application	$\overline{\tau_{j\|k}}$ [min]					
	BAS	MD1	MD2	MD3	HDV	HID
1. HVT	-	-	-	3	-	-
2. IVC	30	-	-	-	-	-
3. MVS	0.0083	-	-	-	-	-
4. HOB	-	0.0083	-	50	-	-
5. WLI	-	-	-	-	-	0.055
6. FTP	0.333	-	-	-	-	-
7. PIM	-	-	-	-	10	-
8. DMM	0.055	-	-	-	-	-
9. MES	-	0.0083	-	20	0.5	-
10. MRA	-	0.0083	-	40	0.5	-
11. MTW	-	0.0083	-	20	-	-
12. FFM	-	0.0083	-	5	0.5	-
13. EMB	-	-	1	-	-	-
14. ECO	0.055	-	-	-	-	-
15. MML	-	0.0083	-	40	0.5	-
16. TIN	-	-	-	0.055	-	-
17. RPC	-	-	0.055	-	-	-
18. UGD	-	0.0083	-	5	-	-
19. ATR	-	0.0083	-	20	-	-
20. TVD	-	-	-	-	90	-
21. ENP	-	-	-	0.055	-	-

If one considered different values for the data rate of the basic service component (e.g., 512, 1 024 or 2 048 kb/s), the respective service components would be the ones from Annex G. For these data rates, the only possibility in some cases is having higher data rates for the service components, like the approach used for UMTS in [Garc00], [GaVC01], which leads to some waste of system resources. However, from the analysis presented in Annex G, one concluded that the only alternative viable choice in the context of the mixture of applications in this work is the choice of a basic data rate of 512 kb/s, besides 384 kb/s.

The aggregate data rate of application k is obtained from these parameters, in the static case (no mobility), by using (5.44) with $H_{j|k} = \mu_{j|k}$ and $H_k = \mu_k$. The results for the product $prop_k \cdot b_k$ (which is the maximum load per application) are presented in Table 5.11 for both up- and downlinks, for the three considered scenarios (BCC, URB and ROA). The values for $prop_k$ are given by applications usage from Table 5.2, while the values of b_k are extracted from Table 5.3.

The sum of the values of the maximum load per application gives the maximum load per user, b_1, last line of Table 5.11, and allows us to define the asymmetry factor between the down- and uplinks, A_f, i.e., the ratio between the values of b_1 for the down- and uplinks, Table 5.12.

Table 5.11 – Maximum Load per User in the BCC, URB and ROA Scenarios: Contribution from the Various Applications.

Application	b_k [kb/s]		$prop_k \cdot b_k$ [kb/s] BCC		URB		ROA	
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
1. HVT	1920.0	1920.0	288	288	211	211	188	188
2. IVC	384.0	384.0	15	15	15	15	15	15
3. MVS	1920.0	0.8	8	0	10	0	4	0
4. HOB	8067.8	1923.8	8	2	8	2	8	2
5. WLI	145.8	4031.8	8	218	3	85	8	226
6. FTP	19.1	384.0	1	27	1	27	1	27
7. PIM	384.0	8064.0	8	161	4	81	6	121
8. DMM	63.4	48.6	10	7	10	7	10	7
9. MES	2731.2	2731.2	49	49	3	3	44	44
10. MRA	2328.0	2328.0	5	5	2	2	7	7
11. MTW	1929.6	1929.6	141	141	42	42	64	64
12. FFM	2736.0	2736.0	19	19	5	5	63	63
13. EMB	63.4	1536.0	2	46	2	46	1	31
14. ECO	15.9	48.6	1	3	1	3	1	3
15. MML	4.8	2328.0	0.4	172	0.2	102	0.3	130
16. TIN	76.5	242.9	3	9	1	2	2	5
17. RPC	9.6	194.3	0	6	1	16	0.3	6
18. UGD	1935.3	1935.3	21	21	64	64	64	64
19. ATR	1935.3	1935.3	70	70	213	213	315	315
20. TVD	0.0	8064.0	0	597	0	726	0	403
21. ENP	0.8	242.9	0.04	12	0.1	24	0.04	12
Total	b_1		**657**	**1868**	**597**	**1678**	**801**	**1734**

Table 5.12 – Asymmetry Factor between the Down- and Uplink.

	BCC		URB		ROA	
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
b_1	657	1868	597	1678	801	1734
A_f	2.688		2.643		2.095	
$b_{1\text{-}UP}+b_{1\text{-}DOWN}$	2525		2275		2535	

One can also note by a straightforward analysis that, if TVD (TV distribution) was not considered, the respective results for the asymmetry factor would be 1.857, 1.540 and 1.623, Table 5.13, which means that this unidirectional application plays a very important role in the existence of asymmetry. Other three applications that are very important, in absolute values, for such asymmetry are WLI (Wireless LAN Interconnection), PIM (Professional Imaging) and MML (Multimedia Library). Without them and without TVD simultaneously, the respective asymmetry factors would be 1.114, 1.144 and 1.082, Table 5.13.

Table 5.13 –Values for the Maximum Load per User without Unidirectional and Strongly Asymmetric Applications.

		Scenario					
		BCC		URB		ROA	
		Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
Without TVD	b_1	775	1440	723	1113	899	1459
	A_f	1.857		1.540		1.623	
Without TVD, WLI, PIM and MML	b_1	902	1005	780	892	1020	1104
	A_f	1.114		1.144		1.082	

For the last two cases (absence of TVD and simultaneous absence of TVD plus WLI, PIM and MML), the respective values for application usage can be obtained by dividing the previous ones (from Table 5.2) by the factors presented in Table 5.14.

Table 5.14 – Factors to Compute each Application Usage in Situations with Less Asymmetry.

	Factors for usage computation		
	BCC	URB	ROA
Without TVD	0.926	0.910	0.950
Without TVD, WLI, PIM & MML	0.778	0.835	0.823

These last values show in a clear way how important is the definition of services and applications on the design of MBS.

5.4.3. Influence of Terminal Mobility

Although a much more accurate approach could be followed (e.g., the one with Markov Additive Processes [ARPP98]), one is looking for a first simple engineering approach to take into account the traffic from mobility in MBS multi-service traffic analysis for MBS cellular planning purposes.

In the considered deployment scenarios, the characteristics of terminal mobility for non-static applications can be the following: pedestrian (PD), urban (UB), main roads (MR) or highways (HW), being characterised by the values for mobility scenarios described in Chapter 4, and different types of mobility are assumed for each application in each of the scenarios. For each of the deployment scenarios, although several choices can be done for the type of mobility of each application, one suggests the characterisation proposed in Table 5.15, where the static type of mobility is represented by ST ($V_{av} = \Delta = 0$ m·s^{-1}).

Table 5.15 – Application types of mobility proposal for the different deployment scenarios

<table>
<tr><th rowspan="2">Application</th><th colspan="3">Type of mobility</th></tr>
<tr><th>BCC</th><th>URB</th><th>ROA</th></tr>
<tr><td>1. HVT</td><td>PD</td><td>UB</td><td>HW</td></tr>
<tr><td>2. IVC</td><td>PD</td><td>ST</td><td rowspan="10">MR</td></tr>
<tr><td>3. MVS</td><td>PD</td><td>UB</td></tr>
<tr><td>4. HOB</td><td>ST</td><td>ST</td></tr>
<tr><td>5. WLI</td><td>ST</td><td>ST</td></tr>
<tr><td>6. FTP</td><td>ST</td><td>UR</td></tr>
<tr><td>7. PIM</td><td>ST</td><td>ST</td></tr>
<tr><td>8. DMM</td><td>ST</td><td>ST</td></tr>
<tr><td>9. MES</td><td>ST</td><td>UB</td></tr>
<tr><td>10. MRA</td><td>ST</td><td>ST</td></tr>
<tr><td>11. MTW</td><td>ST</td><td>ST</td></tr>
<tr><td>12. FFM</td><td>ST</td><td>UB</td><td>HW</td></tr>
<tr><td>13. EMB</td><td>ST</td><td>ST</td><td rowspan="3">MR</td></tr>
<tr><td>14. ECO</td><td>ST</td><td>UB</td></tr>
<tr><td>15. MML</td><td>ST</td><td>ST</td></tr>
<tr><td>16. TIN</td><td>PD</td><td>UB</td><td>HW</td></tr>
<tr><td>17. RPC</td><td>ST</td><td>ST</td><td rowspan="5">MR</td></tr>
<tr><td>18. UGD</td><td>PD</td><td>UB</td></tr>
<tr><td>19. ATR</td><td>ST</td><td>UB</td></tr>
<tr><td>20. TVD</td><td>ST</td><td>ST</td></tr>
<tr><td>21. ENP</td><td>ST</td><td>ST</td></tr>
</table>

In the single-service case, and when no guard channels are considered, the equation for the blocking probability is equal to the one for the handover failure probability [Jabb96]. In this work one is considering that this equality also stands in the multi-service case.

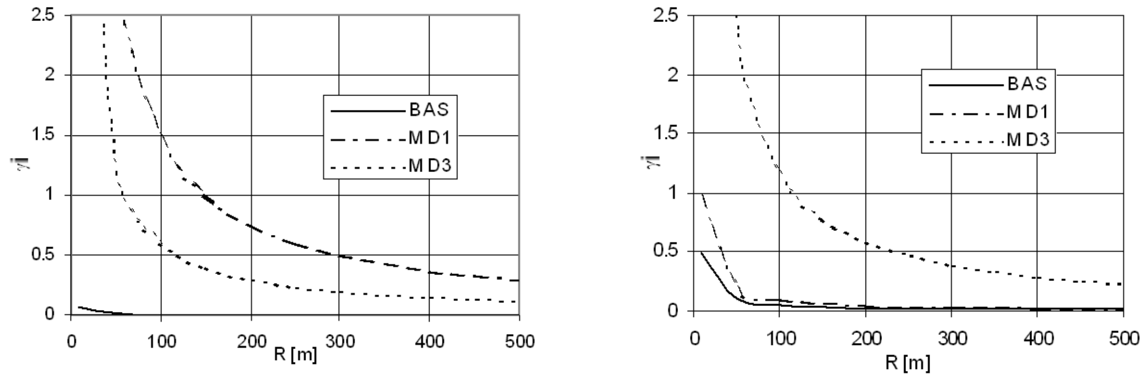
Given the fraction of resource occupancy (usage) of an application, Table 5.2, the mobility does not affect the computation of the blocking probability for given density of users and fraction of active users. Nevertheless it imposes the proportion of new / handover connections. Besides that, for each service component j, the mobility of terminals has influence on the handover failure probability threshold $(P_{hf})_j$, given by (4.23)

$$\left(P_{hf}\right)_{j\,max} = \left(\mu_j \big/ \eta_j\right) \cdot \left(P_d\right)_{max} \tag{5.48}$$

where $(P_d)_{max}$ is the maximum allowed connection dropping probability. One should remember, Section 4.3.2, that η_j is inversely proportional to R. The handover rate, the ratio between the cross-over and the service rates, $\gamma_j = \eta_j/\mu_j$ (as it was already defined in Section 4.3.4) is obtained from the total service rate for each component H_j, knowing the service rate for the static case μ_j (both obtained using (5.43))

$$\gamma_j = \frac{\eta_j}{\mu_j} = \frac{\mathrm{H}_j}{\mu_j} - 1. \tag{5.49}$$

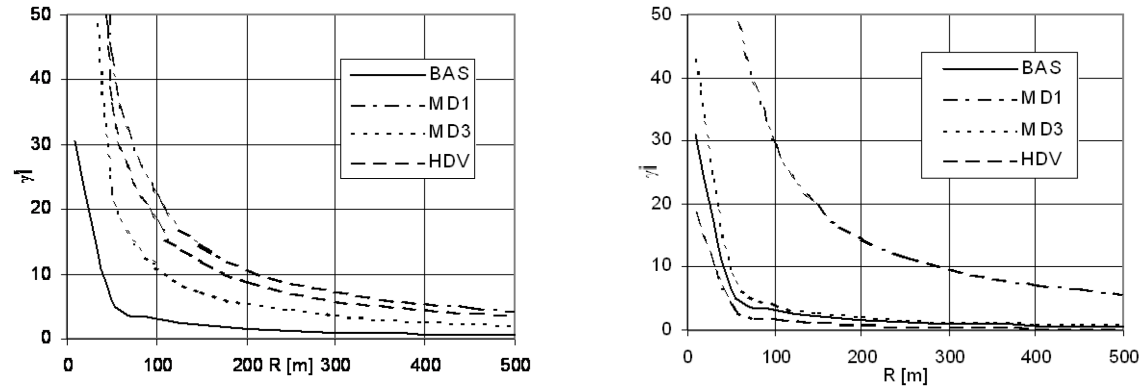
Results are presented in Figs. 5.7, 5.8 and 5.9 for the respective scenarios (BCC, URB and ROA), for both the up- and downlinks. The values of η_j are obtained from (4.27) and from Table 4.2. As the generation rate has the influence of both new and handover connections, the difference consists of re-computing H_j by multiplying $\Lambda_{j|k}$ by $(\mu_k+\eta_k)/\mu_k$ in the numerator of (5.43) when mobility is considered.



a) Uplink.

b) Downlink.

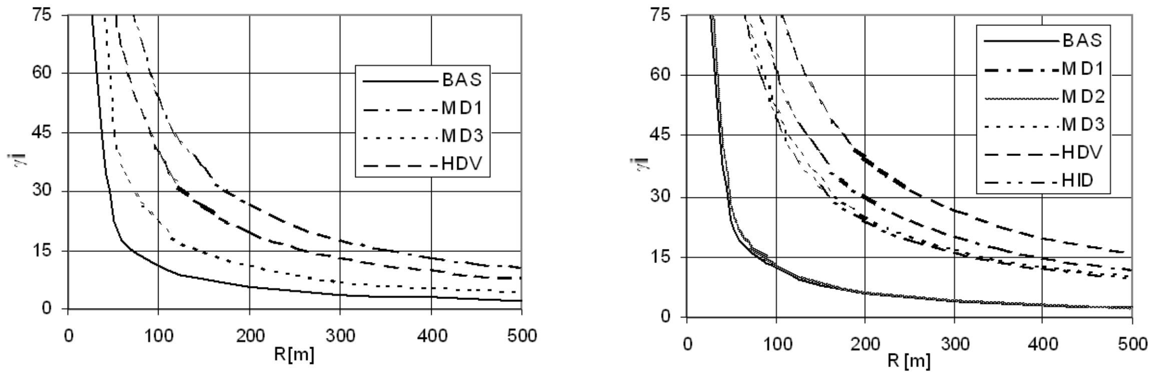
Fig. 5.7 – Handover rate as a function of the cell coverage distance, for the BCC deployment scenario.



a) Uplink

b) Downlink

Fig. 5.8 – Handover rate as a function of the cell coverage distance, for the URB deployment scenario.



a) Uplink b) Downlink

Fig. 5.9 – Handover rate as a function of the cell coverage distance, for the ROA deployment scenario.

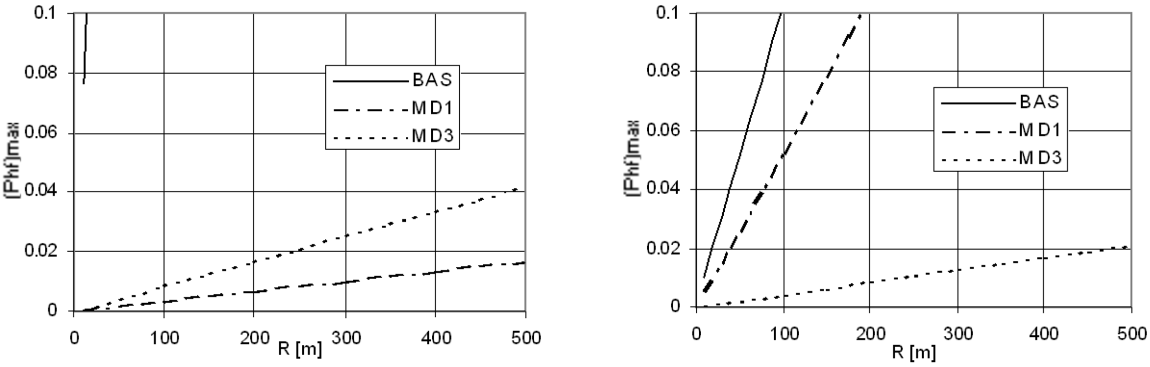
The cases where γ_j is not represented stands for $\eta_j = 0$ (either because the applications using that service component are ‘static’, or because no application uses that service component, e.g., the case of the MD2 and the HID service components at the uplink). For each service component, as the values of H_j are a combination of the number of times it is accessed times the average duration of each access (5.43), one cannot extract a general behaviour from these results. H_j is thus the inverse of the weighted average duration of the accesses of all applications to this service component (having also the contribution from terminal mobility, which makes the analysis still more complex). Besides, it is not expected that the data rate associated to each service component makes a difference. Nevertheless, general conclusions (common to the single-service case) are the following

- γ_j takes higher values for higher mobility scenarios;
- γ_j is a decreasing function with the cell coverage distance.

Regarding the cell coverage distance, in the URB scenario, the coverage distance of cells should be higher than 700 m in order to achieve $(P_{hf})_{j\,max} = 0.02$, whereas in the ROA scenario the coverage distance has even to be higher, as it could be expected. However, as lower coverage distances are foreseen for MBS, lower values of $(P_{hf})_{jmax}$ will be considered in what follows.

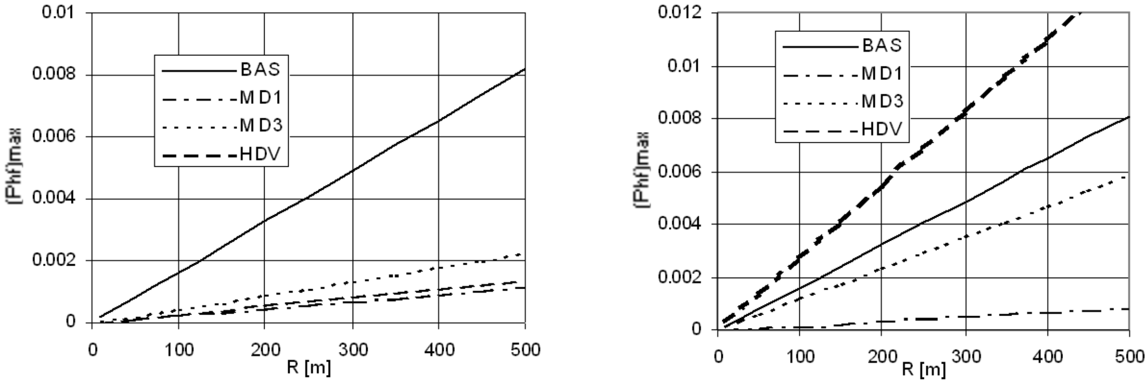
One should have in mind that for a single-service, in the presence of mobility, the computation of the blocking probability by the ‘Erlang-B approach’ is an approximation, whose associated error increases with γ_j [SiSt97]. Thus, in this multi-service approach, which is a generalisation of the single-service one, it is worthwhile to note that the computation of the blocking probability should suffer a similar effect in high mobility situations.

For a connection dropping probability of $(P_d)_{max} = 0.5$ %, the value of the handover rate has important consequences on the handover failure probability threshold. The dependence of that threshold on the maximum coverage distance of cells [Jabb96], $(P_{hf})_{j\,max}(R)$ is the one presented in Figs. 5.10, 5.11 and 5.12 (BCC, URB and ROA scenarios, respectively), both for up- and downlinks.



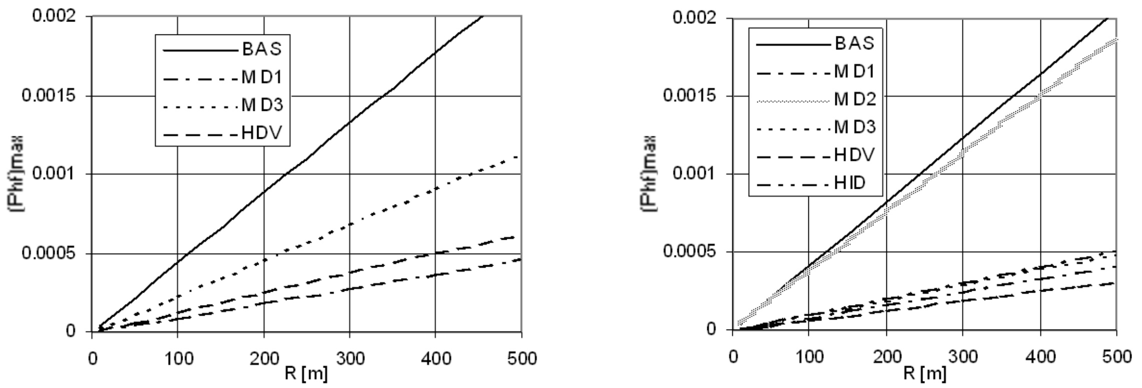
a) Uplink. b) Downlink.

Fig. 5.10 – Maximum handover failure probability as a function of the cell coverage distance, for the BCC deployment scenario.



a) Uplink b) Downlink

Fig. 5.11 – Maximum handover failure probability as a function of the cell coverage distance, for the URB deployment scenario.



a) Uplink b) Downlink

Fig. 5.12 – Maximum handover failure probability as a function of the cell coverage distance, for the ROA deployment scenario.

The deployment scenarios whose curve is not presented stand for $\eta_j = 0$, similarly to the case of the handover rate. These results will be used to obtain the supported traffic, the most limitative service component being considered, which is different from scenario to scenario, in each of the links.

5.5. Design Assumptions

5.5.1. Introduction

Although the MBS frame structure is not standardised yet, the ACTS-SAMBA project has already done some important work on it [PrSv99], and on the MAC protocol, the DSA++, which in 1998/99 was being considered in the standardisation of HIPERLAN-type 2 in ETSI-BRAN [ALMH98].

Assuming the hypothesis that MBS will be built upon the ACTS-SAMBA project 'future system' proposal [PrSv99], which contrasts with the project demonstrator (in terms of the improvement it presents on error detection and correction), one presents some hypothetical situations, where a given bit rate is associated to a given slot, which is considered as the basic MBS channel. As TDMA is used, the actual bit rate associated with the use of a slot in successive frames depends on the frame length (in terms of number of slots). Details are presented here for the OQPSK type of modulation; if 16-OQAM would to be used, the data rate associated with each carrier would be doubled, the corresponding slot durations being 2-to-1 related [GuDE97].

According to [PrSv99], in the case of a Wireless ATM (WATM) system (MBS is an example where a very high terminal mobility can be achieved and handover is possible), two different aspects have to be combined: on the one hand, the ATM like statistical multiplexing leads to a very dynamic assignment of capacity; on the other, Dynamic Channel Allocation, DCA (or even Fixed Channel Allocation, FCA) requires a steady behaviour. Due to these opposite requirements, a new allocation scheme is required [KrSc98].

To be able to use the available bandwidth efficiently, the BS should only allocate the required capacity. A continuous allocation of capacity is difficult to implement in a distributed system, but a stepwise allocation can be achieved, with a step much lower than the capacity offered by one physical carrier (either the down- or uplinks k^{th} frequency), meaning that the capacity has to be divided into smaller parts, the so-called containers, which contain several slots. The containers are associated with the use of a TDMA scheme, and build a frame, which is repeated periodically, Fig. 5.13. A BS is able to allocate one or several containers according to the capacity requested by MSs. These containers are hold for a relatively long time (the same container is used over many frames) in order to provide the required steadiness for the DCA or even, in a simpler approach, for the FCA. Therefore, a container can be seen as a 'channel' that is allocated by BSs, Fig. 5.14.

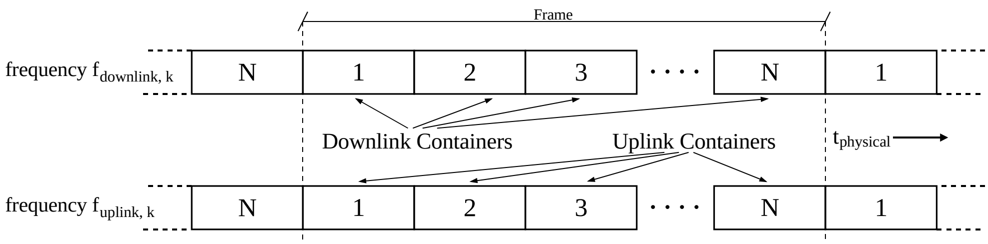


Fig. 5.13 – Frame and container structure on the physical channel for a FDD duplexing scheme [PrSv94].

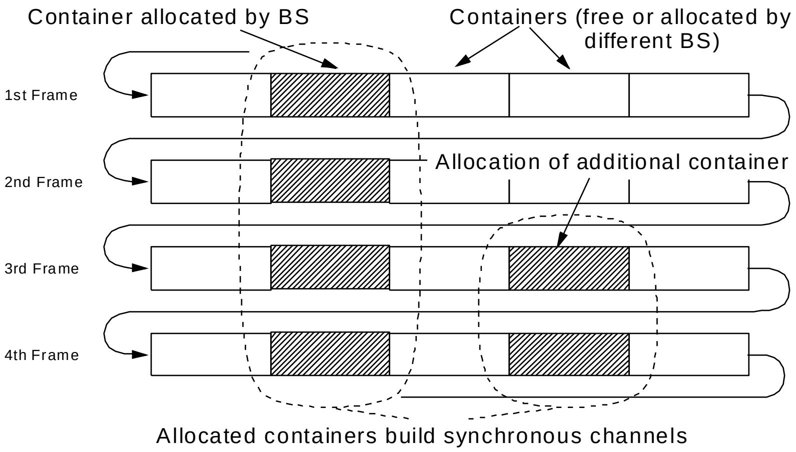


Fig. 5.14 – Container allocation for synchronous 'channels' [PrSv99].

Inside the allocated containers, the access of the BS and the MSs on the physical channel is co-ordinated by using a MAC protocol, in a scheme that offers a high variety of parameters:

- **Number of containers per frame** – The BS is only able to allocate the capacity stepwise. A higher number of containers per frame allows a more precise allocation of capacity.

- **Container Length** – The length of a container influences the frame length. A certain number of containers per frame is required to share the capacity efficiently. Since the frame length is limited, the container length has to be adapted. Since each container has a fixed overhead (guard-time, signalling information), a shorter container length decreases the load that can be carried by the system.

- **Container Allocation** – One of the main problems is how the allocation of a container is recognised by a BS, and when new containers are allocated. The allocation / release of containers depends not only on the load of the BS, but also on the service classes. In case of time critical services the capacity is required immediately. If the specific BS is handling any low priority traffic (like ABR or UBR) this capacity can be used; otherwise, new containers have to be allocated. If several containers are available, it has to be decided at which position within a frame and in which carrier a container should be allocated. Different carrier frequencies are an advantage in case of fading, but lead to difficulties, because of the frequency switching time.

The proposed scheme results in a two level multiplexing: i) within the allocated containers, the BS performs a multiplexing of the traffic of its MSs, which results in a very dynamic capacity assignment to the MSs; ii) the multiplexing of BSs (the use of different containers by different BSs) on the same physical frequency is executed with a reduced dynamic, since the capacity requirements of a BS are steadier. In fact, in the approach for multi-service traffic analysis followed here, one considers fixed allocation of containers to BSs, although broader hypothesis considering a given degree of freedom could be used. By allocating a container, a BS defines a ‘channel’ like in circuit-switching connection, thus the resource usage can be seen from a similar point of view.

In principle, it is possible to allocate the up- and downlinks containers symmetrically or asymmetrically. Symmetrically means that the same containers are allocated for both transmission links; therefore, the BS has the same capacity for up- and downlinks. In case of asymmetric load the maximum of the required capacity in up-/downlink has always to be allocated, which results in an inefficient usage of the radio resources, at least in a FDD mode. If a TDD mode is considered, a higher versatility is achieved, and an optimised use of the up- and downlinks resources can be obtained, according to the asymmetry of the mixture of applications. In this case, as BSs may allocate containers asymmetrically, a different number of containers for each transmission direction is allocated, depending on the current traffic situation. For example, in the case of higher uplink traffic the BS allocates more uplink containers, and vice-versa for the downlink. This enables the BS to cope with asymmetric load more efficiently, since only the required capacity for each link is allocated.

In both cases (symmetric or asymmetric allocation), the MAC protocol has to be adapted to the container structure on the air interface. The adaptations are due to the frame/container structure of the MAC scheme. The resulting signalling scheme in case of asymmetric allocation is discussed with some detail in [KrSv99] and [ALMH98], Fig. 5.15.

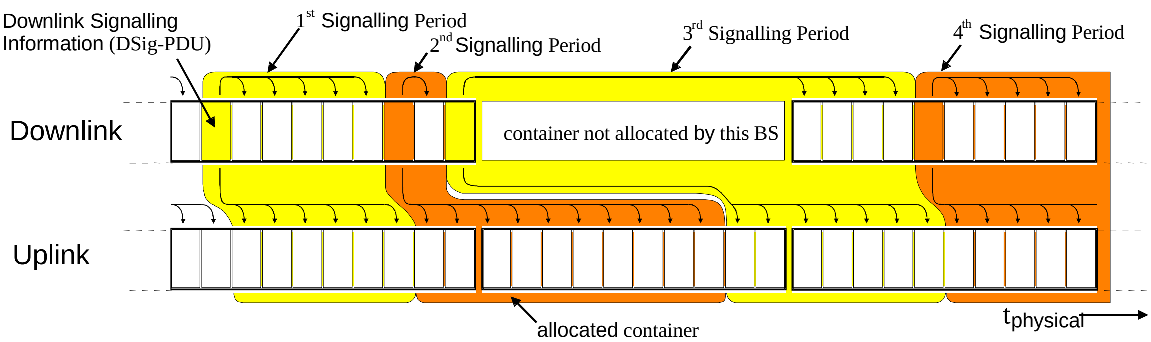


Fig. 5.15 – Example of the signalling scheme in case of asymmetric container allocation [KrSv99].

Although dynamic schemes are foreseen for slot allocation inside each container, i.e., for the allocation of slots to MSs, one is considering a fixed allocation strategy. However, as our analysis is being based on the characteristics of service components, this already partly reflects the dynamic associated with the duration of each connection, which is very useful in order to achieve some initial results for the upper bounds of blocking probability (and even for the handover failure probability, if one uses some additional approximations as assumptions) to be used for cellular planning purposes.

Our work focuses on a system configuration not using guard channels for handover, which, from the analysis presented in Chapter 4, seems to be an appropriate approach, at least when long duration connections are considered.

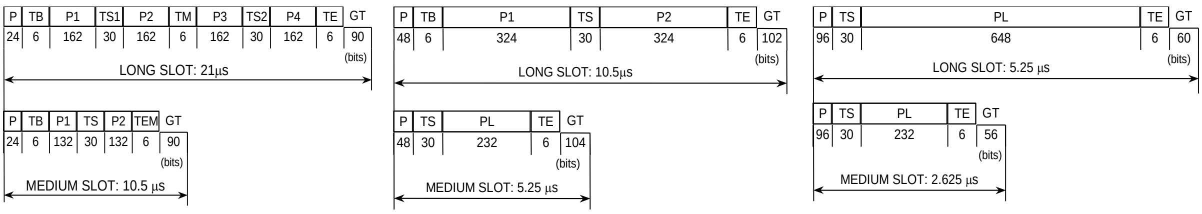
5.5.2. Proposals for Frame and Burst Structure

ACTS-SAMBA proposals for a 'future system' [PrSv99] state that, in several aspects, the foreseen characteristics of the air interface for an early stage of MBS implementation are similar to those adopted in the SAMBA Trial Platform: the same paired band, in the vicinity of 40 GHz; an OQPSK-type modulation scheme, which is compatible with a grossly non-linear power amplification; a TDMA/FDMA scheme (Time/Frequency Division Multiple Access), allowing a wide range of service bit rates through a flexible use of the time slots concerning each available carrier frequency with an appropriate MAC protocol. A paired band in the vicinity of 60 GHz could also have been chosen; however, due to current technological constraints, it seems it only will be useful for later system implementations. In the SAMBA project, considering the same degree of mobility as that allowed by today's cellular systems, the target values of the achievable *service* bit rate per carrier and transmission range have been established for the early days of MBS as follows: around 17 Mb/s, up to about 350 m; around 34 Mb/s, up to 180 m; around 68 Mb/s, up to 60 m (suitable for selected indoor environments). The corresponding *gross* bit rates were chosen to be 40, 80 and 160 Mb/s, respectively. Extensive simulation work, done in SAMBA, has shown that these values are achievable at carrier frequencies close to 40 GHz by the use of moderately directive antennas in both the BS and the MS [GuDE97], when assuming transmit power levels not beyond those employed in the SAMBA Trial Platform. On the one hand, the directivity requirement for an MS antenna obviously implies some kind of 'adaptive' implementation, except for those cases where a certain mobility restriction is accepted; on the other, the moderate MS antenna directivity helps reducing the delay spread and improving the power budget, while allowing full mobility and low-cost, low-size implementations [PrSv99].

For advanced stages of MBS implementation, the availability of efficient linear amplification schemes is foreseen, together with high-gain adaptive antennas. Therefore, it will be possible to double the achievable service bit rate per carrier, while preserving the transmission bandwidth, by using a compatible 16-OQAM scheme: this means that, according to [PrSv99], service bit rates up to 136 Mb/s per carrier will be allowed in selected indoor environments. In the early system implementations (OQPSK-type scheme only), such extremely high rates will also be achievable in those environments by transmitting in parallel over two carriers.

In [PrSv99] three pairs of 'traffic' burst specifications were presented for the near future of MBS (OQPSK-type scheme only), each one corresponding to a specific gross bit rate, e.g. 40, 80 or 160 Mb/s ('control' burst issues not being treated there). For each gross bit rate either a so-called 'standard' long burst or a so-called 'complementary' medium-size burst may be employed for traffic purposes [PrSv99]; the corresponding slot durations are 2-to-1-related. These bursts include the required preambles (Automatic Gain Control, AGC, settling time and on/off switching time issues) and training/tail sequences (equalisation issues); their payloads are derived, through a unified channel encoding procedure, from a 'basic data block', which consists of the 53 octets of a complete ATM cell plus 4 associated control octets. In later implementations, whenever employing the 16-OQAM scheme, each burst payload could concern the information contents of two basic data blocks instead of a single one, further details being given in [PrSv99], although one should note that including two ATM cells in the same slot is not generally well accepted.

The proposed structures for the standard and complementary traffic bursts are depicted in Fig. 5.16, corresponding to gross bit rates (*GBR*) of 40, 80 and 160 Mb/s, respectively. For the long slot type, which is going to receive our attention, from the total of 840 bits (or 105 bytes) per slot, 192 (or 24 bytes) are for preamble (P), training sequences (TS1 and TS2), tails (TBg, TE and TM) and guard time purposes (GT), the remaining 648 bits (or 81 bytes) being used for payload. From these, only 53 bytes can be taken into account for ATM cell bit rate evaluation, whereas only 48 bytes correspond to the user (net) bit rate [PrSv99].



a) *GBR* = 40 Mb/s b) *GBR* = 80 Mb/s c) *GBR* = 160 Mb/s

Fig. 5.16 – Traffic burst structures to be used in long and medium slots for [PrSv99].

Therefore, the ratio between the user bit rate (*UBR*) and the gross bit rate is given by

$$\frac{UBR}{GBR} = \frac{48}{105} = 0.457\,, \tag{5.50}$$

thus, the user bit rate per carrier ($UBR_{carrier}$) is given by

$$UBR_{carrier} = \frac{48 \cdot 8}{T_s} = \frac{384}{T_s}\,, \tag{5.51}$$

where 8 refers to the number of bits in each of the 48 bytes available for the users, and where T_s is the slot duration.

In [KrST98], 160 slots per frame are used, corresponding to 16 containers per frame, hence, to 10 slots per container. In the SAMBA Trial Platform, frames with 80 slots were considered, and 16 containers of 5 slots were used in one of the implementations.

If, for example, one wants to consider frames with 48 slots, the bit rate directly associated with a slot, UBR_{slot} (as each slot is re-used in the next frame, i.e., only 48 slots later), is obtained by dividing the user bit rate per carrier by 48. Results for various GBRs are presented in Table 5.16, corresponding to maximum values of the maximum cell coverage distance, R_{max}.

Table 5.16 – User Bit Rate Associated to a Slot when 48 Slots are Considered in a Frame.

GBR [Mb/s]	R_{max} [m]	T_s [μs]	$UBR_{carrier}$ [kb/s]	UBR_{slot} [kb/s]
40	350	21	18 285.7	381
80	180	10.5	36 571.4	762
160	60	5.25	73 142.9	1 524

One verifies, for example in the first line, that the user bit rate associated to a slot only differs from 384 kb/s by 3 kb/s. In order to achieve 384 kb/s for the proposed frame structure one can either consider T_s = 21 μs, with the bit rate associated to a slot of 384 kb/s being an approximation or, alternatively, considering T_s = 20.83 μs. In the last case, a user bit rate of 384 kb/s – or integer 'multiples' – are exactly associated to a slot. Henceforth, one is going to follow the last approach, and as a consequence the assumptions of Table 5.17 are considered, the last column being included for comparison purposes. One verifies that the actual user bit rates per carrier achieves 18.432, 36.864 and 73.728 Mb/s for the respective values of the *GBR*, low- (LG), medium (MG) and high-gross bit rate (HG), these values being slightly higher than the ones proposed in the SAMBA project.

Table 5.17 – Working Assumptions when 48 Slots are Considered in a Frame.

Case	*GBR* [Mb/s]	R_{max} [m]	T_s [μs]	$UBR_{carrier}$ [kb/s]	UBR_{slot} [kb/s]
LG	40	350	20.83	18 432	384
MG	80	180	10.42	36 862	768
HG	160	60	5.21	73 728	1 536

So, considering the use of the OQPSK modulation, one can analyse various hypothesis for the number of slots per frame, resulting on the equivalent bit rates per slot from Tables 5.18, 5.19 and 5.20, for cases LG, MG and HG, respectively. Examples of the choice of the number of containers per frame are presented, which leads to a certain number of slots per container, thus, to a different bit rate per slot, which numerically gives the basic data rate associated to the system. The cases of interest, i.e., the ones corresponding to a basic data rate (associated with the basic component) B_{s1} = 384 kb/s, are identified in bold.

Table 5.18 – Impact of Different Number of Slots per Frame for Case LG.

Hypothesis	Number of slots per frame	Bit rate per slot [kb/s]	Example of the number of	
			Containers/ frame	Slots/container
1	18	1 024	3	6
2	36	512	6	6
3	**48**	**384**	**6**	**8**
4	96	192	12	8
5	144	128	18	8

Table 5.19 – Impact of Different Number of Slots per Frame for Case MG.

Hypothesis	Number of slots per frame	Bit rate per slot [kb/s]	Example of the number of	
			Containers/ frame	Slots/container
1	36	1 024	6	6
2	72	512	9	8
3	**96**	**384**	**12**	**8**
4	144	192	18	8
5	288	128	36	8

Table 5.20 – Impact of Different Number of Slots per Frame for Case HG.

Hypothesis	Number of slots per frame	Bit rate per slot [kb/s]	Example of the number of	
			Containers/ frame	Slots/container
1	72	1 024	9	8
2	144	512	12	12
3	**192**	**384**	**16**	**12**
4	288	192	24	12
5	576	128	48	12

The explanation is given in more detail in Section 5.5.5.4. It is worthwhile to note that in cases of high bit rate per slot, a service component could have access to a lower bit rate if a scheme was used where it would not have access to the slot in consecutive frames.

From this analysis, a forecast can be already presented for possible maximum MBS user data rates versus mobility, Annex H.

5.5.3. Remarks on the MAC Protocol

The objective of the Dynamic Slot Assignment (DSA++) protocol development was to extend the ATM like statistical multiplexing to the radio interface, in order to fulfil the requirements of the wireless user, [ALMH98]. The virtual ATM multiplexer referred in [ALMH98] represents a distributed queuing system with queues inside the MSs (for uplink cells) and the BS (for downlink cells). For the DSA++ protocol, as in fixed ATM networks with a relatively low data rate (e.g., 20 Mb/s), QoS requirements of real-time-oriented services can only be supported if the transmission order of ATM cells is based on the waiting time inside the queues. As a consequence, BSs need to have current knowledge of the capacity requirements of the MSs. This can be achieved by piggybacking onto uplink ATM cells the instantaneous requirements of each mobile MS. However, it may not be possible to piggyback the newest requirements (e.g., if the MS is idle). In this case, MSs are provided with special uplink signalling slots so that they can transmit their capacity requests to BSs according to a random access scheme. Therefore, one has to note that some slots (up to an expected maximum of 1-2%) could be for this purpose, although it is not being considered by now in our computations.

The DSA++ protocol is implemented on top of a TDMA channel. Time slots may carry either a signalling burst or one ATM cell along with the additional signalling overhead of the physical layer (guard times, training sequences, tails, etc). A TDD is implemented to build the up- and downlinks channels in order to support asymmetric applications, Fig. 5.17. Time slots are grouped together into signalling periods, details given being in [ALMH98] and [PrSv99].

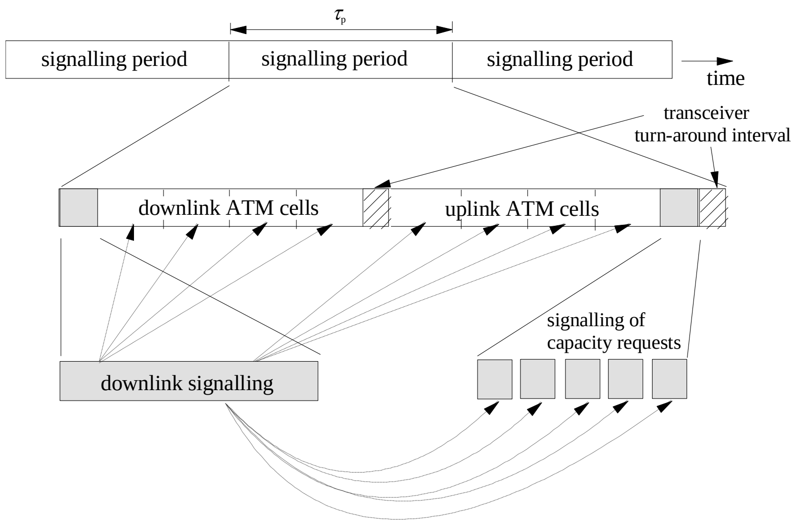


Fig. 5.17 – Signalling periods of DSA++ MAC protocol in the TDD case [VoWe98].

The length of each signalling period, as well as the ratio between the up- and downlink sections, is variable and assigned dynamically by BSs to cope with the current system load. Each signalling period consists of four phases: downlink signalling, downlink cells, uplink signalling and uplink cells. Details on the random access procedures and on the scheduling algorithm are also given in [ALMH98].

On the one hand, it is stated in [PrSv99] that the number of containers per frame shall be high enough to allow more precise allocation of capacity. The total number of containers per operator, which in fact gives the total amount of channels, could be divided by the reuse pattern to obtain the number of channel/cell, which is given by $T/N_{op}\cdot$(number of containers per frame), where T is the total number of carriers and N_{op} is the number of MBS operators. Since each container has a fixed overhead (guard time, signalling information) a shorter container length would decrease the load that can be carried; therefore, long containers, in terms of the number of slots supported, are recommendable. On the other, in terms of the algorithm to compute the blocking probability, although there should be enough granularity for resource allocation purposes, a lower bound exist for the basic bit rate that enables the use of the algorithms in a proper way (in terms of computation time).

After the assignment of a set of containers to a BS, their slots can be used for the communication between the BS and a MS on demand, if available and when necessary, thus, as one is considering more than one application, one is going to use the MMPP model for the superposition of IPP data and video sources, and to consider the related assumptions from Sections 5.2, 5.3 and 5.4.

5.5.4. System Capacity

According to [PrSv99], for each class of environments (to which a gross bit rate is associated) the number of available pairs of carriers (each in one of the 1 GHz bands) is obviously related to the carrier spacing Δf, which will depend on the adopted gross symbol rate R_S and on an appropriately selected '$\Delta f/R_S$ ratio'. When selecting the $\Delta f/R_S$ transmission parameter, it is essential to take the characteristics of the power amplifiers into account. If a grossly non-linear amplifier is to be allowed for OQPSK-type transmission with the modulation pulses recommended in [GuFD94], an adequate choice is in the interval [1.35, 1.47]. The lower value is the one of GSM, which uses the same modulation pulses, while the upper bound is the one proposed by the RACE-MBS project [RoSc94]. It follows that a reasonable number of carriers per GHz is

$$N_{car} \le \frac{1000}{(\Delta f / R_S) \cdot R_S} . \qquad (5.52)$$

Considering values for the $\Delta f/R_S$ parameter in the given range, different values can be obtained for the carrier spacing, Δf, and for the number of carriers per frequency band, N_{car}, as a function of the *GBR*, Table 5.21.

Table 5.21 – Carrier Spacing and Number of Carriers within each 1 GHz Band, N_{car}, for different gross bit rates.

GBR [Mb/s]	Δf [MHz]			N_{car}		
	$\Delta f/R_S$=1.47	$\Delta f/R_S$=1.3883	$\Delta f/R_S$=1.35	$\Delta f/R_S$=1.47	$\Delta f/R_S$=1.3883	$\Delta f/R_S$=1.35
40	29.4	27.77	27.03	34	36	37
80	58.8	55.54	54.06	17	18	18.5
160	117.6	111.08	108.12	8.5	9	9.25

It seems that $\Delta f/R_S$ =1.3883 is the best choice, because it leads to integer values of N_{car} for the different values of *GBR*. Note that adjacent carriers probably cannot be used simultaneously in the same cell, but a minimum carrier separation of $2\Delta f$ seems to be feasible.

The total bit rate per GHz is 663.552 Mb/s, considering 36, 18 or 9 carriers per 1 GHz bandwidth, for cases A, B and C, respectively, i.e., $18.432 \cdot 36 = 36.384 \cdot 18 = 73.728 \cdot 9 = 663.552$.

In a country where four operators will operate either in the 40 or the 60 GHz bands, for *GBR* = 40 Mb/s, nine carriers will be available per operator for each 1 GHz band, i.e., a total of 18 carriers per operator (corresponding to a total supported user bit rate of 1 327.104 Mb/s, thus, to 331.776 Mb/s per operator). For *GBR* = 80 Mb/s, there is a total of 9 carriers per operator (also corresponding to a total supported user bit rate of 1 327.104 Mb/s). For a *GBR* = 160 Mb/s, a total of '4.5 carriers' per operator (also corresponding to a total supported user bit rate of 1 327.104 Mb/s).

The use of the 16-OQAM type of modulation allows double the user bit rate in each of the bands.

5.6. Results

5.6.1. Assumptions

Because the higher service component data rate is 31 872 kb/s, one could think that one would need to consider Case MG, corresponding to *GBR* = 80 Mb/s, the system having 18 carriers at the uplink and 18 carriers at the downlink. However, if one considers that in MBS a terminal can handle more than one carrier, this will not be necessary true.

Having said that, either at the 40 or the 60 GHz bands, one has 2·18·96 = 3 456 channels of 384 kb/s, or 2 592 channels of 512 kb/s. In each country, the available channels are possibly going to be divided by three or four operators. The total amount of channels in each cell is then a fraction of the total number of channels, depending on the number of operators and on the reuse pattern *K*, Table 5.22.

Table 5.22 – Distribution of Channels between the Links According to the Asymmetry Factor.

Type of basic channels	Number of operators	Reuse pattern	Number of channels per cell	Distribution of channels					
				BCC		URB		ROA	
				UL	DL	UL	DL	UL	DL
384 kb/s	3	3	384	100	284	101	283	121	263
		4	288	75	213	76	212	91	197
		5	230	60	170	60	170	73	157
	4	3	288	75	213	76	212	91	197
		4	216	56	160	57	159	68	148
		5	172	45	127	45	127	54	118
512 kb/s	3	3	288	75	213	76	212	91	197
		4	216	56	160	57	159	68	148
		5	172	45	127	45	127	54	118
	4	3	216	56	160	57	159	68	148
		4	162	42	120	43	119	51	111
		5	129	34	95	34	95	41	88

Considering that the system uses a TDD duplexing scheme, it can handle asymmetric applications, and the asymmetry factors from Table 5.12 can be considered in order to obtain the distribution of channels between the up- and downlinks (UL and DL, respectively), Table 5.22. From Table 5.22, one can identify five different cases for the number of channels per cell for channels of each type:

- **384 kb/s:** 384, 288, 230, 216 or 172 channels per cell.
- **512 kb/s:** 288, 216, 172, 162 or 129 channels per cell.

Although one considered the cases of basic channels of 384 and 512 kb/s in Table 5.22, from now on one will concentrate on the case of the 384 kb/s type of channel, and results will be presented only for this case. Depending on the deployment scenario, different types of cells are used, Figs. 5.18-5.19: the four-leaf cell is suitable for coverage in the BCC and the URB scenario, whereas the cigar-shaped cell is suitable for coverage in the ROA one. Depending on the previously mentioned cases, actual maximum coverage distances are considered for each scenario [PrSv99], Table 5.23. The considered values for the actual coverage distance (of R = 100 m for the BCC and the URB scenarios, and R = 150 m for the ROA scenario) correspond to a net cell area of 8 316 m^2 in all cases. These values will be used for our initial analysis of the supported traffic.

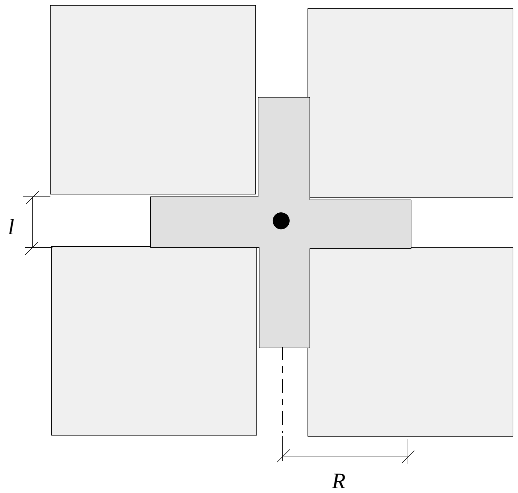


Fig. 5.18 – Four-leaf cell.

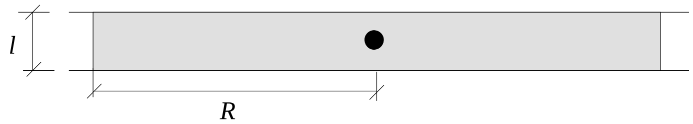


Fig. 5.19 – Cigar-shaped cell.

If the density factors, D_f, from Table 2.34 were considered, the corresponding number of potential users per cell would be (for the fixed values of R to be considered in Section 5.6.2) 257 in the BCC scenario and 100 in the URB and the ROA scenarios, Table 5.23. However, henceforth one is considering 250 user/cell in the BCC scenario, as an approximation, while 100 user/cell are still considered in the URB and the ROA scenarios.

Table 5.23– Actual Cell Dimensions and Considered Number of Potential User per Cell in each Scenario.

Scenario	Cases	R_{max} [m] [PrSv99]	Cell type	Considered values				Computed M_{ENV}	Considered M_{ENV}
				l [m]	R [m]	A_{cell} [m^2]	D_f [user/m^2]		
BCC	LG, MG	350, 180	Four-leaf	22	100	8316	0.031	257	250
URB	LG, MG	350, 180	Four-leaf	22	100	8316	0.012	100	100
ROA	LG, MG	350, 180	Cigar	28	150	8316	0.012	100	100

For the maximum load, the supported number of users is obtained directly from the load by

$$M_{max\_load} = L_{max} / b_1 \ . \qquad (5.53)$$

When the highest data rate service component, i.e., HID, is used at both links, if one considered the distribution of channels between the up- and downlinks according to the asymmetry factor, one would expect that the blocking probability would be higher for the uplink, because less channels are available. Because of these, one starts by considering values for the number of channels at the uplink, c_{UP} (with $LINK = UP$), 2-4% higher than the ones from Table 5.22 (obtained according to the asymmetry factor), in order to balance the blocking probability between the links, Table 5.24, and this is the original case for the analysis. Note that one considers the values of potential users in each deployment scenario, M_{ENV} and also the values users for the maximum load, M_{max_load}, from Table 5.24.

In Section 5.6.2, besides only considering a basic channel of 384 kb/s, one will only deal with the cases of 384 and 288 users per cell (the former corresponding to 3 operators and K = 3, while the latter either can correspond to 3 operators and K = 4 or to 4 operators and K = 3).

Table 5.24 – Considered M_{max_load}, c_{LINK} and M_{ENV} for the 384 kb/s-type of Channel.

Considered values for the analysis		BCC		URB		ROA	
		UL	DL	UL	DL	UL	DL
384 channel/cell	M_{max_load}	55	55	60	61	55	60
	c_{LINK}	104	280	105	279	124	260
288 channel/cell	M_{max_load}	41	41	45	46	41	45
	c_{LINK}	78	210	70	209	93	195
M_{ENV}		250		100		100	

The results for the blocking probability one is seeking are then obtained for these combinations number of channels per cell and deployment scenarios.

5.6.2. Results for the Supported Traffic

5.6.2.1. Absence of Mobility

In this Section, one considers fixed values for the coverage distance (i.e., R = 100 m for the BCC and the URB scenarios, and R = 150 m for the ROA scenario. In order to compute the supported traffic in a MBS multi-service environment, one will compute the blocking probability, and then verify which is the fraction of active users that can be supported for given threshold values for the blocking and/or handover failure probabilities.

In order to isolate the dependence of the activation and arrival rates on the fraction of active users one considers the maximum activation rate (5.46). For this computation, the data from Tables 5.2-5.3 and 5.7-5.10 is taken into account. Results for the maximum activation rate are presented in

Table 5.25. The null values of $\beta_{j\,max}$ in a link correspond to the service components that are not used.

Table 5.25 – Computed Values for the Maximum Activation Rate of each Service Component.

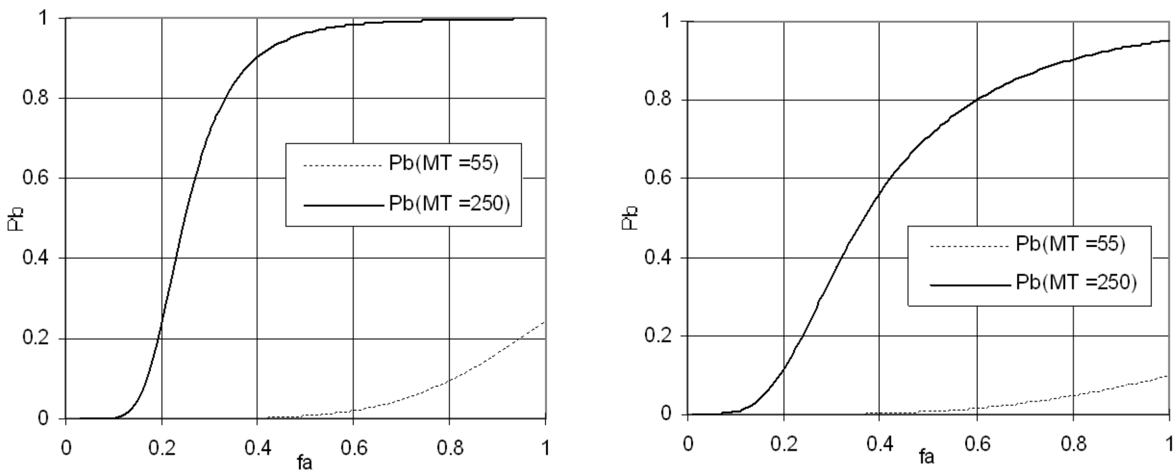
$d\beta_j$ [min^{-1}]	BCC		URB		ROA	
Component	UL	DL	UL	DL	UL	DL
BAS	1.3258	0.7183	1.3373	0.7186	1.2953	0.7178
MD1	0.6412	0.1990	0.4735	0.2652	0.7180	0.3912
MD2	0	0.0990	0	0.2140	0	0.0890
MD3	0.0600	0.2597	0.0504	0.3045	0.05456	0.2193
HDV	0.0052	0.0154	0.00072	0.0071	0.00812	0.01576
HID	0	0.1242	0	0.0483	0	0.1288

For the number of potential users associated with the deployment scenario, $M_T = M_{ENV}$, one concludes that the following inequality stands

$$(\alpha_{HID})_{BCC-DOWN} > (\alpha_{HID})_{ROA-DOWN} > (\alpha_{HID})_{URB-DOWN}. \qquad (5.54)$$

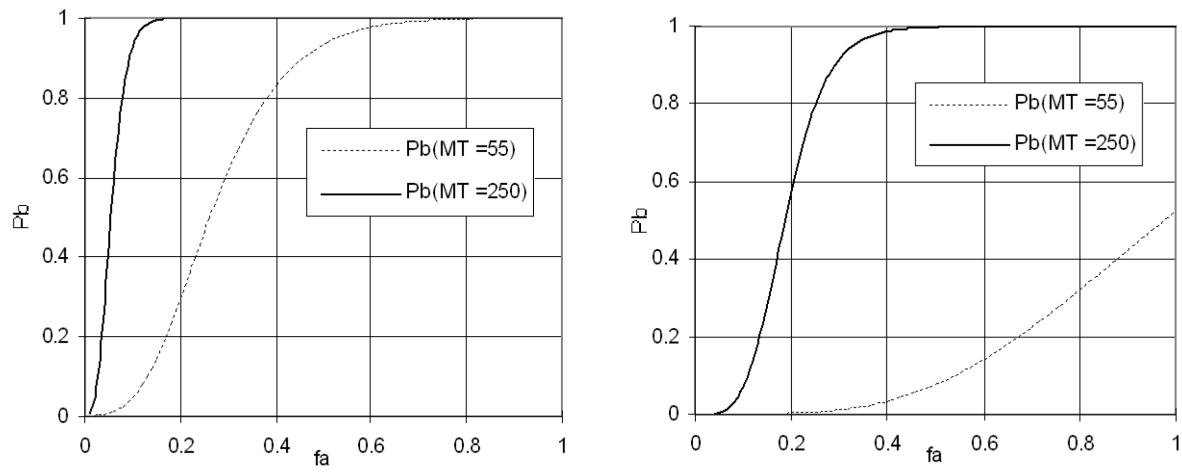
The values for the HID service component are compared for the downlink because one expects it will limit system performance. As the number of potential users associated with each service component, is $N_j = M_T$ for every j, and $M_{ENV\text{-}BCC} = 250 > M_{ENV\text{-}URB} = M_{ENV\text{-}ROA} = 100$, the values of the product of $M_T = M_{ENV}$ by $(-\beta_j)$ explain the inequality. For $M_T = M_{max\_load}$, as the previous relevant difference of the values of M_T between the BCC and the ROA scenario does not exist, the inequality (5.54) does not stand.

Considering the values of M_T and c_{LINK} from Table 5.24, results for the blocking probability were obtained for the up- and downlinks. As an illustration, results for the BCC scenario are presented in Figs. 5.20-5.21 for the HDV and HID service components (and 384 channel/cell), the components that do limit system performance. In this scenario $M_{ENV} = 250$ and $M_{max\_load} = 55$.



a) Uplink b) Downlink

Fig. 5.20 – Blocking probability as a function of the fraction of active users for the HDV component, 384 channel/cell, BCC scenario.



a) Uplink b) Downlink

Fig. 5.21 – Blocking probability as a function of the fraction of active users for the HID component, 384 channel/cell, BCC scenario.

The results for the lowest data rates service components, i.e., the BAS, MD1, MD2 and MD3 components, are presented in Annex I.

P_b is an increasing function with the traffic load, like in the Erlang B or the Engset models (for the single service traffic case). It takes higher values for higher data rates service components. Although one does not present the results, the time blocking probability, presents negligible differences in relation to the blocking probability itself.

These results can be used to obtain the supported fraction of active users in a cell by inverting the process, i.e., obtaining the values of f_a corresponding to a given threshold of the blocking probability, using values of P_b available in a table.

Comparing the HID component blocking probability between the up- and downlinks, one concludes that it is higher for the uplink (even after our slight change increasing the channels available at the uplink relatively to the values obtained using the asymmetry factor). It also confirms that the HID service component will limit the system, as it uses more basic channels than the other service components. However, as the mixtures of applications on the three considered deployment scenarios do not use the HID service component at the uplink, different trade-offs arise in terms of the blocking probability constraint used to obtain the supported traffic.

As a consequence, the system is limited by the HID component at the downlink, whereas the HDV service component limits the system at the uplink. Given a blocking probability threshold of P_b = 2 %, the results for the fraction of the active users, $f_{a[\%]}$, when $M_T = M_{ENV}$, are the ones from Tables 5.26-5.27.

One concludes that, opposite to what one would expect if the HID service component had limited both links, f_a is higher for the uplink. Thus, taking this into account, one obtained results for a new configuration where the number of channels at the uplink was reduced ('change 1' case), with the consequent increase of the number of channels at the downlink. After this step ('change 1' case), in the deployment scenarios where the difference on f_a between the up- and downlinks was still higher than 1.6%, one ran the program for blocking probability computation again for another set of values of c_{UP} and c_{DOWN} ('change 2' case).

Table 5.26 – Supported Fraction of Active Users for P_b = 2% with 384 Channel/Cell, $M_T = M_{ENV}$.

$f_{a[\%]}$			Original case	Change 1	Change 2
M_{ENV} =250	BCC	UL	11.4	7.6	8.5
		DL	7.3	8.5	8.2
M_{ENV} =100	URB	UL	35.6	29.6	26.4
		DL	23.1	25.0	26.0
M_{ENV} =100	ROA	UL	33.7	22.6	-
		DL	17.1	21.1	-

Table 5.27 – Supported Fraction of Active Users for P_b = 2% with 288 Channel/Cell, $M_T = M_{ENV}$.

$f_{a[\%]}$			Original case	Change 1	Change 2
M_{ENV} =250	BCC	UL	6.8	4.7	-
		DL	3.4	4.1	-
M_{ENV} =100	URB	UL	21.1	15.0	-
		DL	11.7	13.4	-
M_{ENV} =100	ROA	UL	20.1	14.7	11.2
		DL	7.1	9.3	10.6

In Tables 5.28-5.29 one presents the values of c_{LINK} that have been considered. One highlights the values of the reduction (in percentage) of the number of uplink channels relatively to the original values from Table 5.24. Results for the supported f_a for 'changes 1&2' are the ones already presented in Tables 5.26-5.27. From the results reported in Tables 5.26 and 5.27, the planner should consider the rightmost ones for analysis purposes, the dimensioning values for c_{UP}, and c_{DOWN} being the ones from Tables 5.28-5.29.

Table 5.28 – c_{LINK} for the 'Change 1&2' Cases with 384 Channel/Cell.

c_{UP}, c_{DOWN}		Original case	Change 1		Change 2	
			Uplink reduction	c_{LINK}	Uplink reduction	c_{LINK}
BCC	UL	104	20 %	83	15 %	88
	DL	280		301		296
URB	UL	105	10 %	95	15 %	89
	DL	279		289		295
ROA	UL	124	20 %	99	-	-
	DL	260		285		-

Table 5.29 – c_{LINK} for the 'Change 1&2' Cases with 288 Channel/Cell.

c_{UP}, c_{DOWN}		Original case	Change 1		Change 2	
			Uplink reduction	c_{LINK}	Uplink reduction	c_{LINK}
BCC	UL	78	15 %	66	-	-
	DL	210		222		-
URB	UL	79	15 %	67	-	-
	DL	209		221		-
ROA	UL	93	15 %	79	25 %	70
	DL	195		209		218

These 'changed' cases correspond, in terms of the blocking probability performance, to a balanced system between the up- and downlinks for P_b = 2%. Between the BCC and URB scenarios, there is no significant difference in c_{LINK} (e.g., c_{UP} = 66-67 and c_{DOWN} = 221-222 in the 288 channel/ cell case), whereas an important difference exists in the ROA scenario, mainly in the 384 channel/cell case.

The results for f_a for $M_T = M_{max\_load}$ are presented in Tables 5.30-5.31. The values of M_{max_load} are the ones from Table 5.24. One did not considered the values from 'change 1&2' cases, because one is using it as a mere indicative value.

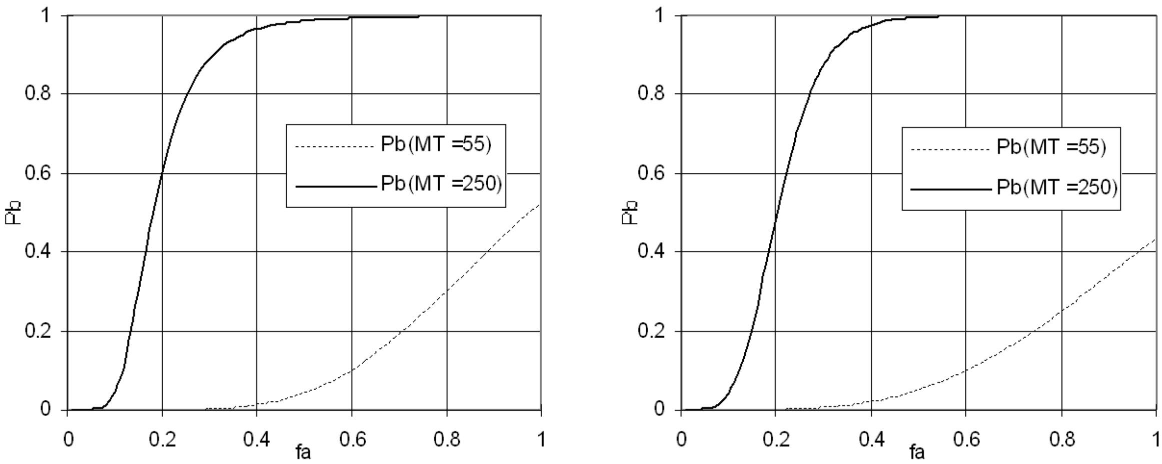
Table 5.30 – Supported Fraction of Active Users for P_b = 2% with 384 Channel/Cell, $M_T = M_{max\_load}$.

$f_{a[\%]}$			Original case	Change 1	Change 2
M_{ENV} =250	BCC	UL	60.2	38.4	43.2
		DL	35.0	41.1	39.6
M_{ENV} =100	URB	UL	64.6	53.2	46.9
		DL	39.1	42.2	44.1
M_{ENV} =100	ROA	UL	68.5	44.4	-
		DL	29.3	36.2	-

Table 5.31 – Supported fraction of active users for P_b = 2% with 288 Channel/Cell, $M_T = M_{max\_load}$.

$f_{a[\%]}$			Original case	Change 1	Change 2
M_{ENV} =250	BCC	UL	47.2	31.8	-
		DL	22.0	26.0	-
M_{ENV} =100	URB	UL	51.6	35.7	-
		DL	26.1	30.2	-
M_{ENV} =100	ROA	UL	55.4	39.4	29.6
		DL	16.1	21.2	24.3

In Fig. 5.22 one presents, as an example, the curves of the blocking probability as a function of f_a, for the BCC scenario and the rightmost cases in Table 5.26 (corresponding to 'change 2', i.e., balanced cases in terms of P_b). From the results for the remaining scenarios, only the values for the chosen coverage distances are highlighted, Tables 5.26-5.27 and 5.30-5.31 (288 channel/cell case). P_b increases with f_a, and a slight asymmetry is still verified.



a) Uplink, HDV service component b) Downlink, HID service component

Fig. 5.22 – Blocking probability as a function of f_a for the 384 channel/cell case, BCC scenario.

Although system capacity results involving f_a are quite interesting, the comparison among the three different scenarios is difficult, as the number of potential users in a cell is different (although the cells have the same net area). Because of this difficulty, it is useful to present results for the number of supported users in a cell, which is given by

$$N_{SU} = f_a \cdot M_T . \quad (5.55)$$

The spectral efficiency can then be defined as

$$S_{ef} = \frac{f_a \cdot M_T \cdot b_1}{c_{LINK} \cdot 384\,[\text{kb/s}]} . \quad (5.56)$$

Results for the supported number of users and for the spectral efficiency for $M_T = M_{ENV}$ are presented in Tables 5.32-5.33. As the results are obtained from the 'changes 1&2' from the original case, one also presents the modified M_{max_load} in these Tables, obtained from

$$Changed\_M_{max\_load} = \frac{c_{LINK} \cdot 384\,[\text{kb/s}]}{b_1} , \quad (5.57)$$

although one has used the original values for M_{max_load} from Table 5.24 in the computations. Worst-case values of the supported f_a between the up- and downlinks are considered to compute the spectral efficiency, meaning that, for example, if the supported f_a for the downlink is lower than for the uplink, the spectral efficiency for the uplink has to be re-computed using the values for the downlink.

Table 5.32 – Supported Number of Users and Spectral Efficiency for 384 Channel/Cell, $M_T = M_{ENV}$.

			N_{SU}	S_{ef}	Worst case S_{ef}	*Changed* M_{max_load}
M_{ENV} = 250	BCC	UL	21.2	0.45	0.44	47
		DL	20.5	0.35	0.35	58
M_{ENV} = 100	URB	UL	26.4	0.51	0.50	51
		DL	26.1	0.40	0.40	65
M_{ENV} = 100	ROA	UL	22.6	0.51	0.47	44
		DL	21.1	0.35	0.35	61

Table 5.33 – Supported Number of Users and Spectral Efficiency for 288 Channel/Cell, $M_T = M_{ENV}$.

			N_{SU}	S_{ef}	Worst case S_{ef}	*Changed* M_{max_load}
M_{ENV} = 250	BCC	UL	11.7	0.33	0.29	35
		DL	10.2	0.23	0.23	44
M_{ENV} = 100	URB	UL	15.0	0.38	0.34	39
		DL	13.4	0.28	0.28	48
M_{ENV} = 100	ROA	UL	11.2	0.36	0.34	31
		DL	10.6	0.23	0.23	46

For the cases where the total maximum load (the sum $b_{1\text{-}UP}+b_{1\text{-}DOWN}$) is lower, the number of supported users is higher, Table 5.12. The spectral efficiency is always lower for the uplink, which results from the combination of values one used for the number of available channels, c_{UP} and c_{DOWN}.

Comparing the 288 and 384 channel/cell cases, one can also conclude that, although the ratio between the number of channels is 0.75, the ratio between the number of supported users, $R_{USER} = N_{SU}(c=288)/N_{SU}(c=384)$, is only approximately 50 %, Table 5.34.

Table 5.34 – Ratio of the Number of Supported Users between the 288 and the 384 Channel/Cell Cases.

	Scenario	R_{USER} [%]
M_{ENV} = 250	BCC	53.7
M_{ENV} = 100	URB	51.3
M_{ENV} = 100	ROA	50.2

This means that when the number of channels per cell decrease, the number of supported users and the spectral efficiency decrease drastically. In the cases when a low amount of channels is available, decreasing the data rate associated with the basic channel, i.e., the slot (leading to a higher number of channels with a different granularity), could possibly solve the problem.

For $M_T = M_{max\_load}$, the results for the supported number of users and for the spectral efficiency are presented in Tables 5.35-5.36, where the *Changed_*M_{max_load} is also presented (although one used the original values from Table 5.24 in the computations). The change would only correspond to considering a slightly lower value of M_{max_load} for the uplink.

Table 5.35 – Supported number of users and spectral efficiency for 384 Channel/Cell, $M_T = M_{max\_load}$.

			N_{SU}	S_{ef}	Worst case S_{ef}	*Changed* M_{max_load}
$M_{ENV} = 250$	BCC	UL	23.8	0.51	0.46	47
		DL	21.8	0.37	0.37	58
$M_{ENV} = 100$	URB	UL	28.2	0.54	0.52	51
		DL	26.9	0.41	0.41	65
$M_{ENV} = 100$	ROA	UL	24.4	0.55	0.49	44
		DL	21.7	0.36	0.36	61

Table 5.36 – Supported Number of Users and Spectral Efficiency for 288 Channel/Cell, $M_T = M_{max\_load}$.

			N_{SU}	S_{ef}	Worst case S_{ef}	*Changed* M_{max_load}
$M_{ENV} = 250$	BCC	UL	13.0	0.37	0.30	0.37
		DL	10.6	0.24	0.24	0.24
$M_{ENV} = 100$	URB	UL	16.0	0.41	0.36	0.41
		DL	13.9	0.28	0.28	0.28
$M_{ENV} = 100$	ROA	UL	12.1	0.39	0.35	31
		DL	10.9	0.23	0.23	46

One can conclude that although, for $M_T = M_{ENV}$, the supported fraction of active users is

$$f_{a\text{-}BCC} < f_{a\text{-}ROA} < f_{a\text{-}URB} \quad (5.58)$$

agreeing with the inequalities (5.54) for the arrival rate, α_j; the inequality is not maintained for $M_T = M_{max\_load}$ because the correspondent inequalities for α_j does not stand anymore.

Instead, one has

$$f_{a\text{-}ROA} < f_{a\text{-}BCC} < f_{a\text{-}URB}. \quad (5.59)$$

The system can support a slightly higher number of users for $M_T = M_{max\_load}$, which agrees with $M_{max\_load} < M_{ENV}$, and it is a consequence of replacing N_j by these values in equation (5.38) for $\lambda_j(n_j)$, and can be viewed as the consequence of the 'Bernoulli-model effect' in the multi-service traffic performance (in opposition to the Poisson model characteristics).

5.6.2.2. Presence of Mobility

When terminal mobility is considered the number of supported users in a cell must be obtained from the worst case between the P_b = 2% and the $P_{hf} = (P_{hf})_{j\,max}$ cases. In a simplified approach, similar to the one from [Jabb96] for single-service systems, one considers that the equation to compute the handover failure probability is equal to the one for the blocking probability, as guard channels for handover are not considered.

The analysis is based in the consideration from Section 5.4.4, and considering the values of $(P_{hf})_{j\,max}$ from Table 5.37. R = 100 m was considered for the BCC and the URB scenarios, whereas, for the ROA scenario, one considered R = 150 m.

Table 5.37 – $(P_{hf})_{jmax}$ for the Various Service Components in the Considered Scenarios.

$(P_{hf})_{jmax}$	R = 100 m		R = 100 m		R = 150 m	
	BCC		URB		ROA	
Component	UL	DL	UL	DL	UL	DL
BAS	0.765846	0.103733	0.001635	0.001620	0.000664	0.000614
MD1	0.003361	0.052250	0.000229	0.000171	0.000140	0.000124
MD2	NA	NA	NA	NA.	NA	0.000563
MD3	0.008407	0.004276	0.000446	0.001170	0.000340	0.000147
HDV	NA	NA	0.000277	0.002734	0.000188	0.000094
HID	NA	NA	NA	NA	NA	0.000154

NA – Not applicable.

In order to obtain the supported fraction of active users, one has to analyse the results for the MD3 service component in the BCC scenario, for the HDV component in the URB scenario, and for the HDV and the HID components (for the up- and the downlinks, respectively) in the ROA scenario.

From this analysis, the values of the supported fraction of active users from Table 5.38-5.39 are obtained. For example, for the BCC scenario, as the supported f_a resulting from the P_{hf} constraints for the MD3 component is always higher than the obtained for P_b = 2% (for the HDV and the HID service components, up- and downlinks, respectively); hence one considers the values obtained for P_b = 2% (both for the HDV and HID components), which can be extracted from Fig. 5.22.

Table 5.38 – Supported fraction of active users for $P_{hf} = (P_{hf})_{jmax}$ with 384 Channel/Cell and Presence of Mobility, $M_T = M_{ENV}$.

$f_{a[\%]}$			Original case	Change 1	Change 2
M_{ENV} =250	BCC	UL	11.4	7.6	**8.5**
		DL	7.3	8.5	**8.2**
M_{ENV} =100	URB	UL	**21.2**	16.9	14.5
		DL	**27.3***	29.1	30.1
M_{ENV} =100	ROA	UL	19.0	**11.3**	-
		DL	3.7	**5.9**	-

* In this case the limitation by P_b = 2% from Table 5.26 leads to $f_{a[\%]}$ = 23.1. However it does not affect the dimensioning of the system as it is the uplink that does limit the system.

Table 5.39 – Supported fraction of active users for $P_{hf} = (P_{hf})_{jmax}$ with 288 Channel/Cell and Presence of Mobility, $M_T = M_{ENV}$.

$f_{a[\%]}$			Original case	Change 1	Change 2
M_{ENV} =250	BCC	UL	6.8	**4.7**	-
		DL	3.4	**4.1**	-
M_{ENV} =100	URB	UL	**10.8**	6.6	-
		DL	**15.8***	17.7	-
M_{ENV} =100	ROA	UP	9.6	6.2	**4.1**
		DL	1.14	1.82	**2.2**

* In this case the limitation by P_b = 2% from Table 5.27 leads to $f_{a[\%]}$ = 11.7. However it does not affect the dimensioning of the system as it is the uplink that does limit the system.

In the remaining scenarios, f_a is obtained from the curves for P_b for the HDV component in the URB scenario (as the P_{hf} can not be defined for the HID component), and from the curves for HDV and HID components (for the up- and downlinks, respectively) in the ROA scenario. The constraint $P_{hf} = (P_{hf})_{jmax}(R)$ is used. The best combination, in terms of the existence of a balance between the up- and downlinks, is identified in bold. These results correspond to the number of supported users and the spectral efficiency from Tables 5.40-5.41 obtained for the best combination in Tables 5.38 and 5.39.

Comparing the values of f_a in the presence and absence mobility, Table 5.42, one concludes that whereas in the BCC scenario the consideration mobility has no impact, it has important consequences in the URB and in the ROA scenarios.

Table 5.40 – Supported fraction of active users with 384 Channel/Cell and Presence of Mobility, $M_T = M_{ENV}$.

			N_{SU}	S_{ef}	Worst case S_{ef}
M_{ENV} = 250	BCC	UL	21.2	0.45	0.44
		DL	20.5	0.35	0.35
M_{ENV} = 100	URB	UL	21.2	0.31	0.31
		DL	27.3	0.43	0.33
M_{ENV} = 100	ROA	UL	11.3	0.25	0.13
		DL	5.8	0.10	0.10

Table 5.41 – Supported fraction of active users with 288 Channel/Cell and Presence of Mobility, $M_T = M_{ENV}$.

			N_{SU}	S_{ef}	Worst case S_{ef}
M_{ENV} = 250	BCC	UL	11.7	0.33	0.29
		DL	10.2	0.23	0.23
M_{ENV} = 100	URB	UL	10.8	0.21	0.21
		DL	15.8	0.33	0.23
M_{ENV} = 100	ROA	UL	4.1	0.13	0.07
		DL	2.2	0.05	0.05

Table 5.42 – Comparison between the Cases of Absence and Presence of Mobility, $M_T = M_{ENV}$.

	Scenario	$f_{a[\%]}$		$\frac{f_{a-with}}{f_{a-without}}$
		Without mobility	With mobility	
384 channel/cell	BCC	8.2	8.2	1
	URB	26.0	21.2	0.82
	ROA	21.1	5.9	0.28
288 channel/cell	BCC	4.1	4.1	1
	URB	13.4	10.8	0.81
	ROA	10.6	2.2	0.21

Comparing the cases of presence and absence of mobility, in URB scenarios only 81-82 % is supported in the presence of mobility while, in ROA scenarios only 21-28 % of the traffic is supported.

For the $M_T = M_{max\_load}$ case, the results for f_a and N_{SU} are the ones from Appendix J. One concludes that the terminal mobility has a similar effect for $M_T = M_{ENV}$ and $M_T = M_{max\_load}$. Because, the terminal mobility affects the system performance mainly in ROA scenarios, one could think that reducing the handover failure probability threshold (via reducing the coverage distance of cells) could be a way to overcome this situation. However, the following example contradicts this idea. For R = 350 m, in the ROA scenario one obtains $(P_{hf})_{max\text{-HDV-UP}} = 0.000438$ and $(P_{hf})_{max\text{-HID-DOWN}} = 0.000359$. This leads to $f_{a\text{-}UP}$ = 13.0 % and $f_{a\text{-}DOWN}$ = 7.2%; if one considered M_T = 250 (in order to use the data already available) there would be a decrease of 34.1% in the supported f_a, relatively to the case of absence of mobility, but it would however be around 6-7 % than in the case of R = 150 m. However, R = 150 m leads to N_{SU} = 33 user/km, whereas R = 350 m only leads to N_{SU} = 10 user /km (active users). The much lower number of cells per unit length causes the difference. Therefore, the associated tradeoffs in optimisation of system capacity should be clarified in a more extensive way by a cost-revenue performance detailed analysis of the system.

5.6.3. Dependence on *R*

5.6.3.1. Assumptions

The starting point of MBS optimisation via an economic analysis consists of obtaining the variation of the spectral efficiency with the coverage distance. However, in Section 5.6.2 the spectral efficiency was computed for fixed values of R, taking into account both the blocking and the handover failure probability thresholds.

Thus, in this Section one has to redo the computations, in order to have the necessary set of results for different values of R, say, $10 \leq R \leq 500$ m. These results will be fed into the economic analysis in next Chapter.

Because one will be interested in the simultaneous contribution of the up- and downlinks, instead of a single link contribution (as it was considered in Section 5.6.2, (5.56)), one defines the total spectral efficiency in the following way

$$\left(S_{ef}\right)_{TOT} = \frac{f_a \cdot M_T \cdot \left(b_{1-UP} + b_{1-DOWN}\right)}{\left(c_{UP} + c_{DOWN}\right) \cdot 384\ [\text{kb/s}]}, \tag{5.60}$$

where the denominator takes into account the simultaneous contribution of the up- and downlink channels, and the numerator includes the sum of the maximum loads, b_1, of up- and downlinks.

When the reuse factor is K = 2 or K = 3, and if the 2 GHz bandwidth (available either at the 40 or the 60 GHz bands) is divided by four operators, there is a total of 9 carriers/cell (i.e., 432 channel/cell) or 6 carrier/cell (i.e., 288 channel/cell), respectively. This is the case of the linear and the ‘Manhattan grid’ geometries. When K = 5 (the case of the irregular urban geometry), if there were four operators (corresponding to 172 basic channels in each cell) the blocking probability would highly exceed its maximum threshold value (P_b = 2 %) for a low value of the fraction of active users in a cell, and the system would be very inefficient.

This explains why one considers only two operators, corresponding to an average of 7.2 carriers/cell (or 345 channel/cell). Although it is an approximated value (because the number of carriers in a cell should be an integer value), one considers it, as far as the approach for the irregular urban geometry is an approximated one in several aspects, and one extra approximation will only have a little impact. Nevertheless, it can rigorously be seen as representing, by a single number, the average number of available carriers in a cluster of five cells, where four cells have seven carriers, while one cell has eight carriers available.

In Sections 5.6.1 and 5.6.2 one has considered a number of user per cell M_T = 250, 100 and 100 (for R = 100, 100 and 150 m) in the BCC, URB and ROA scenarios, respectively. In this Section one is considering that M_T is directly proportional to R, being computed by $M_T = 2.5 \cdot R$, $M_T = R$ and $M_T = 0.67 \cdot R$, respectively. Its dependence on R can be checked in Table 5.43. Although some charts were already presented in Section 5.4.3 for $(P_{hf})_{jmax}(R)$, one also presents the variation $(P_{hf})_{jmax}$ with R, for the discrete values of R one is considering, Table 5.43. These values are very useful in the process of obtaining the supported fraction of active users. The service component that limits the system performance, in terms of handover failure probability, is also identified in bold. For a given link (up- or downlink), it is the highest bit rate service component that has at least one no static application (i.e., non-null cross-over rate) associated with it.

Table 5.43 – Number of users per cell and maximum handover failure probability in the three scenarios.

R [m]	M_T			$(P_{hf})_{jmax}$					
				Four-leaf cell				Cigar shaped cell	
	Four-leaf cell		Cigar shaped cell	BCC		URB		ROA	
	BCC	URB	ROA	UL (**MD3**)	DL (**MD3**)	UL (**HDV**)	DL (**HDV**)	UL (**HDV**)	DL (**HID**)
10	25	10	6	0.000841	0.000428	2.77E-05	0.000273	1.25E-05	1.03E-05
50	125	50	33	0.004203	0.002138	0.000139	0.001367	6.25E-05	5.13E-05
84	210	84	55	0.007062	0.003592	0.000233	0.002230	0.000105	8.65E-05
100	250	100	66	0.008407	0.004276	0.000277	0.002734	0.000125	0.000103
150	375	150	100	0.012610	0.006415	0.000416	0.004101	0.000188	0.000154
200	500	200	133	0.016813	0.008553	0.000555	0.005468	0.00025	0.000205
250	625	250	166	0.021017	0.010691	0.000693	0.006835	0.000313	0.000257
300	750	300	200	0.025220	0.012829	0.000832	0.008202	0.000375	0.000308
350	875	350	233	0.029423	0.014967	0.000970	0.009569	0.000438	0.000359
400	1 000	400	266	0.033626	0.017106	0.001109	0.010937	0.000500	0.000411
450	1 125	450	300	0.037830	0.019244	0.001248	0.012304	0.000563	0.000462
500	1 250	500	333	0.042033	0.021382	0.001386	0.013671	0.000625	0.000513

In the BCC scenario, although it is the MD3 component that limits the system in terms of handover failure probability constraint, one has verified that, in fact, the system is limited by blocking probability constraint, P_b = 2 %, for every R. As it has already been presented in the previous Chapter, because the HID component is not used in the uplink (but only in the downlink), the restriction P_b = 2 % has to be checked for the HDV service component in the uplink and for the HID service component in the downlink.

5.6.3.2. Distribution of the Available Channels between the Links

In this Section one defines the number of channels to be used in each link, in each of the experiences, i.e., in the BCC, URB and ROA scenarios (with R = 100, 100 and 150 m, respectively) considering the cases of 172, 288, 345 and 432 channel / cell. This is done by choosing cases that yield a balance of the supported fraction of active users between the up- and downlinks. In the case of 288 channel/ cell, the 'original' case one is considering in Table 5.44 is the rightmost one from Table 5.29, it corresponding to a balance between the up- and downlinks for P_b = 2 %, i.e., without considering the impact of terminal mobility (which was the approach followed in Section 5.6.2).

However, in some deployment scenarios, the actual MBS operation occurs with considerable terminal mobility, and the necessary adaptation is necessary in order to obtain the number of channel in each link corresponding to a balance associated with the handover failure probability constraint, $P_{hf} = (P_{hf})_{jmax}$, i.e., the 'presence' of mobility is considered in this balance.

Table 5.44 – Values of c_{LINK} for the 'Original' and the '*Change* 1' Cases, 288 Channel/Cell.

c_{UP}, c_{DOWN}		'Original' case		'*Change* 1' case	
		M_{max_load}	c_{LINK}	Uplink increase	c_{LINK}
BCC	UL	41	66	-	-
	DL	41	222		-
URB	UL	45	79	+14 %	90
	DL	46	209		198
ROA	UP	41	70	-10 %	63
	DL	45	218		225

In Table 5.44, one presents the values of c_{LINK} ($LINK$ = UP, DOWN) for the 'original' and the '*change* 1' cases; the latter corresponding to the sought balance. The number of users that corresponds to the maximum load, M_{max_load}, is only presented for the "original" case in the different scenarios, because it is merely indicative, not having any further impact in the context of this Chapter. It is obtained by

$$M_{max\_load} = \frac{L_{max}}{b_{1-LINK}} = \frac{c_{LINK} \cdot 384\,[\text{kb/s}]}{b_{1-LINK}}\,. \qquad (5.61)$$

In the cases of 345 and 432 channel/cell, the 'original' case is an adaptation of the rightmost values of c_{LINK} for 384 channel/cell from Table 5.28. The values of c_{LINK} for the 345 channel/cell case are obtained multiplying the ones form Table 5.28 by (345/384) (and the same procedure is followed for 432 channel/cell), Tables 5.45 and 5.46. In both 'changed' cases, the uplink increase always refers to the 'original' case.

Table 5.45 – Values of c_{LINK} for the 'Original', the '*Change* 1' and the '*Change* 2'Cases, 345 Channel/Cell.

c_{UP}, c_{DOWN}		'Original' case		'*Change* 1' case		'*Change* 2' case	
		M_{max_load}	c_{LINK}	Uplink increase	c_{LINK}	Uplink increase	c_{LINK}
BCC	UL	49	79	-	-	-	-
	DL	49	266		-		-
URB	UL	54	78	+15 %	90	+30%	102
	DL	55	267		255		243
ROA	UL	37	88	- 10 %	80	-20 %	72
	DL	40	257		265		273

Table 5.46 – Values of c_{LINK} for the 'Original' and the '*Change* 1' Cases, 432 Channel/Cell.

c_{UP}, c_{DOWN}		'Original' case		'*Change* 1' case	
		M_{max_load}	c_{LINK}	Uplink increase	c_{LINK}
BCC	UP	61	99	-	-
	DOWN	61	333		-
URB	UP	67	100	+10 %	110
	DOWN	68	332		322
ROA	UP	61	111	-10 %	99
	DOWN	67	321		333

As it was already stressed, one also could consider the case of 172 channel/cell (corresponding to four operators and K = 4). However, considering again the coverage distances of R = 100, 100 and 150 m, for the BCC, URB and ROA, respectively, the values obtained for the blocking probability are too high, even for low values of the f_a (typically lower than 1 %), resulting in a system without enough available capacity.

In Tables 5.47-5.49 are presented the results for the supported fraction of active users for the rightmost case in Tables 5.44-6.46.

Table 5.47 – Supported fraction of active users in the 288 Channel/Cell case.

f_a [%]			Mobility	
			Absence	presence
M(R = 100 m) = 250	BCC	UL	4.7	4.7
		DL	4.1	4.1
M(R = 100 m) = 100	URB	UL	26.9	14.8
		DL	10.0	14.1
M(R = 150 m) = 100	ROA	UL	9.1	3.0
		DL	11.7	2.3

Table 5.48 – Supported fraction of active users in the 345 Channel/Cell case.

f_a [%]			Mobility	
			absence	presence
$M(R = 100\text{ m}) = 250$	BCC	UL	7.0	7.0
		DL	6.5	6.5
$M(R = 100\text{ m}) = 100$	URB	UL	33.8	19.7
		DL	17.0	21.2
$M(R = 150\text{ m}) = 100$	ROA	UL	13.1	5.0
		DL	18.7	4.5

Table 5.49 – Supported fraction of active users in the 432 Channel/Cell case.

f_a [%]			Mobility	
			absence	presence
$M(R = 100\text{ m}) = 100$	BCC	UL	10.5	10.5
		DL	10.4	10.4
$M(R = 100\text{ m}) = 100$	URB	UL	38.8	23.4
		DL	31.1	35.1
$M(R = 150\text{ m}) = 250$	ROA	UL	22.6	11.3
		DL	29.2	10.7

For each deployment scenario, the number of users per cell (corresponding to R = 100, 100 and 150 m in the BCC, URB and ROA scenarios, respectively) is highlighted. The cases of presence and absence of mobility are distinguished. Considering the presence of terminal mobility, the difference on f_a between the up- and downlink is typically lower than 1 %, except in the URB scenario with 432 Channel/Cell. However, the computations were not redone for this case because the results will not be needed in the final analysis, as it will be seen and explained later.

The approach followed in the computation of f_a consisted in obtaining a table with values of P_b for f_a varying from 0.01 to 1 with steps of 0.01 (or less, if necessary). The sought value was then obtained doing a linear interpolation between the two closest neighbour values of the case P_b = 2% or $P_{hf} = (P_{hf})_{max}$. A more complete analysis will be presented in the next Section.

5.6.3.3. Goals for System Capacity

It is also important to define the prospective mature MBS number of users per kilometre in the busy hour. Following the hypothesis from Chapter 2, a rough measure can be obtained in the following way. In the BCC scenario one considers that a density factor of 0.031 user/m^2 correspond to 1250 potential user/km, whereas, in the URB and ROA scenarios, 0.012 user/m^2 correspond to 500 and 333 user/km, respectively, Table 5.50. From Chapter 2, the only measure for the ‘usage’ that takes the number of users in a cell into account is the busy hour rate, whose values for some MBS applications are the presented in Table 2.20. The sum of the values of the busy hour rate gives the percentage of active users.

Table 5.50 – Foreseen number of user/km in mature MBS.

Scenario	No. of potential user/km	$\sum_{S_1} BHR$	Foreseen no. of user/km in mature MBS
BCC	1 250	16.0	200
URB	500	11.7	58
ROA	333	11.7	39

So, taking the values of the *BHR* from Table 2.20 into account, one has summed them for the set of applications simultaneously referred in Tables 2.20 and 2.34 (set S_1, say), and one has considered it as the total *BHR* for mature MBS. As a simplification, one has assumed that the URB and ROA scenarios correspond to 'primary roads' in Table 2.20.

Although, in Chapter 2 one extended the number of applications from Table 2.20 to the ones from Table 2.34, here, one still considers that the total *BHR* is the related with the former table. It means that although some of the users will also have access to applications from Table 2.34, not mentioned in Table 2.20, one does not account for their contribution in *BHR*. Thus, the foreseen number of user/km is 200, 58 and 39 in the BCC, URB and ROA mature MBS scenarios, respectively. It is however worthwhile to note again that this is a rough approach, whose only objective is having comparative target values for the number of users per kilometre in such deployment scenarios.

5.6.3.4. Choice of the Reuse Factor in Regular Geometries

While the 'Manhattan grid' geometry was associated with the BCC and URB scenarios, the linear geometry was associated to the ROA scenario. The blocking probability was computed, as a function of f_a, using the algorithm from Section 5.3.5, and tables were generated in this way for different coverage distances (and respective M_Ts). One solved either the equation P_b = 2 % or $P_b = (P_{hf})_{max}$, depending on the case of absence or presence of mobility, respectively. Note that one assumes, as an approximation, that P_{hf} is equal to P_b, as no guard channels for handover are used.

For regular geometries, one assumed reuse factors of K = 3 or K = 2, corresponding to 288 or 432 channel/cell, respectively. The values of the supported fraction of active users are presented in Figs. 5.23-5.25, for K = 3, and Appendix L, for K = 2 (where UP and DOEN sesignate the up- and downlinks, respectively).

The balance between the links one is pursuing is maintained as R varies, confirming the planning of the experiences one has defined in Tables 5.44-5.45. The only case where this balance is not achieved is for the URB scenario with 432 channel/cell (but it was not achieved even in the initial experience planning from Section 5.6.3.2). Even so, one has not redone the computations because one will not need it in the final analysis.

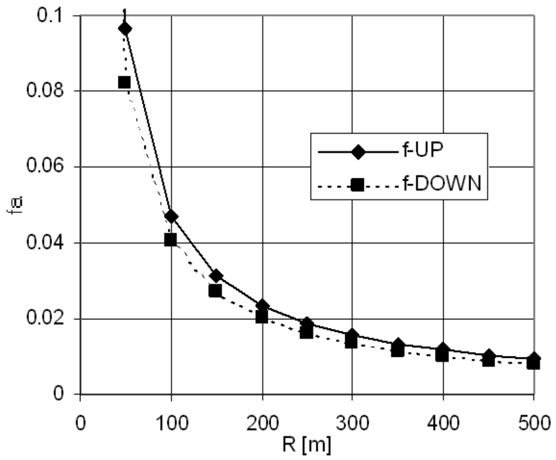
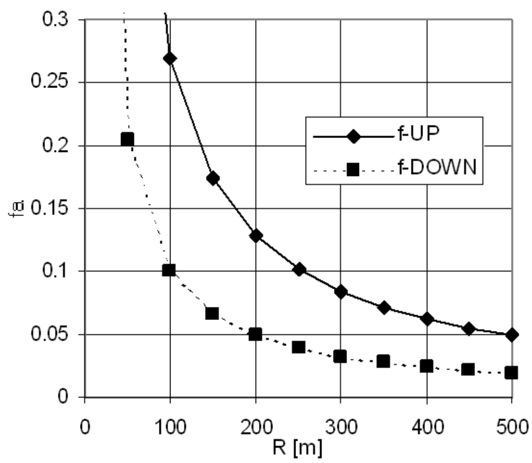
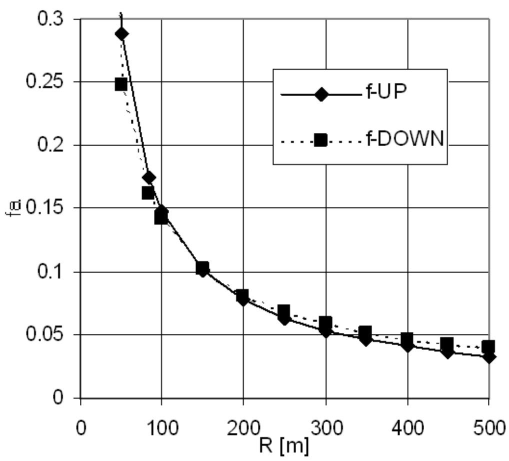


Fig. 5.23 – Supported fraction of active users as a function of *R* for the BCC scenario, both in absence and presence of mobility, *K* = 3.

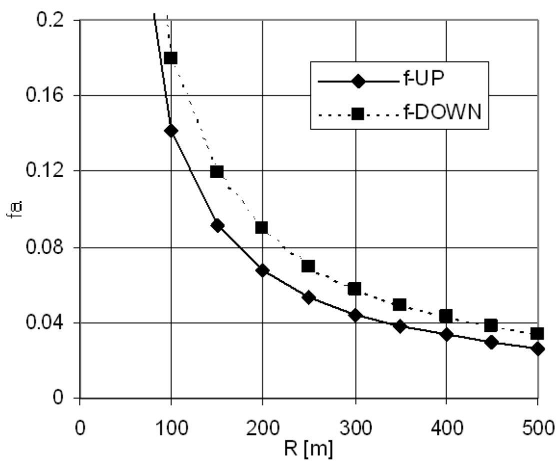


a) Absence of mobility

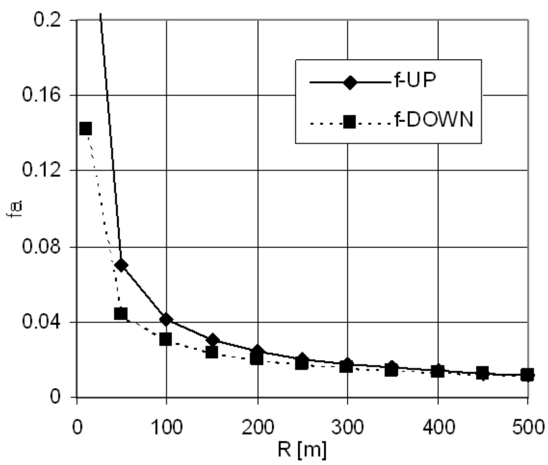


b) Presence of mobility

Fig. 5.24 – Supported fraction of active users as a function of *R* for the URB scenario, *K* = 3.



a) Absence of mobility



b) Presence of mobility

Fig. 5.25 – Supported fraction of active users as a function of *R* for the ROA scenario, *K* = 3.

The total spectral efficiency is computed according to (5.60), whereas the individual link spectral efficiency is computed according to (5.56). While the link spectral efficiency was computed using the respective link fraction of active users, the total spectral efficiency was computed using the worst-case f_a, i.e., the lower f_a between the up- and downlinks, for each R (from Figs. 5.23-5.25 and Figs. L.1-L.3). Results are presented in Figs. 5.26-5.28 (for K = 3), and in Appendix L (for K = 2). In these figures, while UP and DOWN designate the up- and downlinks, TOT refers to the total spectral efficiency.

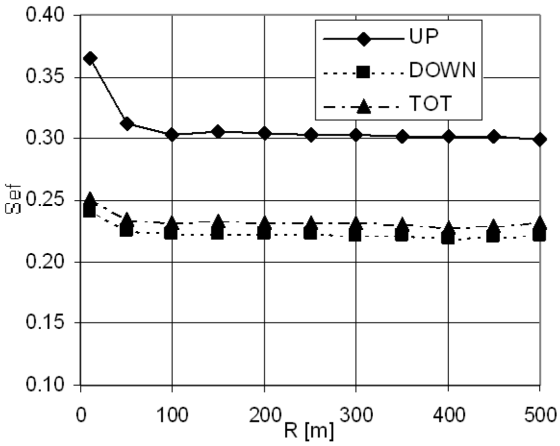
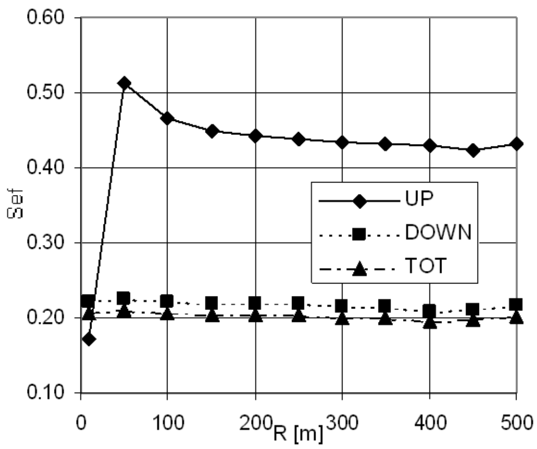
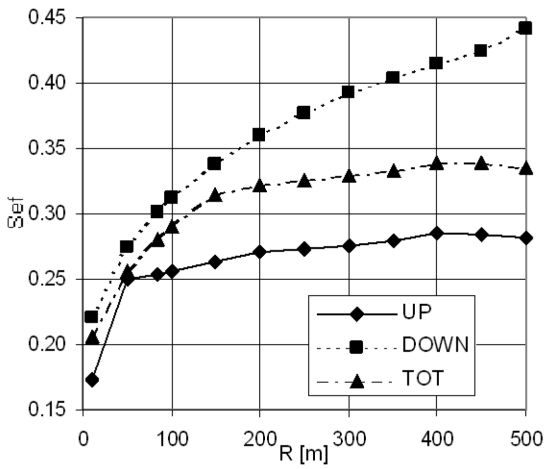


Fig. 5.26 – S_{ef} as a function of R for the BCC scenario, both in absence and presence of mobility, K = 3.

In the balanced cases, Figures 5.26, 5.27.b), 6.28.b), L.4 and L.6.b), one verifies that the curve for the total spectral efficiency always lays between the curves for each link spectral efficiency. In the remaining cases, Figures 5.27.a), 5.28.a), and L.6.a), a different behaviour occurs: the total spectral efficiency is always lower than the minimum value of the spectral efficiency between the up- and downlinks.

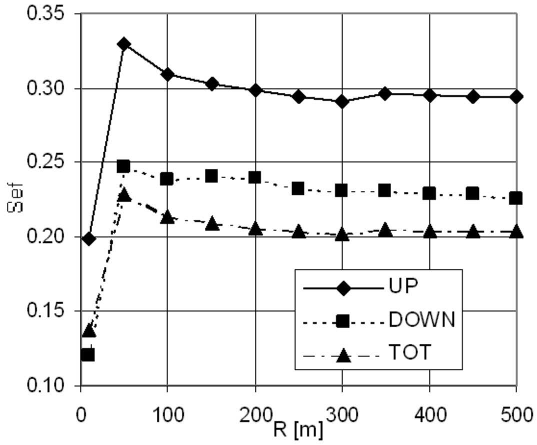


a) Absence of mobility

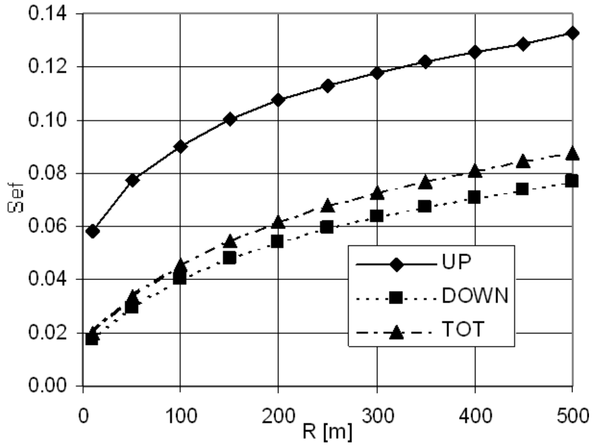


b) Presence of mobility

Fig. 5.27 – Spectral efficiency as a function of R for the URB scenario, K = 3.



a) Absence of mobility



b) Presence of mobility

Fig. 5.28 – Spectral efficiency as a function of R for the ROA scenario, $K = 3$.

From the values of f_a for the up- and downlinks, one also can obtain the number of supported users per kilometre (obtained multiplying the number of users per cell by the number of cells per kilometre, $N_{c/km}$)

$$No.\ users/km = M_T \cdot f_a \cdot N_{c/km} \tag{5.62}$$

Results will be presented in next Chapter, after computing the number of cells per kilometre, differently defined, according to the different cellular geometries.

A summary of the results of the fraction of active users, the number of users per kilometre and the total spectral efficiency is presented in Table 5.51 for R = 100 m in all the scenarios.

Table 5.51 – Summary of results for f_a, the number of users per kilometre and $(S_{ef})_{TOT}$.

K	Scenario	R [m]	M_T	mobility	Limiting link for $R \leq 150$ m	f_a [%]	Supported No. of users/km	$(S_{ef})_{TOT}$ [%]
$K = 3$	BCC	100	250	absence	DL	4.1	53	23.3
				presence*	DL	4.1	53	23.3
	URB	100	100	absence	DL	10.0	53	20.7
				presence	DL	14.1	74	29.1
	ROA	100	66	absence	UL	14.2	47	21.4
				presence	DL	3.0	10	4.6
		150	100	absence	UL	9.1	30	20.9
				presence	DL	2.0	8	5.3
$K = 2$	BCC	100	250	absence	DL	10.5	137	39.5
				presence*	DL	10.4	137	39.5
	URB	100	100	absence	UL	31.0	164	42.5
				presence	DL	23.5	124	32.2
	ROA	100	66	absence	UL	36.0	118	36.3
				presence	DL	15.1	50	15.2
		150	100	absence	UL	22.6	75	34.5
				presence	DL	10.3	34	16.3

* Because the BCC scenario is a low mobility one, the mobility has no impact.

Results are also included for R = 150 m in the ROA scenario, for comparison purposes (with the values previously presented); in each case, one identifies the link that limits the system for $R \leq 150$ m.

Although the supported number of users is typically lower when mobility is considered, in the URB scenario, for K = 3, the strong asymmetry in the case without mobility causes strong degradation in the downlink (this explains why, unexpectedly, 70 users are supported in the presence of mobility, while only 50 can be supported in the absence of mobility).

In the cases of interest, i.e., the balanced ones (with the consideration of mobility), the downlink always limits the system (lower supported f_a). However, this trend is not always maintained for all range of coverage distances in some cases, namely the cases of K = 3 / URB scenario, K = 2 / BCC scenario and K = 2 / ROA scenario, the change occurring for R = 150, 250 and 350 m, respectively, a different link having to be considered in the computation of $(S_{ef})_{TOT}$ for higher Rs.

Finally, in order to define the pairs (K, R) to be used, one has to compare the values of the supported with foreseen number of user/km (i.e., the results from Table 5.51 with the ones from the very simple analysis in Section 5.6.3.3, which are used as a reference, they being 200, 58 and 39 user/km, in the BCC, URB and ROA scenarios, respectively).

In Table 5.52 one lists the values of the supported number of user/km that overcome the foreseen ones (or, if not, that are the highest ones), and one concludes that, for R = 100 m, the number of supported user/km is:

- 137 in the BCC scenario with K = 2, i.e., 68.5 % of the foreseen users can be supported
- 74 in the URB scenario with K = 3, i.e., the foreseen number of user/km is overcame in 28 %
- 50 in the ROA scenario with K = 2, i.e., the foreseen number of user/km is overcame in 28 %

One also verifies that in the ROA scenario, for R = 150 m, the number of supported user/km is 34, i.e., only 87 % of the foreseen users can be supported.

Table 5.52 – Comparison between the foreseen and the supported number of user/km.

Scenario	R [m]	Foreseen no. of user/km in mature MBS	K	Supported no. of user/km
BCC	100	200	2	137
URB	100	58	3	74
ROA	100	39	2	50
	150		2	34

5.7. Conclusions

An MMPP model was proposed for the modelling of the superimposition of MBS data and video IPP sources. Given the correspondence between applications and its bearer service components, an algorithm for the Bernoulli case of the Bernoulli-Poisson-Pascal model was used to compute the blocking probability, and the influence of terminal mobility (via the handover failure probability threshold) in the results was taken into account, via a simple model. After having the characterisation of each application service components (a_j, $n_{j|k}$ and $\mu_{j|k}$), it is straightforward to obtain the activation rate, $\left(-\beta_j^{norm}\right)$, and thus the associated arrival rate, α_j^{norm}, which does not depend on the mobility scenarios. It is thus possible to apply the algorithm for the computation of the blocking probability associated with each component. The mobility does not have to be considered in the blocking probability computation for each value of f_a (i.e., the algorithm does not suffer any change when mobility is considered) because the normalised activation rate does not depend on it.

By defining the different types of terminal mobility associated with each application it is possible to compute the values of H_j and, consequently, the values of $(P_{hf})_{j\ max}$ corresponding to a given connection dropping probability threshold. In each scenario, the different values of the maximum handover failure probability are identified in this way, making the constraints associated with each deployment scenario available and ready to use.

In order to distribute the available resources between the up- and downlinks in a balanced way, one first considered the blocking probability constraint, P_b = 2 %, but only in an approximated way. One started by obtaining results for fixed values of R, considering the distribution of resources according to this constraint. One studied the dependence of the supported fraction of active users on the scenario and on the number of users per cell (the values M_{ENV}, corresponding to the number of users associated with the density of the deployment scenario, and M_{max_load}, associated with the maximum load that can be actually supported). As the considered mixtures of applications do not use the HID service component at the uplink, it only limits the system at the downlink, whereas the HDV service component limits the uplink.

Although the results for the fraction of active users are quite interesting, the comparison among the three different scenarios is difficult, as the number of potential users in a cell is different (although the cells have the same net area). So, alternatively one presented results for the number of supported users in a cell and for the spectral efficiency.

For instance, considering 384 channel/cell, 20.5 users can be supported in the BCC scenario, 26.1 in the URB scenario and 21.1 in the ROA scenario, for cells with 100, 100 and 150 m, respectively, i.e., the most favourable results were obtained for the URB scenario (where the maximum load per user is lower), while the worst results were obtained for the ROA scenario. In the latter case, although cells are 50 % higher, the number of supported users is even so of the order of magnitude of the BCC scenario. Comparing the cases of 288 and 384 channel/cell one also concludes that, although the number of channels is only 25 % lower, the supported number of users decreases 50 %. This problem could be solved by decreasing the data rate of the basic channel, i.e., the slot, leading to a higher number of slots in a cell, and thus to a different channel granularity.

High terminal mobility strongly degrades the system performance. Only 81-82 % of the traffic is supported in the URB scenario relatively to the static case. In the ROA scenario the influence is more drastic: only 28 % of the traffic is supported in the 384 channel/cell case relatively to the static case, and 21 % in the 288 resource/ cell case.

The variation of the supported traffic with the coverage distance was also studied, and the case of balance between the links with the $P_{hf} = (P_{hf})_{max}$ constraint was considered (in opposition to the balance according to $P_b = 2$ %). This allowed us to choose $K = 3$ for the urban scenario, whereas $K = 2$ is needed in the BCC and ROA scenarios. $K = 3$ corresponds to the 40 GHz band and/or the upper 1 GHz sub-band of the 60 GHz band, while $K = 2$ corresponds to the lower 1 GHz sub-band of the 60 GHz band (and only a part of it in the case of the 'Manhattan grid' geometry, more precisely).

A summary of the values of the achieved values for f_a, the supported number of user/km and $(S_{ef})_{TOT}$ are presented in Table 5. 53, considering $R = 100$ m for comparison purposes.

Table 5.53 – Summary of the Results.

Scenario	K	Limiting link	f_a [%]	Supported no. user/km	$(S_{ef})_{TOT}$ [%]
BCC	2	DOWN	10.4	137	39.5
URB	3	DOWN	14.1	74	29.1
ROA	2	DOWN	15.1	50	15.2

The spectral efficiency is lower for the ROA scenario because of the high terminal mobility, which strongly degrades system performance.

This is a general approach to multi-service traffic, where most of the applications are RT, or can be viewed as being RT (e.g., when one only takes the minimum data rate in an ABR application), as in UMTS [Garc00], [GaVC01].

Finally, it is worthwhile to note that some limitations can be identified. Regarding the model, although it is widely divulged, some kind of validation (in terms of simulation and/or the use of real data, i.e., traces for multimedia, Web applications, …) is needed, namely for the correspondence between service components and applications. Regarding the approach, one has to remind that the values for the parameters were proposals of our own, based in the characterisation of applications one has found in literature; hence, some changes can occur when real data becomes available. However, all the aspects of the proposed methodology will remain, and the algorithm will be run with the new values for the parameters.

Finally, it is worthwhile to note that, although one considered that the delay is kept under acceptable values using the DSA++ protocol, this assumption has to be properly evaluated for actual implementations of the algorithm.

Chapter 6

Cost/Revenue Optimisation

6.1. Introduction

MBS deployment optimisation can be achieved by seeking optimum values of a merit function taking into account both costs and revenues. This chapter closes the analysis of MBS cellular planning engineering, in this thesis, via a simple approach of MBS cost / revenue performance, with the objective of joining the contributions from the previous chapters together. By no means is it intended to perform a complete economic study, but only to present initial contributions.

In practice, frequency reuse constraints impose the cost component, through the values of the coverage distance and the achieved reuse factor, while multi-service traffic engineering determines the revenues, together with the frequency reuse aspects, the latter allowing for the determination of the number of available channels in each cell, Fig. 6.1.

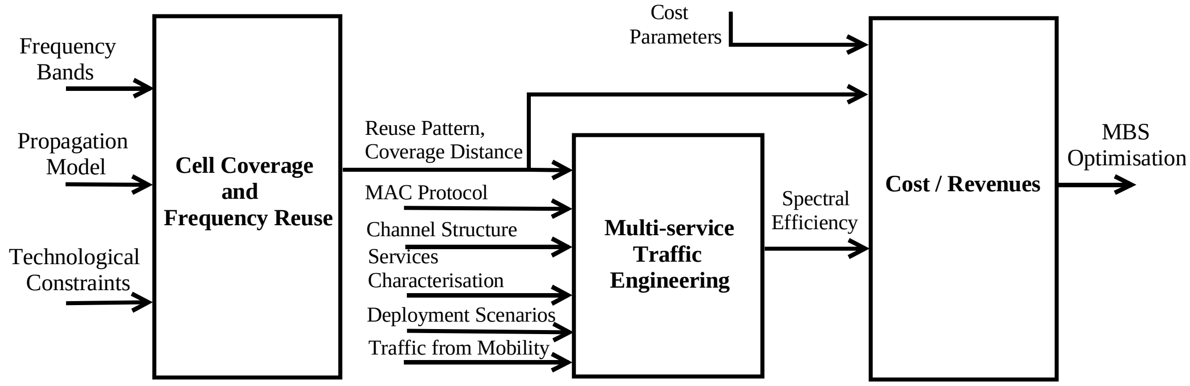


Fig. 6.1 – MBS optimisation.

From the deployment scenarios taken in Chapter 2, one considers the Business City Centre (BCC), Urban (URB) and Main Roads (ROA) scenarios. The analysis is done for both regular and irregular coverage geometries; the linear and the ‘Manhattan grid’ geometries being the examples of the former case, whereas a totally irregular real urban geometry is an example of the latter, Chapter 3. Together with cell coverage constraints, frequency reuse will determine the costs, a comparison between the 40 and the 60 GHz bands being in order. On the other hand, the revenues component is affected by the number of channels in each cell, and by the characteristics of the combination of applications that make use of it, through data and video service components. The traffic from mobility has also a strong impact in revenues, Chapter 4. Revenues depend on system capacity and are stipulated by the supported multi-service traffic, Chapter 5. The supported load (i.e., the sum of the supported kb/s) is a measure of the supported traffic (resulting from multi-service), and depends on the blocking and handover failure probability thresholds.

Because of the impact of these different contributions in MBS economic analysis, a cost/revenue function has to be developed, taking into account the cost of building and maintaining the infrastructure, and the way the number of channels available in each cell affects operators’ revenues; fixed costs for licensing and bandwidth auctions (or ‘beauty contests’) should also be taken into account. The economic analysis is referred as a cost/revenue performance analysis, because optimising costs do not necessarily mean optimising net revenues.

The high capacity desired for MBS and the high operating frequency lead to micro-cellular configurations, hence requiring a large number of BSs to be deployed. For cost efficiency, these BSs should be inexpensive to manufacture and install; in particular, a small number of types should exist, and their installation should not require extensive adjustments. In [FeGa00], the MODAL (Microwave Optical Duplex Antenna Link) project concept is proposed to providing an alternative technique for the generation of millimetre waves by using optical technology, offering the perspective of reduced installation and maintenance costs when compared to more conventional solutions.

Some useful cost/revenue models were already developed in [GaSr95] and [BrVe96], in a simpler context: a single service system is considered in the former case, while some simplifications (not considering the multi-service traffic analysis) were assumed in the latter one. As an hypothetical scenario, one is considering that MBS will succeed when the costs of deploying its infrastructure and operating the system will be of the order magnitude of today’s voice systems, a little bit higher in an initial phase, decreasing down to values comparable to today’s GSM ones in the following years. One is also expecting that, although the available average data rates increase from generation to generation by a factor near $10\cdot\sqrt{2}$ (from circa 10 kb/s in GSM to 144 kb/s in UMTS, and to 2 Mb/s in MBS; 1 920 kb/s will be considered as an hypothesis in next Sections), users will not be willing to spend much more per minute during a call (or equivalent). It is worthwhile noting that in MBS the referred 1 920 kb/s are faced as the net user load, i.e., the ‘silent’ periods of each application can be explored in order to allow for the use of the shared resources by other applications, as it was previously explained. As ATM is used, resources are shared in a way that the multiplexing of different sources (the service components the applications have access to) is possible. Although one considers a project duration of five years, one will analyse costs and revenues in an annual basis. Furthermore, the analysis is made under the assumption of null rate of interest.

The organisation of this chapter is as follows. In Section 6.2, the main components of system cost and revenues are identified, and a model is proposed, in the form of a merit function. In Section 6.3, values are proposed for model parameters, under some simple (and futuristic, in some way) hypothesis. In Section 6.4, results for the normalised cost and for the 'net' cost are presented, leading to a kind of price list for MBS applications, which is not 'the MBS price list', but only 'an hypothetical MBS price list', obtained under the assumptions one has considered in this work. As optimum values for the maximum cell coverage distance are not achieved for the 'net cost', some deployment strategies that allow for maximising profits whilst guaranteeing a given system capacity are discussed at the end of the chapter, regarding the use of larger or smaller cells in different MBS operation phases. In Section 6.5, one considers arbitrary urban geometries, and results are obtained for the 'net cost', taking the supported traffic into account. The possibility of supporting, at least, the foreseen number of users is discussed, and results for the revenue per basic channel and for application prices are obtained, in the form of a 'hypothetical MBS price list'. Finally, a comparison between regular and irregular geometries is presented, and the variation of the profit with the revenue per basic channel is discussed. Conclusions are drawn at the end of the Chapter.

6.2. Model

6.2.1. Components

The economics of cellular systems can be viewed from the points of view of different entities: the subscribers, the network operators, the service providers, the regulator and the equipment vendors [GaSr95]. In this work one is considering the operator/service provider's point of view, whose primary interest is to improve the bottom line of his business. Although one is aware that in future mobile multimedia systems the network operator and the service providers could be different entities [BGID00], one is not distinguishing them in this work. Thus it is considered, as a simplification, that the operator is the service provider.

In the cellular planning process, the objective of the operator is to determine an optimal operation point that maximises its expected revenues. Examples of major decisions include the type of technology to use, the size of the cell and the number of channels to use in each cell.

In this section the main components of system cost and revenues are identified, in particular those that bear a direct relationship to either the maximum cell coverage distance or the number of frequency groups. One will consider the cost per unit length or unit area of i) linear-coverage, ii) Manhattan grid and iii) irregular urban geometries incurred during a year of system operation. It must be kept in mind that the system is considered to have a transmission structure formed by a set of frequency carriers, each supporting a TDMA frame structure, meaning that each BS comprises a number of transceivers equal to the number of carriers assigned to it.

System cost has two major parts: (i) capital costs (cell site planning and installation), and (ii) operating expenses (operation, administration and maintenance) [Reed93], [SVJK93]. The capital cost is taken to consist of

- a fixed part (e.g., licensing and spectrum auctions or fees),
- a part proportional to the number of BSs per kilometre or square kilometre (e.g., the installation costs of the BSs, and the cost of hardware common to all), and
- a part proportional to the total number of transceivers per kilometre or square kilometre (e.g., the cost of the transceivers).

One is assuming that the cost of the connection between BSs and the Switching Centre, i.e., the fixed part of the network (e.g., the cost of laying fibre), is not a fixed cost. Instead, one considers that it is proportional to the number of BSs, which can be true if, e.g., the mobile operator contracts this service from a fixed network operator.

The operating cost during system lifetime is taken to contain

- a part proportional to the number of transceivers per kilometre or square kilometre, and
- a part proportional to the number of BSs per kilometre or square kilometre.

The costs and revenues will be taken in an annual basis.

One will start by considering the linear coverage geometry. Let T be the number of carriers available, for either transmission link, up-/downlink, and N_{op} the number of MBS operators. For a linear geometry one then has

- the maximum cell coverage distance is R,
- the number of BSs per kilometre is given by $1(2R_{[\mathrm{km}]})$,
- the number of different frequency groups required is K,
- the number of carriers per cell is $T/(N_{op} \cdot K)$, and
- the number of carriers per kilometre is $T/[K \cdot N_{op} \cdot (2R_{[\mathrm{km}]})]$.

Therefore, the system cost will thus contain a fixed term C_{fi}, and terms proportional to the number of BSs and to the number of transceivers. Letting C_{fb} and C_{ft} denote the corresponding coefficients, the overall cost per unit length per year is

$$C_{0\,[€/\mathrm{km}]} = C_{fi\,[€/\mathrm{km}]} + C_{fb\,[€]} \frac{1}{2R_{[\mathrm{km}]}} + C_{ft\,[€]} \frac{T}{K \cdot N_{op} \cdot (2R_{[\mathrm{km}]})} \tag{6.1}$$

System capacity is usually defined with reference to QoS constraints, such as call blocking probability (for real time applications) or packet delay (for non-real time ones). Its calculation involves a multi-service traffic analysis, explaining why the results from Chapter 5 are fed into the revenue function via the spectral efficiency, $S_{ef}(R)$.

Letting B_0 denote the overall user bit rate supported by one transceiver, the system (bit) capacity per kilometre is then

$$B\,[\text{b/s/km}] = \frac{B_0\,[\text{b/s}]\, S_{ef} \cdot T}{K \cdot N_{op} \cdot (2R\,[\text{km}])}. \tag{6.2}$$

The revenue per cell per year, $(R_v)_{cell}$, can be obtained as a function of the revenue per transceiver per year, R_{vt},

$$(R_v)_{cell}\,[€] = \frac{T \cdot S_{ef} \cdot R_{vt}\,[€]}{K \cdot N_{op}}. \tag{6.3}$$

The revenue per kilometre per year, R_v, apart from a constant that depends on the number of slots per frame (each frame, in turn, corresponding to a carrier) and on the number of busy hours per year, does depend on S_{ef}, K and R, similarly to B. It is obtained by multiplying the revenue per cell per year by the number of cells per kilometre, which, in the linear coverage geometry case, is given by

$$N_{c/km}\,[\text{km}^{-1}] = \frac{1}{2R\,[\text{km}]}, \tag{6.4}$$

yielding

$$R_v\,[€/\text{km}] = \frac{(R_v)_{cell}\,[€]}{2R\,[\text{km}]} = \frac{T \cdot S_{ef} \cdot R_{vt}\,[€]}{K \cdot N_{op} \cdot (2R\,[\text{km}])} \tag{6.5}$$

A 'net cost' function (in €/km/year) results from (6.1) and (6.5)

$$C_n\,[€/\text{km}] = C_{fi}\,[€/\text{km}] + \frac{C_{fb}\,[€]}{2R\,[\text{km}]} + \frac{T}{K \cdot N_{op} \cdot (2R\,[\text{km}])} \cdot \left(C_{ft}\,[€] - R_{vt}\,[€]\, S_{ef}\right), \tag{6.6}$$

and further considering $C_{fi} = 0$, in order to simplify the analysis, one gets

$$C_n\,[€/\text{km}] = \frac{1}{2R\,[\text{km}]} \cdot \left(C_{fb}\,[€] + \frac{T}{K \cdot N_{op}} \left(C_{ft}\,[€] - R_{vt}\,[€]\, S_{ef}\right) \right) \tag{6.7}$$

The analysis of the cases with $C_{fi} \neq 0$ can then be done by comparing the 'net cost' obtained by (6.7) with the fixed cost threshold, ($-C_{fi}$). If C_n is lower than ($-C_{fi}$) the system becomes profitable.

Two types of urban geometries can be distinguished: the 'Manhattan grid' and the arbitrary urban ones. While the 'Manhattan grid' is a regular geometry allowing an analysis similar to the one of the linear coverage geometry, the latter case is not, and its cellular planning has to be done on a case-by-case basis, making use of cellular planning tools as the ones from [VeBr98] and [SWCD95].

In the linear geometry, the number of cells per kilometre is given by (6.4), while the 'net cost' per cell is given by the second term in (6.7). In the 'Manhattan grid' geometry, from Fig. 3.11, one can conclude that the cell *net street area* is $2{\cdot}l{\cdot}(2R\text{-}l/2)$, thus, the number of cells by net square kilometre is $1/[2{\cdot}l_{[km]}{\cdot}(2R_{[km]}\text{-}l_{[km]}/2)]$, yielding to the following 'net cost' cost function, for $C_{fi} = 0$, in €/km²/year,

$$C_n\,[€/\text{km}^2] = \frac{1}{2\cdot l_{[\text{km}]}\cdot\left(2R_{[\text{km}]} - l_{[\text{km}]}/2\right)}\cdot\left(C_{fb}\,[€] + \frac{T}{K\cdot N_{op}}\cdot\left(C_{ft}\,[€] + R_{vt}\,[€]\cdot S_{ef}\right)\right). \tag{6.8}$$

It is rather natural to define a cost function, in €/km²/year, for a two-dimensional system. Nevertheless, in order to have a quantitative comparison with the linear coverage geometry, one can consider the following: a cell is formed by two street portions, each with equivalent length ($2R$-$l/2$) and width l. As a consequence, for each of the street segments composing the cell, one can consider a 'linearised net cost' function, as follows

$$\left(C_n\right)_{lin}\,[€/\text{km}] = \frac{1}{\left(2R_{[\text{km}]} - l_{[\text{km}]}/2\right)}\cdot\left(C_{fb}\,[€] + \frac{T}{K\cdot N_{op}}\cdot\left(C_{ft}\,[€] + R_{vt}\,[€]\cdot S_{ef}\right)\right), \tag{6.9}$$

where the number of cells per kilometre is given by

$$N_{c/km}\,[\text{km}^{-1}] = \frac{1}{\left(2R_{[\text{km}]} - l_{[\text{km}]}/2\right)}. \tag{6.10}$$

This 'net cost' function can be very useful for comparison purposes, and can consequently simplify the analysis. Furthermore, this simplification is still more important because, in Fig. 3.11, one is artificially assuming that the dimensions of the blocks of building are varying with R. As its side has length ($2R$-l), the net street area artificially varies with R, which is not true in an actual environment. The 'linearised net cost' function does not suffer from this effect (because one is considering the equivalent street length instead of the net street area). Thus, one can directly compare the linear geometry with the 'Manhattan grid' one, the difference between them coming from the possibility of having different values of K, and from a slight difference in the number of cells per kilometre, as $1/(2R_{[km]})$ is slightly different from $1/(2R_{[km]}\text{-}l_{[km]}/2)$ for low values of R.

In the case of the irregular urban geometry, considering that N_c is the number of cells necessary to cover a given area, and that A_n is the corresponding net street area, the number of cells per km² is given by $N_c(R)/A_n$, whereas the "net cost" function, in €/km²/year, is given by

$$C_n\,[€/\text{km}^2] = \frac{N_c}{A_n\,[\text{km}^2]}\cdot\left(C_{fb}\,[€] + \frac{T}{K\cdot N_{op}}\cdot\left(C_{ft}\,[€] + R_{vt}\,[€]\cdot S_{ef}\right)\right). \tag{6.11}$$

The comparison between the two urban geometries is possible by comparing the results obtained from (6.8) and (6.11).

6.2.2. Normalised Cost

In [BrVe96], because of the lack of knowledge about the combinations of applications in each deployment scenario, their characterisation parameters and their multi-service traffic analysis, it was considered that system revenues were associated with the "raw" bit rate per kilometre, which was used as a measure to system capacity. In that context, a normalised cost function was identified in order to cope with not knowing the actual values for parameters C_{fi}, C_{fb} and C_{ft}, it being defined, in km^{-1}/year (or km^{-2}/year), as

$$C^* = \frac{C_n(C_{ft}) - C_{fi}}{C_{fb}} . \tag{6.12}$$

Adapting it to the terminology used to represent C_n, the following equation for the normalised cost for the linear coverage geometry is obtained

$$C^*[\mathrm{km}^{-1}] = \frac{1}{2R[\mathrm{km}]} \cdot \left(1 - \frac{r_c}{K}\right) \tag{6.13}$$

with the cluster (corresponding to a set of K cells) revenue-to-cost ratio being given by

$$r_c = \frac{T}{N_{op}} \cdot \frac{R_{vt}[€]\, S_{ef} - C_{ft}[€]}{C_{fb}[€]}. \tag{6.14}$$

It provides the number of times the net revenue per cluster is higher than the cost associated with the installation and maintenance of a cell BS, and its associated equipment and infrastructures.

Analysing the 'net cost' function for $C_{fi} = 0$, it is concluded that it should be higher than the reuse factor (i.e., the 'cluster size'), in order to obtain a profitable system. It is however worthwhile to note that, with the introduction of the multi-service traffic performance in the analysis, r_c is not a fixed parameter anymore, it depending on R via $S_{ef}(R)$. Consequently, in comparison to the approach used in [BrVe96], r_c has lost some of its significance, in conjunction with C^*. The generalisation of equation (6.13) to the urban geometries is straightforward.

6.3. Parameters

Values for the model parameters have to be introduced in hypothetical scenarios in order to understand the tradeoffs involved in the economic analysis. This is due to the dependence of the cluster revenue-to-cost ratio on R, which makes the analysis with the normalised cost difficult. The goal is to grasp the impact of the choice of R and related frequency reuse parameters (e.g., the reuse pattern) on the MBS economic analysis. For $C_{fi} = 0$, the 'net cost' function, C_n, has several parameters, namely R, K, N_{op}, S_{ef}, C_{fb}, R_{vt} and C_{ft}. Besides, one is considering coverage distances of up to 500 m.

The reuse pattern depends on the frequency band, and on the coverage and reuse geometries. Values taken from the analysis in Chapter 3 are considered:

- K= 2 in the [62, 63] GHz sub-band of the 60 GHz band for $R \geq 66$ m, in the linear geometry;

- K = 2 in the [62.0, 62.5] GHz sub-band of the 60 GHz band for $R \geq 175$ m, in the 'Manhattan grid' geometry (lower Rs being however allowed for frequencies near 62 GHz);
- K = 3 in the remaining 60 GHz band (because oxygen attenuation imposes a different atenuation along the band) and in the 40 GHz one, for both linear and 'Manhattan' geometries;
- K = 5 at both frequency bands, for the irregular geometry (in the considered case studies).

For the regular geometries (linear and 'Manhattan grid'), one considered four system operators per band, i.e., N_{op} = 4, each using a 0.5 GHz bandwidth, from a total of 2 GHz. For the irregular urban geometry, because of the higher K, the number of channels available in each cell would be much lower if N_{op} = 4 was considered, and the blocking probability would be near to one (much higher than the target value P_b = 0.02) for very low values of the fraction of active users (lower than 1 %, typically). In this way, one had to consider N_{op} = 2 for the irregular coverage urban geometry, because a higher N_{op} would make the system unfeasible.

The values for the spectral efficiency arise from the analysis in Chapter 5 of the total spectral efficiency, $(S_{ef})_{TOT}$, which copes with the simultaneous contributions of up- and downlinks.

As a hypothesis, one uses the data extracted from [GaSr95] for the costs in US dollars ($), with slight adaptations. As only micro-cells are used in MBS, with coverage distances up to, near 800 m maximum, one only considers the cases of cell ranges of a) 300 m and b) 800 m (cases 1 and 2 of [GaSr95], respectively, labelled here as ***a*** and ***b***), Table 6.1.

Table 6.1 – Input cost parameters associated with cell base stations (extracted from [GaSr95]).

Cell type	Cell range [m]	Setup cost [$]	Channel cost [$/year]	Maintenance and opera -tion costs [$/year]
a	300	20 000	300	2 500
b	800	150 000	500	3 500

One has also assumed that MBS will only be viable when the cost of deploying and operating the system will decrease to the order of magnitude of the costs associated with today's systems, which will possibly be achievable by using the MODAL concept [FeGa00]. The MODAL project concept offers the prospect of reduced installation and maintenance costs when compared with more conventional electronic solutions. The MODAL concept consists in generating and modulating the radio carrier frequency centrally by resorting to photonic technology, in order to distribute the signal to BSs optically via fibre and passive splitters, and to use a transparent antenna unit in the BSs.

According to the reasoning in the introduction of this chapter, one can assume that the average load is 1 920 kb/s; our initial assumptions state that a unidirectional 1 920 kb/s MBS connection will cost approximately as much as a today GSM call, thus, e.g., a 8 064 kb/s unidirectional connection will cost 4.2 times more than it, whereas a 384 kb/s call will cost a fifth. Consequently, it is also natural to consider that the cost associated with the usage of the correspondent *fraction* of the transceiver infrastructure (supporting 1 920 kb/s, unidirectionally) will cost as much as a second generation system channel. Therefore, one assumes the following:

- The cost associated with a 384 kb/s basic unit (during one year time) is one fifth of the cost of a second generation channel.
- As each frame has 48 slots, there are 48 basic units of 384 kb/s associated to the carrier, and there are 48/5 = 9.6 times 1 920 kb/s available; consequently, under our assumptions, the cost of an MBS transceiver will be 9.6 times the cost of a today's second generation channel (for comparison purposes, note that a GSM carrier has eight channels, instead of '9.6').

Besides considering cases ***a*** and ***b*** from Table 6.1 as the initial ones, one has associated three additional cases to each one: the cases with 60 % and 100 % higher costs, and the case with 40 % lower costs, Table 6.2; hypothesis 1 and 5 correspond to the original cases ***a*** and ***b***, respectively. The costs of a BS-tower, $C_{BS\text{-}tower}$, of maintenance and operation, $C_{mnt\&op}$, of each 1 920 kb/s (5 basic channels), C_{1920}, and of the basic channel of 384 kb/s, C_{384}, are presented in Euros (€), assuming a parity between US Dollar and Euro. One also assumes that the estimated BS tower life is five years [GaSr95], and that the duration of the project is five years, N_{year}.

Table 6.2 – Hypothesis for MBS costs.

Hypothesis	Label	$C_{BS\text{-}tower}$ [€]	$C_{mnt\&op}$ [€/year]	C_{1920} [€/year]	C_{384} [€/year]
1	case *b*	150 000	20 000	500	100
2	case *b* + 60 %	240 000	32 000	800	160
3	case *b* + 100 %	300 000	40 000	1 000	200
4	case *b* - 40 %	90 000	12 000	300	60
5	case *a*	20 000	2 500	300	60
6	case *a* + 60 %	32 000	4 000	480	96
7	case *a* + 100 %	40 000	5 000	600	120
8	case *a* - 40 %	12 000	1 500	180	36

Finally, $C_{BS\text{-}tower}/N_{year}$ represents the annual cost of a BS equipment and infrastructure, which is true in the approximation of a null rate of interest, if the calculations were made in real terms, i.e., in constant Euros [Litt79]. Such is the approach followed here. A complete economic analysis based on discounted cash flows (e.g., to compute the net present value) will need the appropriate adaptations. As a consequence, in the model from (6.8) one has

$$C_{fb} = C_{BS-tower} \big/ N_{year} + C_{mnt\&op} \tag{6.15}$$

$$C_{ft} = 9.6 \cdot C_{1920} \,. \tag{6.16}$$

In the following only hypothesis 7, 5 and 4 are analysed.

Although the discussion in this section is based on the hypothesis that C_{fi} = 0, a fixed cost component exists that has to be taken into account, because of licensing and frequency auctions (or 'beauty contests'). In a country like Portugal, one can consider that in a medium phase of MBS deployment an operator can cover the equivalent to 2 000 km of highways, roads and streets.

Considering that a 0.5 GHz license will cost 200 000 000 € (twice the price of an UMTS license in Portugal), under the simple assumptions of null rate of interest, one obtains an annual fixed cost of 40 000 000 €. Dividing this value by the considered number of kilometres of the MBS network, one obtains an annual fixed cost per kilometre

$$C_{fi}(N_{op} = 4) = \frac{40\,000\,000}{2\,000} = 20\,000 \text{ €/km/year} \tag{6.17}$$

When only two operators are considered, this cost will be twice the previous one

$$C_{fi}(N_{op} = 2) = \frac{2 \cdot 40\,000\,000}{2\,000} = 40\,000 \text{ €/km/year.} \tag{6.18}$$

Finally, one will further consider, as an hypothesis, that the operator's target net revenue per kilometre per year is expected to be 130 000 ± 15 000 €.

Taking the models from Section 6.2.2 into account, and considering the parameters from Section 6.2.3, a very rough estimation of the costs and revenues can be obtained, allowing to grasp how the cost and revenues components depend on the parameters, and how they relate to each other (in order to achieve hypothetical profitable configurations).

6.4. Regular Urban Geometries

6.4.1. Assumptions

Although the 'net cost' function is simple, the spectral efficiency contribution computation is rather complex to obtain, because there are several assumptions regarding the applications and service components usage behind it, and because the algorithm to compute the blocking probability is complex. From the values of f_a for the up- and downlinks, Figs. 5.23-5.25 and L.1-L.3, one has obtained the spectral efficiency, Figs. 5.26-5.28 and L.4-L.6, and the number of supported users per kilometre (5.62), Appendix M.

Considering that costs and revenues are taken on an annual basis, one follows the approach of considering six busy hours per day (i.e., 60 min), 240 busy days per year [GaSr95] (e.g., in Portugal the year 2000 had a total of 249 working days to which one subtracted nine days, roughly considering that it is an average value for the number of Summer and other holidays for the whole population), and a 384 kb/s basic channel revenue $R_{384\,[€/\text{min}]}$. The revenues are then proportional to the load supported by the system, in kb/s, which is reflected in the analysis via the spectral efficiency. It is, in turn, the minimum S_{ef} obtained from the blocking and handover failure probabilities constraints, i.e., between the case P_b = 2 % and the case $P_{hf} = (P_{hf})_{max}(R)$.

The revenue per cell per year is then obtained by

$$R_{v\_cell}[€] = \frac{6 \cdot 240 \cdot 60 \cdot S_{ef} \cdot T \cdot 48 \cdot R_{384}[€/\min]}{K \cdot N_{op}} \tag{6.19}$$

where T·48/N_{op} gives the number of 384 kb/s channels available in the cell. Note that 48 denotes the number of slots per frame, numerically corresponding to the number of basic channels (of 384 kb/s) per carrier, i.e., $R_{vt} = 48 \cdot R_{384}$. Thus, the revenue per transceiver is

$$R_{vt}[€] = 86400 \cdot 48 \cdot R_{384}[€/\min]. \tag{6.20}$$

Replacing the cost per carrier/transceiver, C_{ft}, by $48 \cdot C_{1920}/5 = 9.6 \cdot C_{1920}$, where C_{1920} is the cost associated with a 1 920 kb/s set of channels, and further considering T = 72 and C_{fi} = 0, one gets

$$C_n[€/\text{km}] = \frac{1}{2R[\text{km}]} \cdot \left[C_{fb}[€] - \frac{3456}{K \cdot N_{op}} \left(86400 \cdot S_{ef} \cdot R_{384}[€/\min] - C_{1920}[€]/5 \right) \right] \tag{6.21}$$

for the linear coverage geometry, with the restriction that 3456/($K \cdot N_{op}$) should be multiple of 48 (the number of slots per frame). Note that T·48 = 3456 represents the sum of slots from of all carriers (each carrier contributing with one frame).

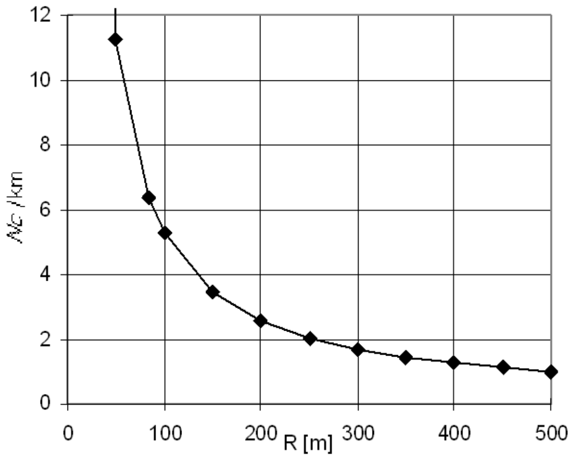
6.4.2. Normalised Costs

For C_{fi} = 0, the normalised cost, C^*, represents the number of times the net cost is higher than the cost of a BS equipment and infrastructure, it being a function of the revenue-to-cost ratio, r_c. In this section, in order to have a first insight into the behaviour of the 'net cost' function, in the linear coverage and the 'Manhattan grid' geometries, results for the normalised cost are analysed. Note that in the 'Manhattan' geometry a 'linearised net cost' function is considered.

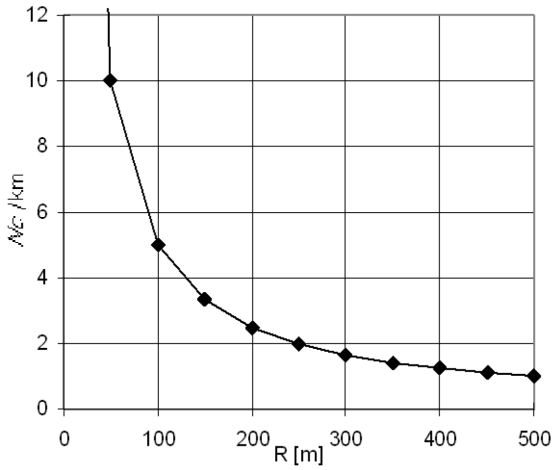
The approach one follows consists in decomposing the normalised cost function (6.13) into two factors:

- the number of cells per kilometre, $N_{c/km}(R)$, (6.4) and (6.10)
- the other term, (1-r_c/K).

Let us first analyse the $N_{c/km}$ component For the linear geometry (ROA scenario) and for the 'linearised' case of the Manhattan grid geometry (BCC and URB scenarios). Results are presented in Fig. 6.2. The number of cells per kilometre is slightly higher for the 'Manhattan grid' geometry, although the difference becomes negligible for R > 150 m.



a) BCC and URB scenarios



b) ROA scenario

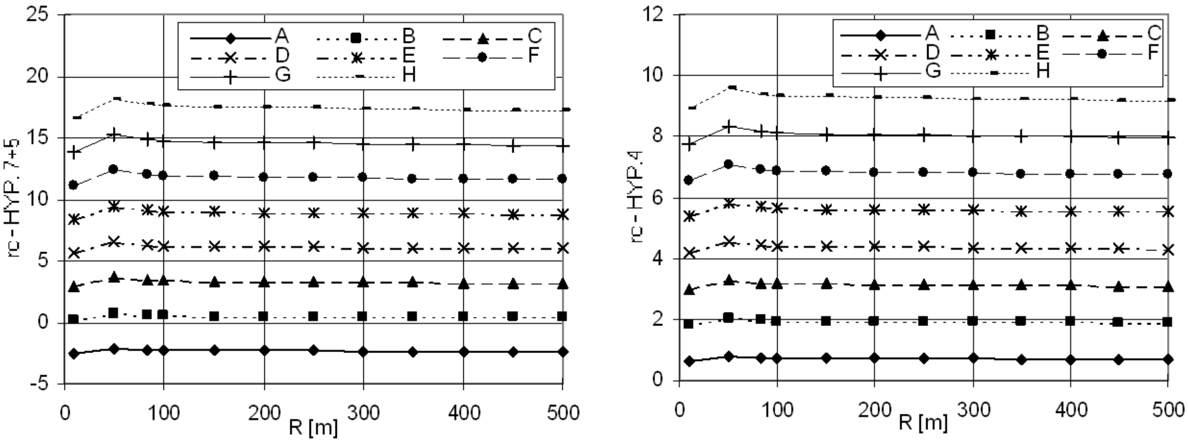
Fig. 6.2 – Number of cells per kilometre.

Regarding the second term, if r_c were a constant value, C^* would be proportional to $N_{c/km}(R)$, it being a decreasing or increasing function, depending on the signal of $(1\text{-}r_c/K)$. If $r_c > K$, the signal would be negative (corresponding to a profitable system), it being positive otherwise. So, basically, the normalised cost function would follow the shape of $\pm N_{c/km}(R)$, depending on the ratio r_c/K. Instead of representing $(1\text{-}r_c/K)$, one will present the curves of $r_c(R)$ for each of the selected scenarios, reuse patterns (K = 2 in the BCC and ROA scenarios, and K = 3 in the URB scenario), and hypothesis in terms of the values for R_{384} (hypothesis 7, 5 or 4, from Table 6.2). In Table 6.3, besides the values of C_{fb} and C_{1920}, one presents the values of R_{384} for eight different cases (A, B, C, …, H), which will label the plots with results. Because from HYP. 7 to HYP. 5 C_{fb} and C_{1920} decrease by half, one also considered that R_{384} is the half in all cases. The results in this table correspond to K = 3, in the URB scenario (in the presence of mobility).

Table 6.3 – Assumptions for K = 3 (288 channel/cell) in the URB scenario (in the presence of mobility).

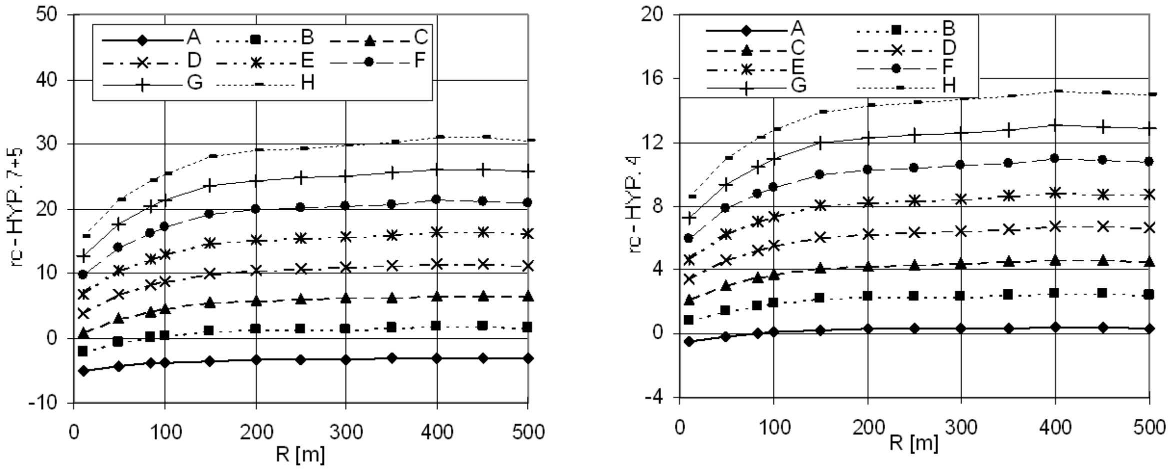
HYP.	C_{fb} [€/year]	C_{1920} [€/year]	R_{384} [€/min]							
			A	B	C	D	E	F	G	H
7	13 000	600	0.0025	0.005	0.0075	0.01	0.0125	0.015	0.0175	0.02
5	6 500	300	0.00125	0.0025	0.00375	0.005	0.00625	0.0075	0.00875	0.01
4	30 000	300	0.0025	0.005	0.0075	0.01	0.0125	0.015	0.0175	0.02

Results for the other combinations of reuse pattern, scenario and type of mobility (to be considered in the results for r_c, C_n and C^*) are presented in Appendix N. Although the values of R_{384} are presented in these tables for every combination of K and deployment scenario, one only presents graphical results for the pre-selected cases, i.e., i) K = 2 / BCC scenario (432 channel/cell), ii) K = 3 / URB scenario (288 channel/cell) and iii) K = 2 / ROA scenario. For instance, R_{384} = 0.01 €/min corresponds to the cases G, D and A in Tables N.3, 6.3 and N.4, for the BCC, URB and ROA scenarios, respectively, represented by a grey cell background in tables. The respective graphs of $r_c(R)$ are presented in Figs. 6.3-6.5, where values for the total spectral efficiency (5.60) from chapter 5 were used as input.



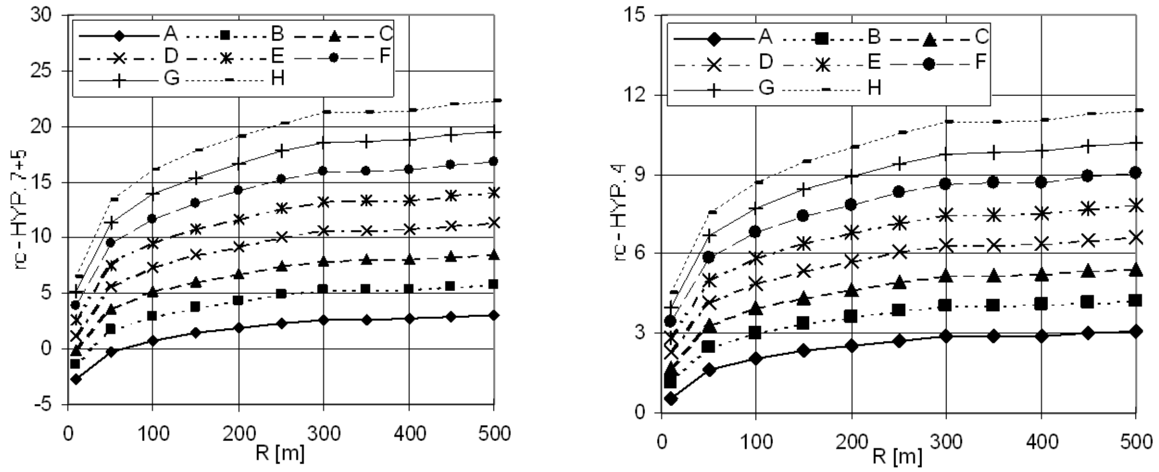
a) HYPs. 7 and 5 b) HYP. 4

Fig. 6.3 – Cost-to-revenue ratio as a function of *R* in the BCC scenario.



a) HYPs. 7 and 5 b) HYP. 4

Fig. 6.4 – Cost-to-revenue ratio as a function of *R* in the URB scenario.



a) HYPs. 7 and 5 b) HYP. 4

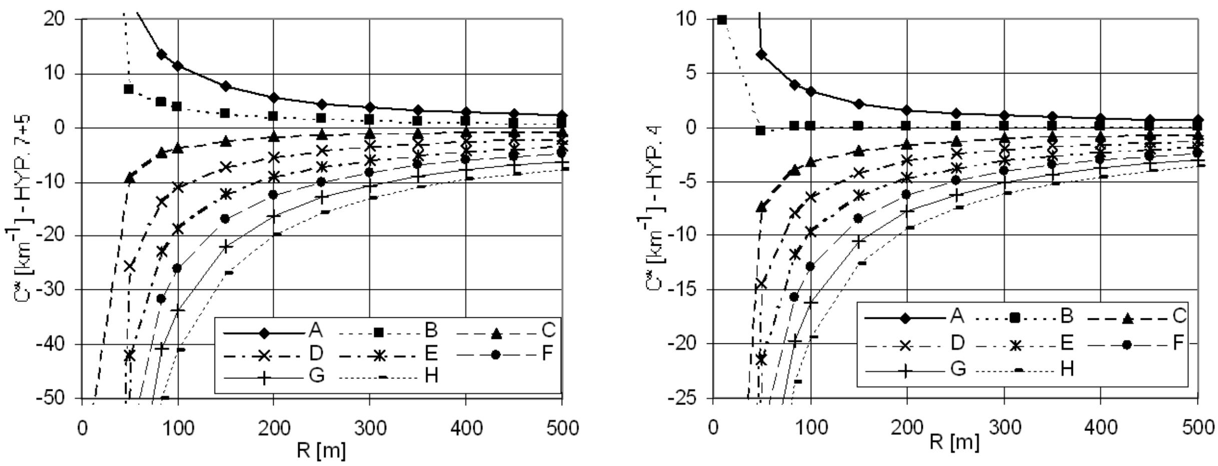
Fig. 6.5 – Cost-to-revenue ratio as a function of *R* in the ROA scenario.

In HYP. 7, for example, considering R = 100 m and R_{384} = 0.01 €/min, one obtains r_c = 14.7, 8.7 and 0.8 for the BCC, URB and ROA scenarios, respectively, cases G, D and A. Comparing these results with the values of $(S_{ef})_{TOT}$ from Table 5.53 for the respective scenarios, $(S_{ef})_{TOT}$ = 39.5, 29.1 and 15.2 %, one concludes that r_c is higher for higher values of the spectral efficiency, which could be expected, as $r_c(R)$ is a linear function of the spectral efficiency. Thus, it follows the monotonic behaviour of $S_{ef}(R)$, which typically is a slightly decreasing function in the BCC scenario (for R > 50 m), and an increasing function for URB and ROA scenarios. The reason for this difference is related to the differences in terminal mobility: low mobility in the BCC scenario, and considerably higher mobility in the URB and ROA scenarios. In the BCC scenario r_c is approximately constant for the range of all Rs, a different behaviour occurring for the URB and ROA scenarios: r_c is an increasing function up to R = 200-300 m, a stationary behaviour being observed for higher values of R (which is related to the stationary behaviour of the total spectral efficiency for higher values of R).

The curves of r_c are coincident in HYPs. 7 and 5 because the ratios between C_{fb} and C_{1920}, and between R_{384} and C_{1920} are equal, what does not occur in HYP. 4 (note that C_{ft} is directly proportional to C_{1920} (6.16)).

The results for the normalised cost (per year) are presented in Figs. 6.6-6.8. Analysing it for R = 100 m and R_{384} = 0.01 €/km, i.e., again cases G, D and A in the respective scenarios, one obtains C^* = -33.7, -10.1 and 3.1 km^{-1}, respectively. The curves of C^* in HYPs. 5 and 7 are again coincident, as the curves for r_c.

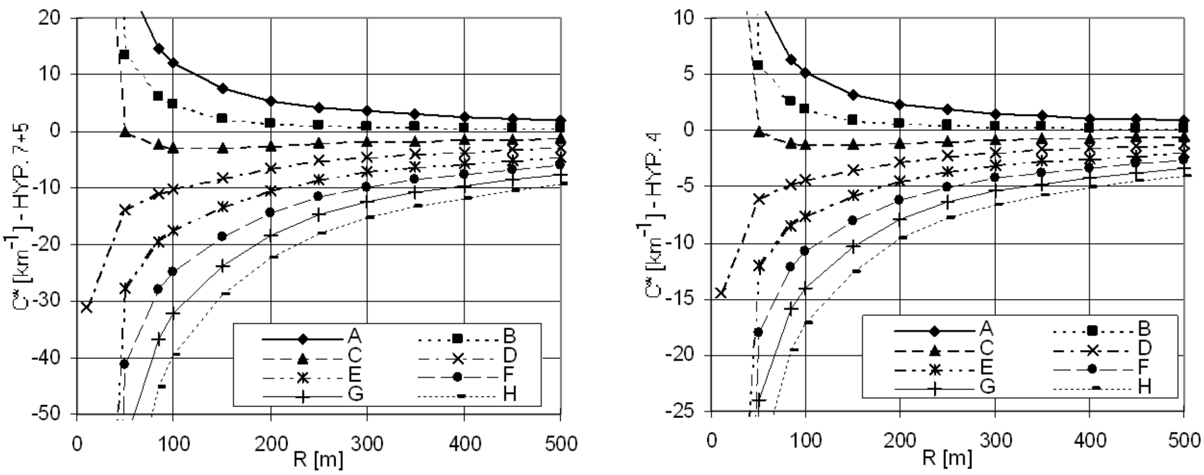
Comparing the two cases with K = 2 (the BCC and ROA scenarios), one concludes that lower (negative) values of the normalised cost correspond to higher values of r_c, and thus higher revenues. Nevertheless, one cannot directly compare these results with the ones of the URB geometry because a different scale factor is introduced with K =3. Negative values of C^* correspond to profitable systems (depending however on C_{fi}).



a) HYPs. 7 and 5

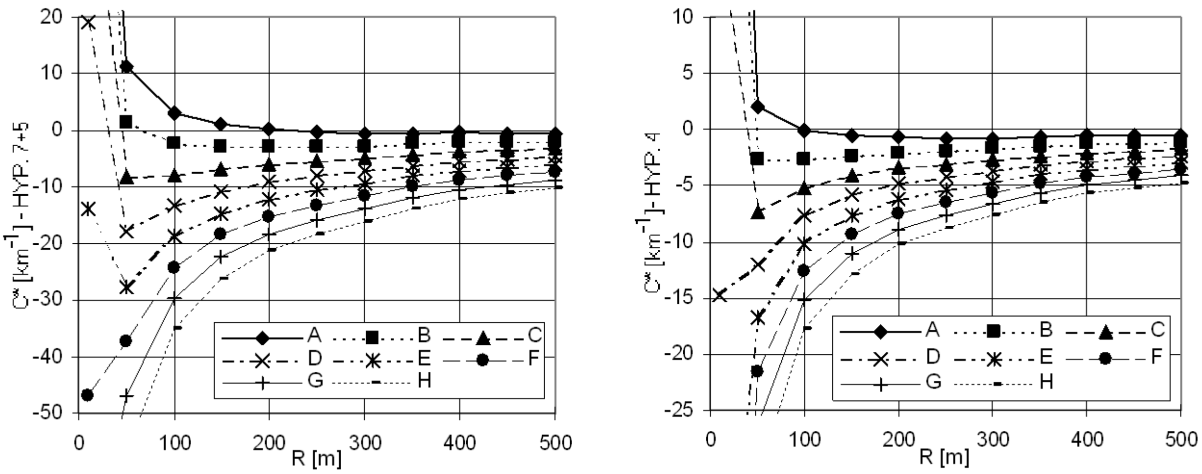
b) HYP. 4

Fig. 6.6 – Normalised cost as a function of R in the BCC scenario.



a) HYPs. 7 and 5 b) HYP. 4

Fig. 6.7 – Normalised cost as a function of *R* in the URB scenario.



a) HYPs. 7 and 5 b) HYP. 4

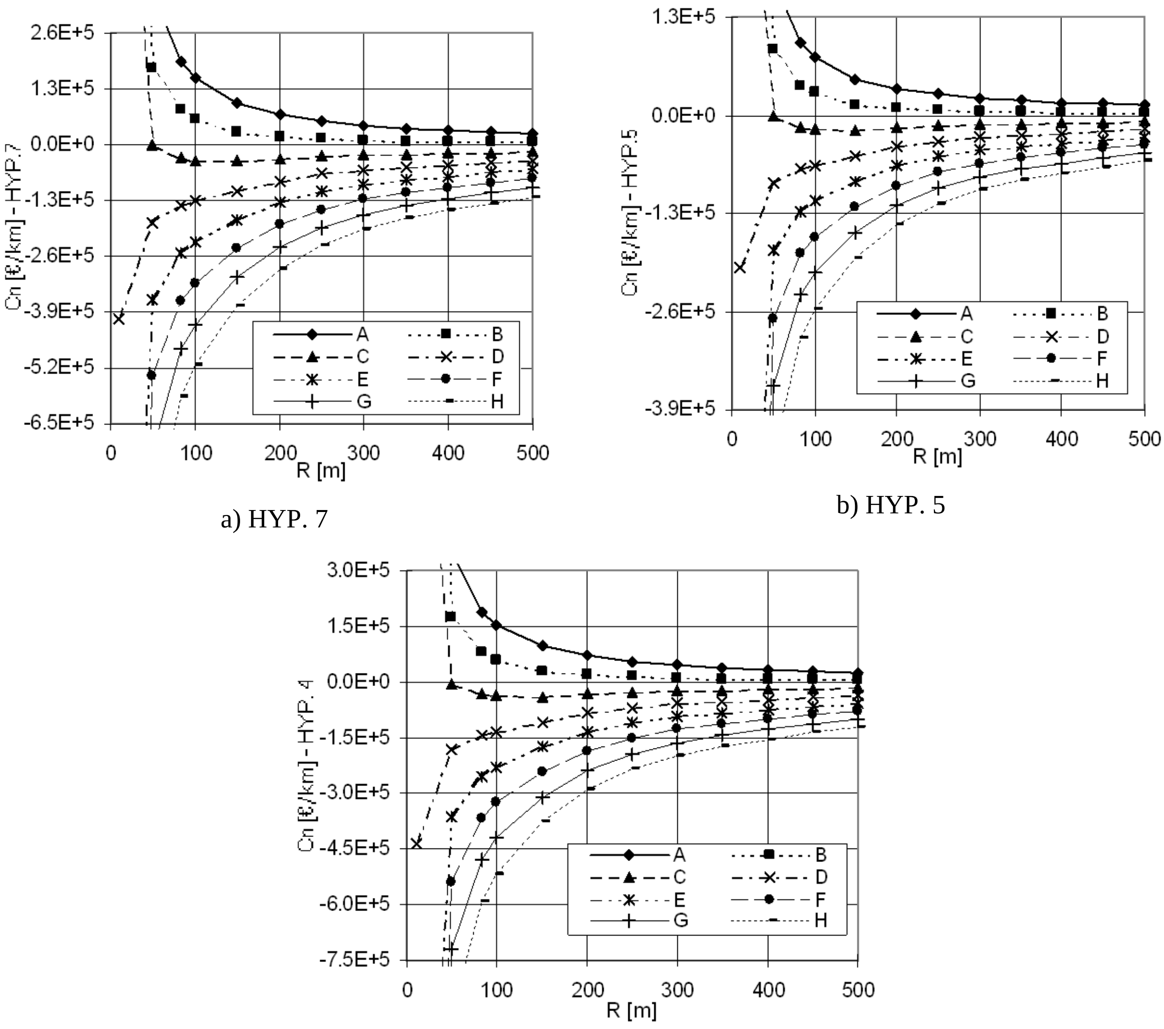
Fig. 6.8 – Normalised cost as a function of *R* in the ROA scenario.

Finally, it is important to analyse the difference in the monotonic behaviour of $(S_{ef})_{TOT}(R)$ among the various scenarios: it is a decreasing function in the BCC scenario (but almost constant), and increasing in the other two, URB and ROA. In the BCC scenario, as r_c is approximately constant, thus, C^* follows the behaviour of $N_{c/km}$. In the URB and ROA scenarios, as the mobility is high, r_c is stationary only for higher *R*s, it being an increasing function for lower *R*s. The impact of this difference consists in the existence of a minimum of C^* for some values of R_{384} (expressed in terms of cases A, B, ..., G and H), Figs. 6.6-6.8, when $(S_{ef})_{TOT}(R)$ is increasing (the cases of the URB and ROA scenarios in the presence of mobility). In the BCC scenario, however, this behaviour does not occur due to low terminal mobility, which has not been taken into account for the BCC scenario. Besides, the sign of C^* depends on the sign of $(1-r_c/K)$. Consequently, $r_c > K$ corresponds to $C^* < 0$, i.e., profitable configurations (depending on the actual fixed costs), whereas $r_c < K$, corresponding to non-profitable configurations, $C^* > 0$.

6.4.3. ‘Net Costs’

In this section, one presents the values for the ‘net cost’, which are obtained by multiplying the normalised cost by C_{fb}. One discusses the impact of these results in the price the user has to pay for her/his connection, so that the operator achieves a net revenue of 150 000 ± 15 000 €/km/year, while the annual payment of the fixed cost associated with licensing is 20 000 €/km/year.

The results for $C_n(R)$ are presented in Fig. 6.9 and Appendix O, where the values of R_{384} are labelled with A, B, …, G and H, and can be extracted from Table 6.3 and Appendix N. In HYP. 7, C_n takes twice of the values of C_n in HYP. 5 (because the parameters C_{fb}, C_{1920} and R_{384} are also the double), while in HYP. 4 different values arise, the comparison with HYPs. 5 and 7 not being so straightforward. In order to analyse these results, one considers the values of K, scenario and R from Table 5.51, the values obtained for r_c, C_n, and R_{384} being presented in Tables 6.4 and 6.5. One can conclude that there is no difference in shape between the curves from Fig. 6.9 and 6.7, there only being a difference in the scale factor because $C_n(C_{ft}) = C^* \cdot C_{fb}$, for $C_{fi} = 0$.



a) HYP. 7

b) HYP. 5

c) HYP. 4

Fig. 6.9 – Net cost as a function of R in the URB scenario, K = 3.

Table 6.4 – Results for r_c and C_n as a function of *K*, the scenario and *R*.

K	Scenario	*R* [m]	M_T	mobility	r_c			C_n [€/km]		
					HYP 7	HYP 5	HYP 4	HYP. 7	HYP. 5	HYP. 4
K = 3	BCC	100	250	absence	8.71	15.39	5.50	-131 026	-142 046	-132 507
				presence	8.71	15.39	5.50	-131 026	-142 046	-132 507
	URB	100	100	absence	9.82	15.75	5.98	-156 421	-146 221	-157 903
				presence	8.72	17.07	5.51	-131 189	-161 302	-132 670
	ROA	100	66	absence	10.47	16.62	6.26	-161 828	-147 519	-143 228
				presence	10.47	15.74	6.26	-171 187	-145 997	-172 668
		150	100	absence	13.07	19.08	7.39	-145 388	-116 111	-146 321
				presence	13.39	22.55	7.53	-155 782	-146 537	-156 751
K = 2	BCC	100	250	absence	6.22	11.89	4.42	-145 080	-170 170	-192 276
				presence	6.22	11.89	4.42	-145 080	-170 170	-192 276
	URB	100	100	absence	7.28	10.33	3.56	-181 687	-143 319	-123 921
				presence	5.87	10.49	4.27	-133 264	-146 021	-180 459
	ROA	100	66	absence	7.64	10.25	3.91	-183 375	-133 986	-143 379
				presence	7.31	11.68	3.95	-182 754	-166 495	-154 833
		150	100	absence	9.38	14.33	4.72	-159 908	-133 674	-135 921
				presence	8.41	15.44	5.37	-144 232	-151 100	-175 097

Table 6.5 – Values of R_{384} (the cases A, B, …, G and H are highlighted in the left part of each column)

K	Scenario	*R* [m]	M_T	mobility	HYP. 7		HYP. 5		HYP. 4	
					Case	R_{384} [€/min]	Case	R_{384} [€/min]	Case	R_{384} [€/min]
K = 3	BCC	100	250	absence	D	0.0125	F	0.00875	D	0.01125
				presence	D	0.0125	F	0.00875	D	0.01125
	URB	100	100	absence	E	0.015	G	0.01	E	0.015
				presence	D	0.010	F	0.0075	D	0.01
	ROA	100	66	absence	E	0.015	G	0.01	E	0.015
				presence	D	0.07	F	0.0045	D	0.07
		150	100	absence	F	0.0175	H	0.00125	F	0.0225
				presence	D	0.07	G	0.05	D	0.07
K = 2	BCC	100	250	absence	D	0.00625	F	0.004375	D	0.00625
				presence	D	0.00625	F	0.004375	D	0.00625
	URB	100	100	absence	D	0.00625	E	0.00375	C	0.005
				presence	E	0.0075	G	0.005	E	0.0075
	ROA	100	66	absence	E	0.015	F	0.0875	D	0.0125
				presence	D	0.07	F	0.045	C	0.06
		150	100	absence	F	0.00875	H	0.005625	E	0.0075
				presence	D	0.0175	G	0.0125	D	0.0175

Although the curves for r_c, C^* and C_n are not presented for all the cases (combinations of scenario and *K*) in Figs. 6.9 and O.1-O.2, in Tables 6.4-6.5 one still presents the results for all combinations, in order to give a broader view (however, the cases associated with the curves in Figs. 6.9 and O.1-O.2 are highlighted with a broader border in Tables 6.4-6.5). As in Table 5.51, one considered the cases of *R* = 100 m for every scenario, and also *R* = 150 m only for the ROA scenario.

A summary of these results for R = 100 m are presented in Table 6.6. To achieve an annual 'net revenue' (or profit) of 150 000 €/km, R_{384} should be higher for the deployment scenarios with lower associated spectral efficiency (for a given value of K). Because results also depend on K, results for K = 2 are included for the URB scenario, in order to be possible to compare all the scenarios with the same K. In this case, in HYPs. 7 and 4, the results for R_{384} are equal, except in the ROA scenario, where there is a slight difference. In HYP. 5, r384 takes 64-71 % of its value in HYPs. 7 and 4. Thus, the consequence of decreasing C_{fb} and C_{1920} to the half (from HYP. 7 to HYP. 5) is to achieve a user saving of 30-36%, while the change from HYP. 7 to HYP. 5, considering a higher C_{fb} (more than two-fold) and a lower C_{1920} (twice the value), does not mean a significant difference to the user expenses.

Table 6.6 – Summary of the results for $(S_{ef})_{TOT}$, the supported number of user/km, R_{384} and the net cost, in the presence of mobility.

Scenario	K	$(S_{ef})_{TOT}$	Supported no. of user/km	HYP. 7		HYP. 5		HYP. 4	
				R_{384} [€/min]	C_n [€/km/year]	R_{384} [€/min]	C_n [€/km/year]	R_{384} [€/min]	C_n [€/km/year]
BCC	2	39.5	137	0.00625	-145 080	0.004375	-170 170	0.00625	-192 276
URB	2	32.2	117	0.0075	-133 264	0.005	-146 021	0.0075	-180 459
	3	29.1	74	0.010	-131 189	0.0075	-161 302	0.010	-132 670
ROA	2	15.2	50	0.070	-182 754	0.0450	-166 495	0.060	-154 833

Comparing the scenarios for K = 2, for R = 100 m and K = 2, whereas the spectral efficiency takes values $(S_{ef})_{TOT}$ = 39.5, 32.2 and 15.2 %, the revenue from each basic channel has to be at least R_{384} = 0.00625, 0.010 and 0.070 €/min, respectively, i.e., the prices in the ROA scenario have to be around one order of magnitude higher than in the BCC scenario. R_{384} has an increase of about 20 % from the BCC to the URB scenario, and an increase of more than 700 % from the URB to the ROA scenario (the only exception for the last is associated with HYP. 4). Also note that when K = 3 is considered in the URB scenario, the increase from the BCC to the URB scenario rises to 60 %.

Thus, from these results for R_{384}, a price list for MBS applications can be obtained, in €/min. The data rate of each application is a weighted sum of the data rates of service components that support it, the weights depending on the number of times each service component is accessed during the application and on the average duration of each access (5.44). The billing is done in a 'per min' basis, and not by volume of information. However, the volume of information is reflected in the price per min of each service component, as it is proportional to the service component data rate. It is also worthwhile to note that, as a consequence of this approach, ABR applications will only be billed by the minimum guaranteed data rate during the application. An example of a price list for the BCC scenario is presented in Table 6.7.

Table 6.7 – MBS price list, in €/min, BCC scenario.

Application	b_k [kb/s]		Applications price [€/min]					
			HYP. 7		HYP. 5		HYP. 4	
	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
1. HVT	1920	1920	0.03125	0.03125	0.02188	0.02188	0.03125	0.03125
2. IVC	384	384	0.00625	0.00625	0.00438	0.00438	0.00625	0.00625
3. MVS	1920	0.8	0.03125	0.00001	0.02188	0.00001	0.03125	0.00001
4. HOB	8067.8	1923.8	0.13131	0.03131	0.09192	0.02192	0.13131	0.03131
5. WLI	145.8	4031.8	0.00237	0.06562	0.00166	0.04594	0.00237	0.06562
6. FTP	19.1	384	0.00031	0.00625	0.00022	0.00438	0.00031	0.00625
7. PIM	384	8064	0.00625	0.13125	0.00438	0.09188	0.00625	0.13125
8. DMM	63.4	48.6	0.00103	0.00079	0.00072	0.00055	0.00103	0.00079
9. MES	2731.1	2731.2	0.04445	0.04445	0.03112	0.03112	0.04445	0.04445
10. MRA	2328.0	2373.0	0.03789	0.03789	0.02652	0.02652	0.03789	0.03789
11. MTW	1929.6	1929.6	0.03141	0.03141	0.02198	0.02198	0.03141	0.03141
12. FFM	2736.0	2736.0	0.04453	0.04453	0.03117	0.03117	0.04453	0.04453
13. EMB	63.4	1536	0.00103	0.02500	0.00072	0.01750	0.00103	0.02500
14. ECO	15.9	48.6	0.00026	0.00079	0.00018	0.00055	0.00026	0.00079
15. MML	4.8	2328.0	0.00008	0.03789	0.00005	0.02652	0.00008	0.03789
16. TIN	76.5	242.9	0.00125	0.00395	0.00087	0.00277	0.00125	0.00395
17. RPC	9.6	194.3	0.00016	0.00316	0.00011	0.00221	0.00016	0.00316
18. UGD	1935.3	1935.3	0.03150	0.03150	0.02205	0.02205	0.03150	0.03150
19. ATR	1935.3	1935.3	0.03150	0.03150	0.02205	0.02205	0.03150	0.03150
20. TVD	0	8064	0.00000	0.13125	0.00000	0.09188	0.00000	0.13125
21. ENP	0.8	242.9	0.00001	0.00395	0.00001	0.00277	0.00001	0.00395

However it cannot be faced as 'the MBS price list', but only as 'an hypothetical MBS price list', obtained under the assumptions one considers in this work (which cannot be faced as definitive ones at all). For this purpose, the total data rate of applications has been considered. The lowest data rate applications are the cheapest ones, e.g., IVC, FTP, DMM, TIN or ENP. The most expensive ones, in €/min, are the following:

- The applications with one of the links data rates higher than or equal to 4 032 kb/s (which, furthermore, are strongly asymmetric ones). These are the cases of HOB, WLI, PIM and TVD.
- The symmetric ones with both links data rate higher than or equal to 1 920 kb/s. These are the cases of HVT, MES, MRA, MTW, FFM, UGD and ATR.

As an example, these applications are highlighted in Table 6.7 with different levels of a grey in background for HYP. 7.

The total price of an application is computed for its average duration, an example being presented in Table 6.8 (also for the BCC scenario). It is obtained by summing the prices per minute of the up- and downlink connections.

Table 6.8 – MBS applications total price, P_c, in €,for their average duration, BCC scenario.

Application	$\bar{\tau}$ [min]	P_c [€]		
		HYP. 7	HYP. 5	HYP. 4
1. HVT	3	0.1876	0.1312	0.0938
2. IVC	30	0.3750	0.2626	0.1875
3. MVS	120	3.7516	2.6261	0.0016
4. HOB	50	8.1312	5.6918	1.5656
5. WLI	15	1.0199	0.7139	0.9843
6. FTP	0.33	0.0022	0.0016	0.0021
7. PIM	10	1.3750	0.9626	1.3125
8. DMM	5	0.0092	0.0064	0.0040
9. MES	20	1.7782	1.2446	0.8891
10. MRA	40	3.0312	2.1218	1.5156
11. MTW	20	1.2562	0.8794	0.6281
12. FFM	5	0.4454	0.3118	0.2227
13. EMB	1	0.0260	0.0182	0.0250
14. ECO	5	0.0053	0.0037	0.0040
15. MML	40	1.5187	1.0631	1.5156
16. TIN	15	0.0780	0.0546	0.0593
17. RPC	5	0.0166	0.0116	0.0158
18. UGD	5	0.3150	0.2204	0.1575
19. ATR	20	1.2600	0.8820	0.6300
20. TVD	90	11.8125	8.2688	11.8125
21. ENP	20	0.0794	0.0555	0.0791

From these applications, the most expensive are the ones with the highest average duration ($\bar{\tau} \geq 40$ min), i.e., MVS, HOB, MRA and TVD. As an example the prices, P_c, for the BCC scenario in the HYP. 7 and HYP. 4 are presented:

- MVS, $\bar{\tau}$ = 120 min, $(P_c)_{MVS}$ = 3.7516 €.
- HOB, $\bar{\tau}$ = 50 min, $(P_c)_{HOB}$ = 8.1312 €.
- MRA, $\bar{\tau}$ = 40 min, $(P_c)_{MRA}$ = 3.0312 €.
- TVD, $\bar{\tau}$ = 90 min, $(P_c)_{TVD}$ = 11.8125 €.

It is also important to analyse the price of the applications with the highest usage, U. Under the hypothesis one is taking, their prices will be the ones from Table 6.9.

From this set, the most expensive ones are WLI, MTW, MML and ATR. However, it is worthwhile to note that a today's typical GSM call (at least in Portugal) has a similar price, with a lower duration. Finally, note that the only application with high foreseen demand and rather high price is TVD, 11.8125 € for a 90 min connection. However, it is a typical price to watch a pay-per-view film in a hotel today. Because of that, the high price will possibly not deteriorate the demand.

As different assumptions were considered for the usage in the BCC and URB scenarios, different results for the prices arise. The prices have an approximate increase of 60 % from the BCC to the URB scenario and a 150 % increase from the BCC to the ROA scenario.

Table 6.9 – Price of the applications with the highest usage.

Application	Average duration [min]	U [%]	P_c [€]
HVT	3	15.0	0.1876
IVC	30	4.0	0.3750
FTP	15	5.4	1.0199
TVD	0.33	7.0	0.0022
DMM	5	15.0	0.0092
MTW	20	7.3	1.2562
ECO	5	7.0	0.0053
MML	40	7.4	1.5187
TIN	15	3.6	0.0780
ATR	20	3.6	1.2600

If the operator wanted to have only a price for each application, he would have to compute an average value, depending on the weight of each deployment scenario in the overall system. It is also worthwhile to note that another possibility is having different prices in different areas, depending on the scenario.

6.4.4. Deployment Strategies

Because, for the value of the net revenue one is assuming as a goal, the net cost function does not have a minimum value in the zone of interest (50 ≤ R ≤ 350 m), it is important to explore different criteria to optimise MBS design. In this section one will isolate the cost and the revenue parcels, and compare their results for different values of R. A choice will be done for a value of R that minimises the cost, whilst guaranteeing a given number of supported user per kilometre.

Different strategies can then be followed in different phases of MBS deployment (initial, medium term or mature operation). An analysis of the profit, defined as the ratio between the 'net revenue' and the cost, in percentage, is also presented in order to help the clarification of the choice of possible deployment strategies. The medium term and the mature phases of operation are compared.

From (6.19) and (6.21) it is straightforward to conclude that, for C_{fi} = 0, the total cost and revenue per kilometre in a linear coverage geometry are defined by

$$C_{tot\,[€/km]} = \frac{1}{2R_{[km]}} \cdot \left(C_{fb\,[€]} + \frac{T \cdot 48 \cdot C_{1920\,[€]}/5}{K \cdot N_{op}} \right) \qquad (6.22)$$

$$R_{ev\_tot\,[€/km]} = \frac{1}{2R_{[km]}} \cdot \left(\frac{86400 \cdot S_{ef} \cdot T \cdot 48 \cdot R_{384\,[€]}}{K \cdot N_{op}} \right) = \frac{1}{2R_{[km]}} \cdot \frac{C_{fb\,[€]}}{K} \cdot \left(r_c + \frac{T \cdot 48}{N_{op}} \cdot \frac{C_{1920\,[€]}}{5 \cdot C_{fb\,[€]}} \right). \qquad (6.23)$$

the constant 86 400 min coming from (6.19) and (6.20). Note that $C_{tot} = C_0 - C_{fi}$. The annual cost and the revenue associated with each BS is obtained by multiplying the previous equations by $2R_{[km]}$, yielding

$$C_{bs}\,[€] = C_{fb}\,[€] + \frac{T \cdot 9.6 \cdot C_{1920}\,[€]}{K \cdot N_{op}} \tag{6.24}$$

$$(R_{ev})_{bs}\,[€] = \frac{C_{fb}\,[€]}{K} \cdot \left(r_c + \frac{T \cdot 9.6}{N_{op}} \cdot \frac{C_{1920}\,[€]}{C_{fb}\,[€]} \right). \tag{6.25}$$

C_{bs} is constant, and easy to obtain. $(R_{ev})_{bs}$ basically follows the shape of $r_c(R)$, it being $r_c(R)$ times a scale factor, C_{fb}/K, plus a constant. This can be verified in Fig. 6.10, where it is presented, as an illustration, an example for the BCC scenario, (HYP. 7). The other cases can be easily derived using the curves from Figs. 6.3-6.5 for $r_c(R)$, and the values from Table 6.2 for the cost parameters.

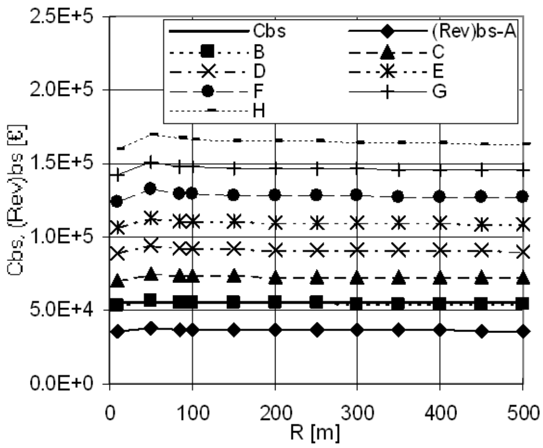


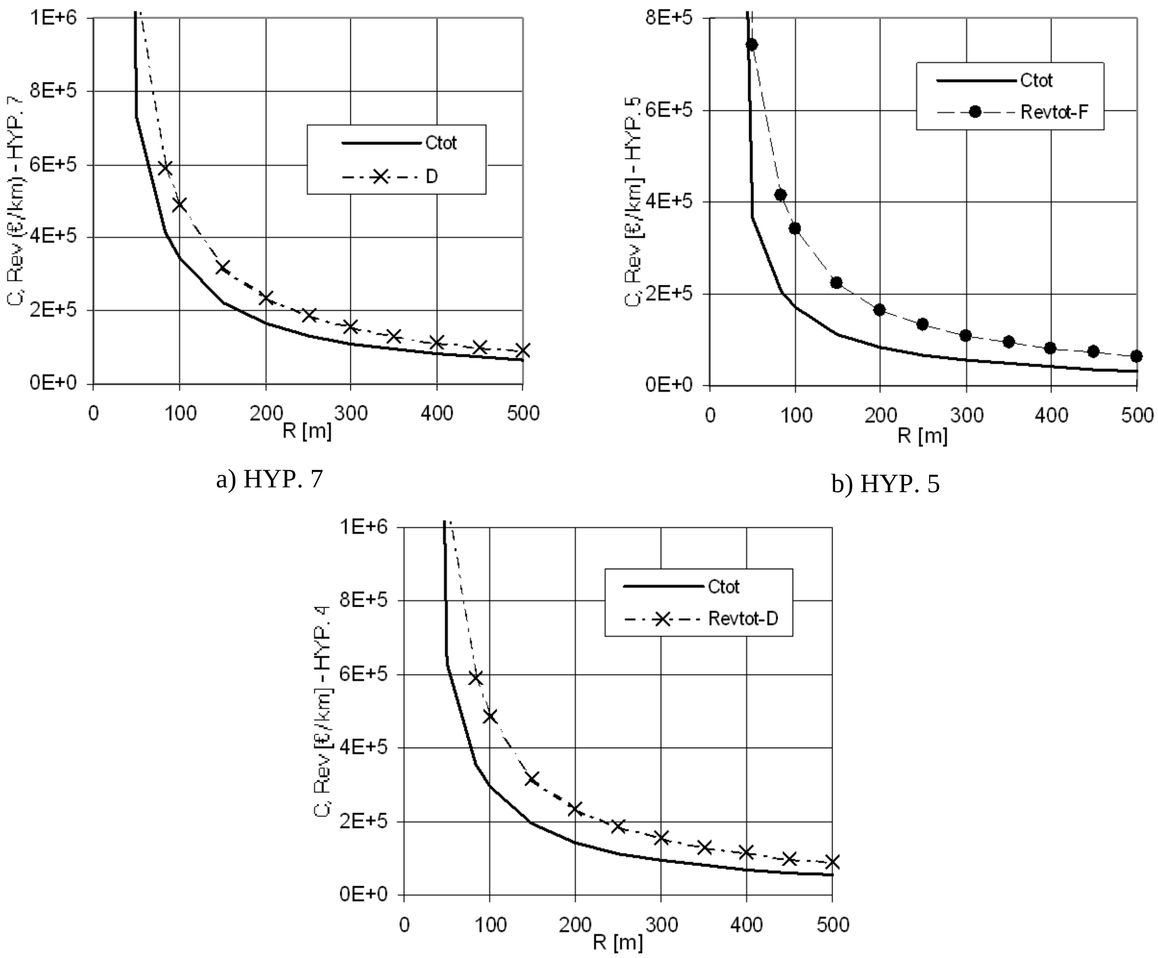
Fig. 6.10 – C_{bs} and $(R_{ev})_{bs}$: example for the BCC scenario in the HYP. 7.

One verifies that C_{bs} is constant, and that $(R_{ev})_{bs}(R)$ follows $r_c(R)$, which is almost constant in the BCC scenario. The cases A, D, E, F, G and H correspond to profitable configurations because $(R_{ev})_{bs} > C_{bs}$. The curves for the total cost and revenue per kilometre are presented in Fig. 6.11 and in Appendix P. Although the revenues could be presented for all the cases (A, B,…, H), they are only presented for the case of interest, i.e., the case for which the goal net revenue is achieved (which has already been identified in Table 6.6).

In Table 6.10 one presents the achieved values for the total cost and revenues for R = 100 m and R = 200 m, as well as the respective profit, P_{ft},

$$P_{ft} = (R_{ev.tot} - C_{tot}) / C_{tot} \,. \tag{6.26}$$

While, in the BCC scenario, the profit slightly increases with the decrease of R, it strongly decreases in the URB and ROA scenarios. The respective comparison of the number of supported users per kilometre between the cases of R = 100 m and R = 200 m is presented in Table 6.11, as well as the comparison between the foreseen and the actually supported number of users per kilometre.



a) HYP. 7

b) HYP. 5

c) HYP. 4

Fig. 6.11 – Total cost and revenue for the BCC scenario.

Table 6.10 – Total cost and revenues, in €/km/year, for *R* = 100 and 200 m.

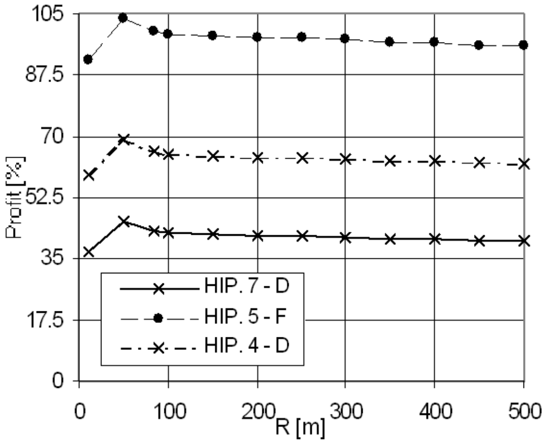
Scenario	*R* [m]	HYP. 7, case D				HYP. 5, case F				HYP. 4, case D*			
		$R_{ev[€/km]}$	$C_{[€/km]}$	$C_{n[€/km]}$	P_{ft} [%]	$R_{ev[€/km]}$	$C_{[€/km]}$	$C_{n[€/km]}$	P_{ft} [%]	$R_{ev[€/km]}$	$C_{[€/km]}$	$C_{n[€/km]}$	P_{ft} [%]
BCC	100	488 149	343 069	145 080	42.3	341 704	171 534	170 170	99.2	488 149	295 873	192 276	65.0
K = 2	200	233 830	166 684	67 146	40.3	163 681	83 342	80 339	96.4	233 830	143 753	90 077	62.7
URB	100	382 829	251 640	131 189	52.1	287 122	125 820	161 302	128.2	382 829	250 159	132 670	53.0
K = 3	200	205 950	122 262	83 688	68.4	154 462	61 131	93 331	152.7	205 950	121 542	84 408	69.4
ROA	100	525 823	343 069	182 754	53.3	338 029	171 534	166 495	97.0	450 706	295 873	154 833	52.3
K = 2	200	287 543	166 684	120 859	72.5	184 849	83 342	101 597	121.8	244 466	143 753	100 713	71.5

* Except in the ROA scenario, where one has chosen case C.

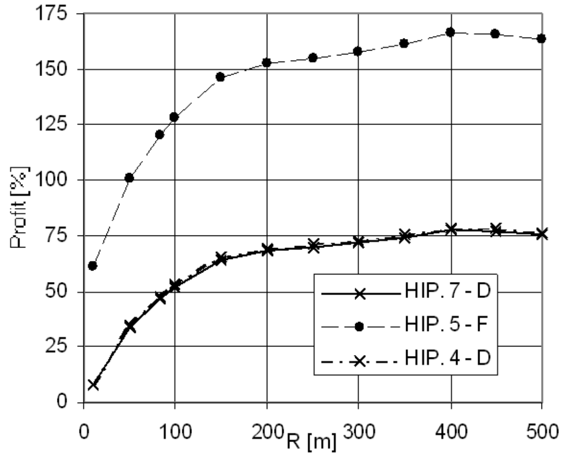
Table 6.11 – Comparison of the number of supported users per kilometre.

Scenario	Foreseen no. of user/km	No. of supported user/km		Ratio of no. of user/km between *R* = 200 and 100 m	Ratio supported/ foreseen no. of user/km	
		R = 100 m	*R* = 200 m		*R* = 100 m	*R* = 200 m
BCC	200	137	66	0.482	0.685	0.330
URB	58	74	41	0.554	1.276	0.707
ROA	39	50	28	0.560	1.282	0.718

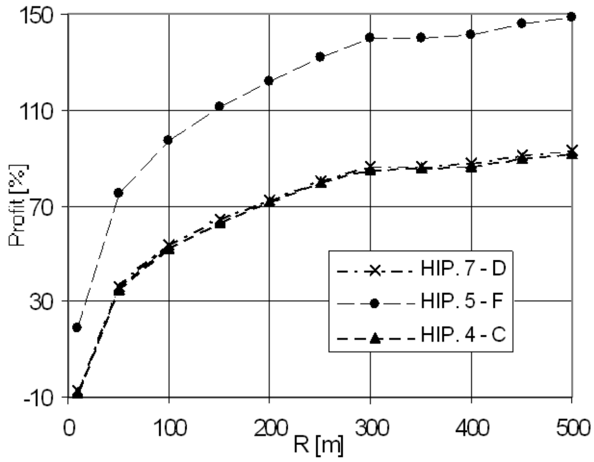
The variation of the profit with *R* is presented in Fig. 6.12 (values have been presented in Table 6.10 for *R* = 100 and 200 m). The shape of the curves is equal to the shape of the curves of $r_c(R)$, thus, the associated increasing behaviour is a consequence of the increasing behaviour of $S_{ef}(R)$. In the URB and ROA scenarios, the foreseen number of users for mature MBS can only be achieved with cells with *R* = 100 m. However, during the initial phase, while 70 % of the foreseen mature MBS users were not achieved, one can use cells with *R* = 200 m.



a) BCC scenario



b) URB scenario



c) ROA scenario

Fig. 6.12 – Profit as a function of *R*.

In the case of the BCC scenario, cells with *R* = 100 m (or less) should be used, but the foreseen number of users cannot be achieved by a single operator. One only can support around 70 % of the foreseen mature MBS users using cells with *R* = 100 m, thus, this is the initial solution to be followed. But, as one is considering the 'Manhattan grid' geometry, an important remark has to be done: *K* = 2 is only possible in the [62.0, 62.5] GHz sub-band for $R \geq 175$ m (but for frequencies near 62 GHz, lower *R*s can be considered). Thus, there is a limitation in the use of cells with *R* = 100 m in the BCC scenario. Nevertheless, it is worthwhile to note that four different operators together can support more than 200 user/km (4·66 = 264, more precisely).

In a medium term scenario, assuming that the number of foreseen users will be half of the mature number of users in MBS, one concludes that they can be supported using cells with R = 200 m in the URB (K = 3 is used in the range of feasible Rs) and ROA (in the linear coverage geometry K = 2 is allowed for $R \geq 66$ m) scenarios. This solution has the advantage of corresponding to a higher profit (e.g., 72.5 against 53.3 % in the ROA scenario, or 68.4 against 52.1 % in the URB scenario, HYP. 7). Although beginning with cells with R = 200 m (changing it later to R = 100 m) is very easy to implement in the ROA scenario, it will be more difficult in the URB scenario. As the ROA scenario has a linear geometry, the system can be designed in the beginning using cells with R =200 m, it being very easy to introduce cells with R = 100 m in between, in a later phase. In the URB scenario, which has a 'Manhattan grid' geometry, these changes will be much more complex to achieve, or even unlikely.

6.5. Arbitrary Urban Geometries

In this section, results for the normalised and 'net cost' are presented for arbitrary urban geometries, and a comparative analysis between the regular and the irregular urban geometries is worked out. Only the BCC and the URB scenarios are considered, i.e., the deployment scenarios corresponding to urban geometries. In the particular case of the URB scenario, only the case of presence of mobility is considered.

In order to verify if the goals for system capacity (in terms of supported versus foreseen number of users per kilometre) are achieved, one presents a summary of the results for f_a, the number of user/km and the spectral efficiency in Table 6.12. The values one is going to use in the remaining of this section correspond to the lowest f_a between the up- and downlinks, i.e., the worst-case situation (although an approximated balance was achieved).

Table 6.12 – Summary of the results for f_a, the number of user/km and the spectral efficiency for the irregular geometry.

Scenario	R [m]	M_T	Link	f_a [%]	No. of user/km	S_{ef} [%]	$(S_{ef})_{TOT}$ [%]
BCC	84	210	UP	8.32	104.0	37.8	31.1
			DOWN	7.77	97.1	29.8	
URB	84	84	UP	23.2	116.6	29.9	33.6
			DOWN	24.5	122.3	36.9	

In Table 6.13 a comparison between the foreseen and the supported number of user per kilometre is presented. Values for the regular coverage geometry are also included for comparison purposes. Note that for irregular urban geometries it is difficult to define the number of user/km, because cells from different shapes exist, thus, one considered, only for comparison purposes, that it is defined by the ratio between the number of users per cell and $2R$. Although, in the URB scenario the supported number of user/km largely overcomes the foreseen number of user/km, in the BCC scenario, only half of the foreseen users can be supported. However, assuming that two operators will exist, together they can support the foreseen number of user per km, but being individually limited to supporting more than half of the foreseen BCC users in their market deploying strategies. More users can be supported in the URB scenario (owing to the lower associated maximum load per user).

Table 6.13 – Comparison between the foreseen and the supported number of user/km for the irregular and for the 'Manhattan grid' urban geometries.

Scenario	R [m]	No. of user/km		
		Foreseen	Supported	
			Irregular	'Manhattan grid'
BCC	84	200	97	166
URB	84	58	116	87

Note that in the irregular geometry K = 5 in both scenarios, whereas, for the 'Manhattan grid' geometry, K = 2 in the BCC scenario, and K = 3 in the URB scenario. This explains the higher number of supported users in the URB scenario in the irregular urban geometry, because the URB geometry presents a lower maximum load per user, compared with the BCC scenario, while K is the same for both geometries.

In the 'Manhattan grid' geometry, it is worthwhile to note that when R decreases from 100 to 84 m, there is an increase of the supported number of users from 137 to 166, i.e., 83 % of the foreseen users can be supported with R = 84 m. The 'net cost' is obtained by using equations (6.8) and (6.11), corresponding respectively to the following equations to the normalised cost per unit area (defined by the product of the number of cells per km^2 by (1-r_c/K))

$$C^* = \frac{1}{2 \cdot l_{[km]} \cdot \left(R_{[km]} - l_{[km]}/2\right)} \cdot \left(1 - \frac{r_c}{K}\right) \tag{6.27}$$

$$C^* = \frac{N_c}{A_{n\,[km^2]}} \cdot \left(1 - \frac{r_c}{K}\right), \tag{6.28}$$

r_c being defined by (6.14). Again, it is worthwhile to note that in the case of the 'Manhattan' geometry a linearised 'net cost' function, (6.9), was obtained dividing C_n by 2·l_{km}, with the purpose of comparing results with the linear coverage geometry.

A typical value for the coverage distance in the irregular urban geometry is R = 84 m. For this coverage distance, the number of cells per km^2 is 144.8 for the 'Manhattan grid' geometry (conside-ring l = 22m), and 202.1 for the irregular urban geometry (for the cases worked out in Section 3.5, with N_c = 115 cells, a area A = 2.54 km^2, 22.4 % being net cell area, i.e., A_{nc} = 2.54·0.224 = 0.569 km^2). As a consequence, in the irregular urban geometry, an extra amount of 40 % of cells is needed to cover the same 'net' area, because of the irregularities and the consequent difficulties in coverage.

Besides, the achieved reuse pattern is 5, instead of K = 2-3. Because of the different reuse pattern, it is difficult to compare the results of r_c between the geometries, thus, one having to compare r_c/K. But, in the irregular urban geometry itself, the values of r_c can easily be compared between the different hypothesis for the parameters C_{fb} and C_{1920} (HYPs. 7, 5 and 4). Therefore, one first analyses the 'net cost' function, only discussing the impact of r_c/K in the variation of the normalised cost afterwards. The considered values for R_{384}, C_{1920} and C_{fb} are presented in Tables 6.14-6.15.

Table 6.14 – Assumptions for K = 5 (345 channel/cell) in the BCC scenario.

HYP.	C_{fb} [€/year]	C_{1920} [€/year]	R_{384} [€/min]							
			A	B	C	D	E	F	G	H
7	13000	600	0.0040	0.004625	0.00525	0.005875	0.0065	0.007125	0.00775	0.008375
5	6500	300	0.0017	0.002325	0.00295	0.003575	0.0042	0.004825	0.00545	0.006075
4	30000	300	0.0035	0.004125	0.00475	0.005375	0.0060	0.006625	0.00725	0.007875

Table 6.15 – Assumptions for K = 5 (345 channel/cell) in the URB scenario (with the presence of mobility).

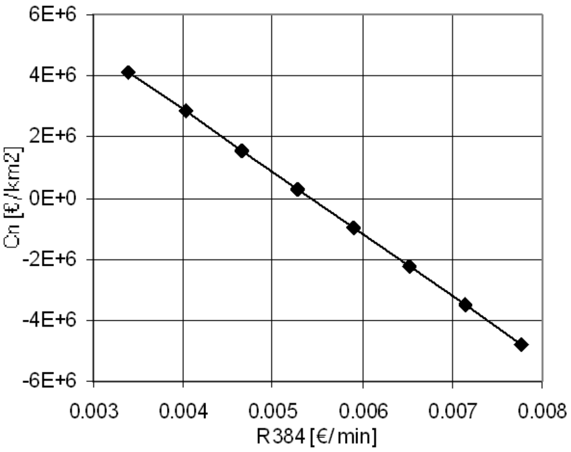
HYP.	C_{fb} [€/year]	C_{1920} [€/year]	R_{384} [€/min]							
			A	B	C	D	E	F	G	H
7	13000	600	0.0034	0.004025	0.004650	0.005275	0.00590	0.006525	0.007150	0.007775
5	6500	300	0.0025	0.002813	0.003125	0.003438	0.00375	0.004063	0.004375	0.004688
4	30000	300	0.0036	0.004225	0.004850	0.005475	0.00610	0.006725	0.007350	0.007975

The value for the 'net cost' threshold in these 2D systems can be obtained by dividing the linear 'net cost' threshold (which was 150 000 €/km in the linear coverage geometry) by $2l$. However, one has to consider the fixed cost of the license as being twice the value of the regular geometries case, because only two operators (with 1 GHz bandwidth each) are considered, instead of four. If the system was linear, the threshold would then be 170 000 €/km. Dividing it by $2{\cdot}l$ one thus obtains a threshold of 3 863 636 €/km^2 (net km^2). However, from now on, one considers a threshold of 3 500 000 ± 350 000 €/km^2, as an approximation. From the results of the 'net cost' for the irregular urban geometry (an example being given Fig. 6.13 for the URB scenario), one extracted the values of C_n approximately corresponding to this threshold, Table 6.16.

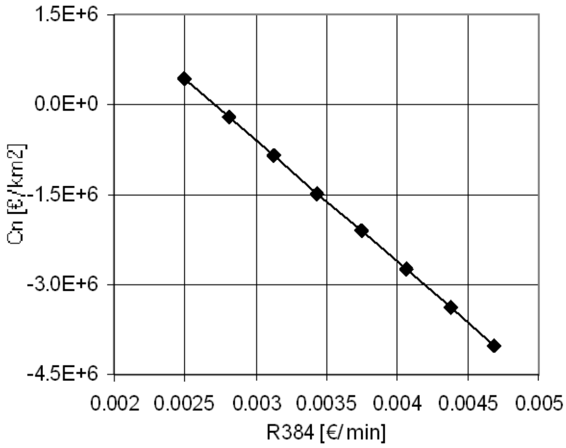
The respective results for r_c are also presented in Table 6.16. Values for the 'Manhattan grid' geometry (with R = 84 m) were also included for comparison purposes. In Table 6.17 one presents the respective values of R_{384}, and one identifies the associated cases (A, B, …, G and H) from Tables 6.14-6.15, associated with the pair scenario / hypothesis. On the one hand, in the 'Manhattan grid' geometry K = 2 (corresponding to 432 channel/cell) is associated with the BCC scenario, and K = 3 (288 channel/cell) is associated with the URB one. On the other, K is 5 (345 channel/cell) for the irregular geometry. One concludes the following for the latter geometry:

- In the BCC scenario, R_{384} is higher (associated with the lowest number of channel/cell, 345 against 432, and the lowest number of supported user/km, 97 against 166);

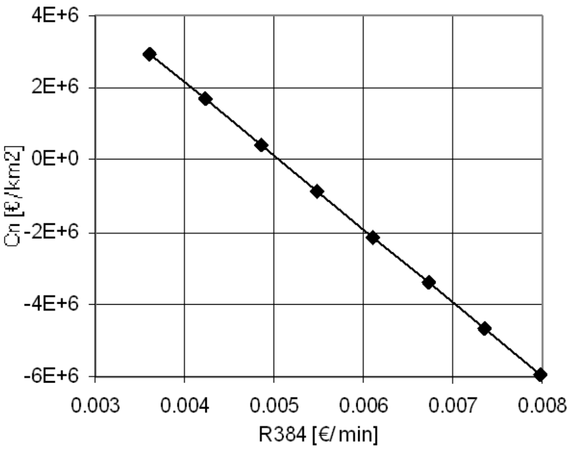
- In the URB scenario, R_{384} is lower (associated with the highest number of channel/cell, 345 against 288, and the highest number of supported user/km, 116 against 87).



a) HYP. 7



b) HYP. 5



c) HYP. 4

Fig. 6.13 – C_n as a function of R in the URB scenario (considered as an irregular urban geometry).

Table 6.16 – Values of r_c and C_n – comparison between the irregular and the regular urban geometries.

Geometry	Scenario	R [m]	M_T	K	r_c			C_n [€/km^2]		
					HYP. 7	HYP. 5	HYP. 4	HYP. 7	HYP. 5	HYP. 4
Irregular	BCC	84	210	5	11.72	18.50	7.76	-3 529 451	-3 546 988	-3 346 551
	URB	84	84		11.67	17.85	7.80	-3 505 998	-3 377 173	-3 398 288
'Manhattan Grid'	BCC	84	210	2	6.29	9.14	3.22	-4 035 545	-3 359 955	-2 642 455
	URB	84	84	3	8.16	16.23	5.26	-3 236 455	-4 148 523	-3 276 977

Table 6.17 – Values of R_{384} (the cases A, B, …, G and H are highlighted in the left part of each column).

Geometry	Scenario	R [m]	M_T	K	HYP. 7		HYP. 5		HYP. 4	
					case	R_{384} [€/min]	case	R_{384} [€/min]	case	R_{384} [€/min]
Irregular	BCC	84	210	5	G	0.00775	F	0.004825	G	0.00725
	URB	84	84		G	0.00715	G	0.004375	F	0.006725
'Manhattan Grid'	BCC	84	210	2	D	0.00625	E	0.004375	C	0.0050
	URB	84	84	3	D	0.010	F	0.0075	D	0.010

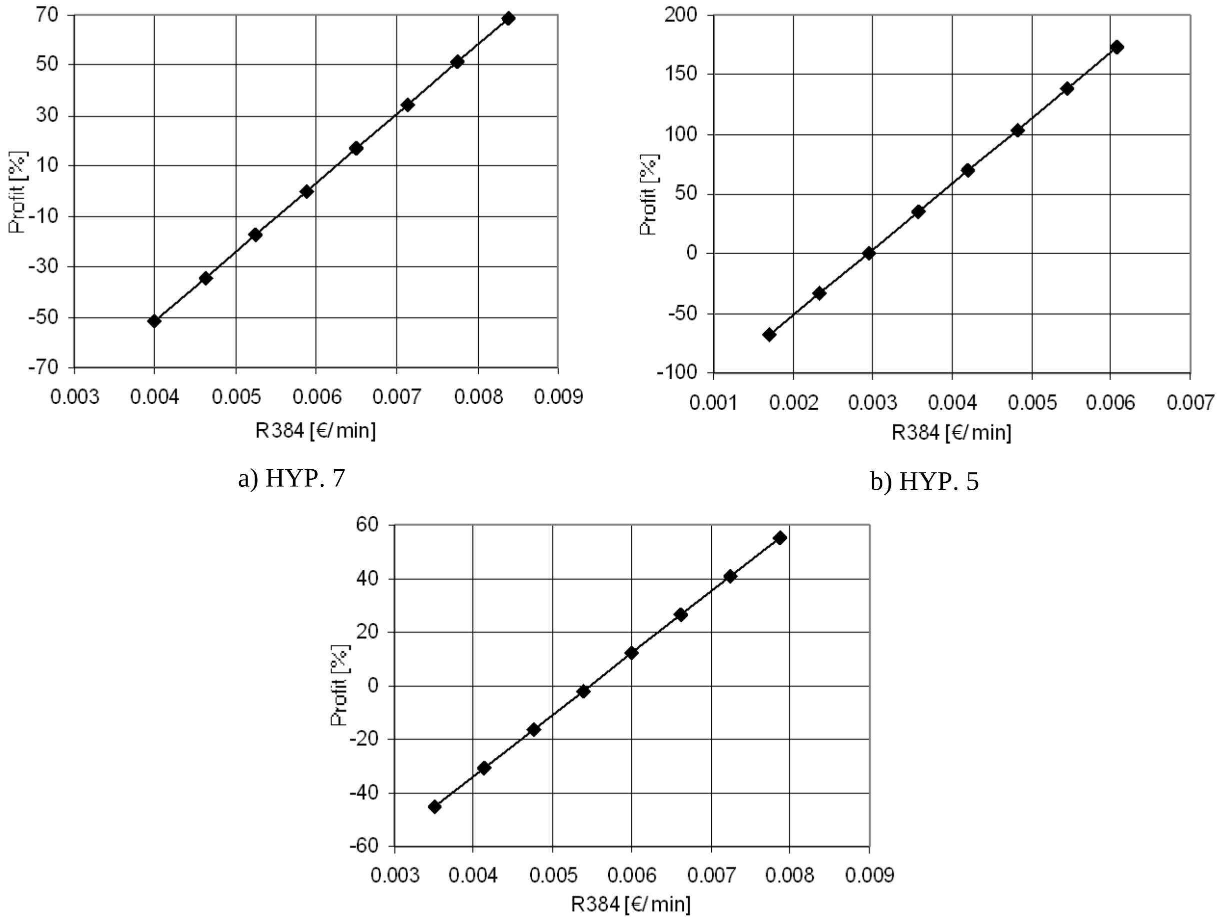
The differences in r_c/K result from the need of compensating the number of cells/km^2, (6.27) and (6.28): $N_{c/km^2} = 144.8$ in 'Manhattan grids', and $N_{c/km^2} = 202.1$ for the irregular geometry, Table 6.18.

Table 6.18 – Difference in the values of r_c/K between the geometries.

Geometry	Scenario	r_c/K		
		HYP. 7	HYP. 5	HYP. 4
Irregular	BCC	2.34	3.70	1.55
	URB	2.33	3.57	1.56
'Manhattan Grid'	BCC	3.14	4.57	1.61
	URB	2.72	5.41	1.75

The differences in r_c/K between the hypothesis 7, 5 and 4 come from different values of C_{fb}. The highest C_{fb} is the lowest r_c/K has to be. As in Section 6.4.3, from these results one can obtain a price list, in €/min, and the respective price of the applications for their average duration, Appendix Q.

In Figs. 6.14-6.15 one presents the curves for the achievable profit as a function of R_{384}.



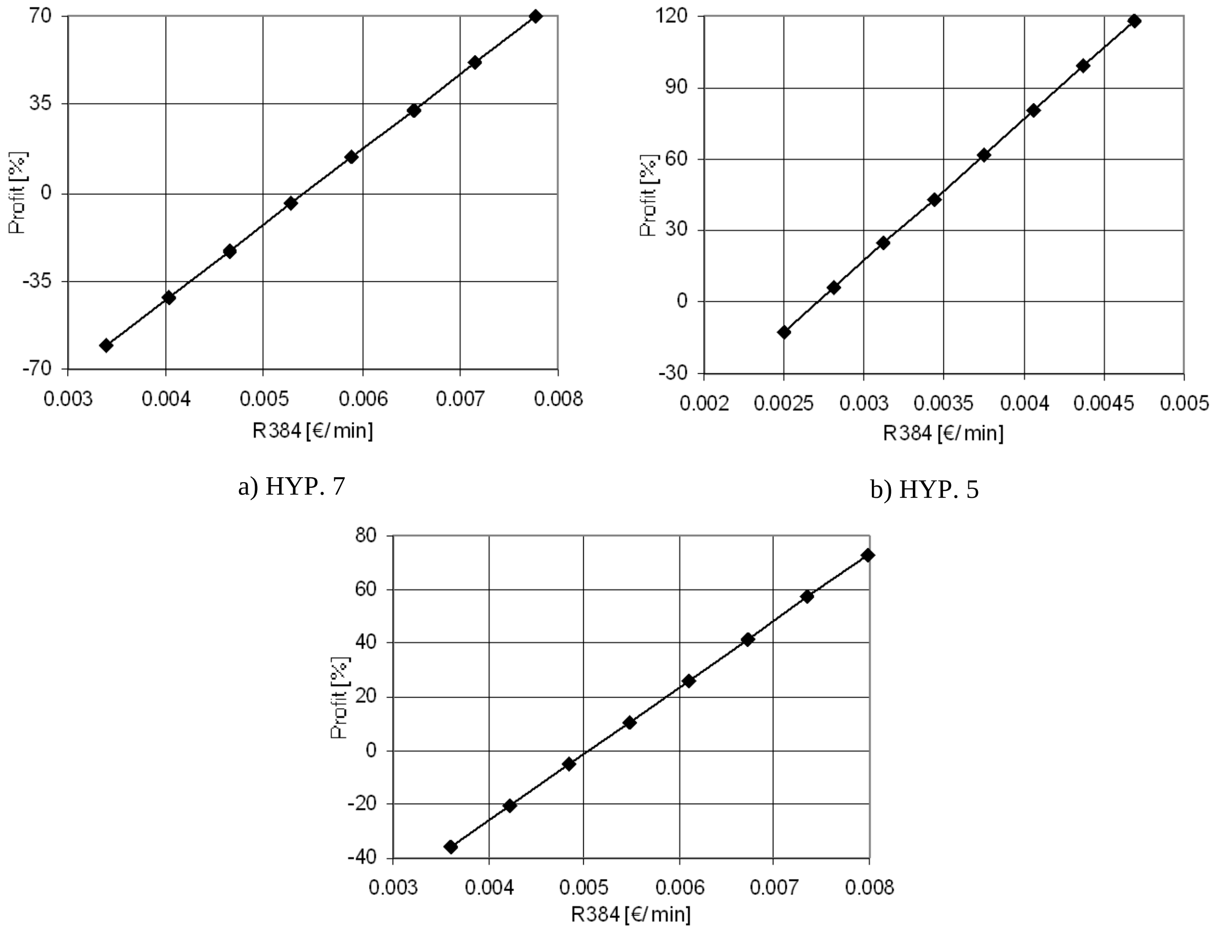
c) HYP. 4

Fig. 6.14 – Profit as a function of R_{384} in the BCC scenario.

Results for the profit that corresponds to the goal net revenue (3 500 000 ± 350 000 €/km^2) are presented in Table 6.19. Comparing these results for the profit with the ones for the regular urban geometry, Table 6.10, one concludes that the profit is typically higher in the irregular urban geometry for the BCC scenario (associated to higher values of R_{384}, and the lowest values of the number of channels per cell), and lower in the URB scenario (associated to lower values of R_{384}, and the highest values of the number of channels per cell).

Table 6.19 – Profit for a goal net revenue of 3 500 000 ± 350 000 €/km^{2}.

Scenario	Profit [%]		
	HYP. 7	HYP. 5	HYP. 4
BCC	51.8	104.0	41.0
URB	51.4	99.1	41.6



a) HYP. 7

b) HYP. 5

c) HYP. 4

Fig. 6.15 – Profit as a function of R_{384} in the URB scenario.

The pair HYP. 4/BCC scenario is an exception, explained by the lower value achieved for C_n.

6.6. Conclusions

A 'net cost' model was presented for the design tradeoffs between reuse pattern, K, the coverage distance, R, and the spectral efficiency, $S_{ef}(R)$, which allows for optimising the cellular planning in linear and urban coverage geometries. This model allows the determination of the revenue per channel that achieves a given value for the annual profit per kilometre. The normalised cost was also introduced, for comparison purposes. The existence of profitable cell configurations for the system was seen to depend critically on the relation between the reuse pattern and the parameter r_c (the cluster revenue-to-cost ratio).

As a working hypothesis, one considered that MBS will only be viable when the cost of deploying and operating the system will decrease to the order of magnitude of the costs associated with today's systems. Several hypothesis for costs were considered based in this assumption (HYPs. 7, 5 and 4).

Results were first achieved for the cluster revenue-to-cost ratio, r_c, and for the 'net cost', C_n, in regular geometries (the linear and the 'Manhattan grid' ones) for the cases BCC scenario / K = 2, URB scenario / K = 3 and ROA scenario / K = 2, as defined in Section 5.6.4. From the variation of C_n with R one concludes that in HYP. 7 C_n takes twice the value of C_n in HYP. 5 (because the parameters C_{fb}, C_{384} and R_{384} are also the double). The comparison with HYP. 4 is not so straightforward, because of the difference in parameters.

In order to achieve an annual 'net revenue' of 150 000 €/km, the revenue per basic channel, R_{384}, should be higher for the scenario with lower associated spectral efficiency, for a given value of R. For example, comparing the BCC, URB and ROA scenarios for R = 100 m and K = 2, whereas the spectral efficiency takes values $(S_{ef})_{TOT}$ = 39.5, 32.2 and 15.2 %, the revenue from each basic channel has to be R_{384} = 0.00625, 0.010 and 0.070 €/min, respectively, i.e., the prices in the ROA scenario have to be around one order of magnitude higher than in the BCC scenario.

An MBS 'hypothetical price list' was obtained from these results, applications with higher average data rate being the most expensive ones (also depending on their average duration). Different results arise for prices in different scenarios. As it is not foreseen that prices will depend on the deployment scenario, operators will have to compute each application price considering the relative weight of each scenario in the overall system, although the differentiation of prices is also a possibility.

For the value of the net revenue one is assuming as a goal, it is important to explore different criteria to optimise MBS design in these regular geometries, because the net cost function does not have a minimum value in the zone of interest ($50 \leq R \leq 350$ m). A choice was done of a value of R that minimises the net cost whilst guaranteeing a given number of supported users per kilometre.

In a medium term scenario, if one assumes that the number of foreseen users will be half of the mature MBS number of users, one concludes that they can be supported using cells with R = 200 m in the URB and ROA scenarios. However, in the URB and ROA scenarios, the foreseen number of users for mature MBS can only be achieved with cells with R = 100 m. This solution has the advantage of corresponding to a higher profit (e.g., 72.5 against 53.3 % in the ROA scenario, or 68.4 against 52.1 % in the URB scenario, hypothesis 7). In the BCC scenario, however, some limitations exist because one cannot use cells with R < 175 m whilst considering K = 2, and the foreseen supported users can only be supported by at least three operators together (from the four one is considering).

Because results for frequency reuse in irregular urban geometries are also available from Chapter 3 (for the centre of Lisbon), it is also important to obtain results for costs and revenues for these geometries, and extract some conclusions, by comparing the irregular and the 'Manhattan grid' geometries. The first difference comes from the number of operators (2 instead of 4) and from the reuse pattern (K = 5 instead of 2-3). Using cells with an average coverage distance R = 84 m, the difference in achieved prices between the URB and BCC geometries is not relevant, although more users can be supported in the URB scenario (owing to the lower associated maximum load per user). A price list was also obtained.

On the one hand, in the 'Manhattan grid' geometry, K = 2 (corresponding to 432 channel/cell) is associated with the BCC scenario, and K = 3 (288 channel/cell) is associated with the URB one. On the other, K is 5 (345 channel/cell) for the irregular geometry. As a consequence, one concludes the following for irregular geometries:

- In the BCC scenario, R_{384} is higher (associated with the lowest number of channel/cell, 345 against 432, and the lowest number of supported user/km, 97 against 166);
- In the URB scenario, R_{384} is lower (associated with the highest number of channel/cell, 345 against 288, and the highest number of supported user/km, 116 against 87).

Comparing the results for the profit with the ones for the regular urban geometry one concludes that the profit is typically higher in the irregular urban geometry for the BCC scenario (associated with higher values of R_{384}, and the lowest values of the number of channels per cell), and lower in the URB scenario (associated to lower values of R_{384}, and the highest values of the number of channels per cell).

Although there are no optimum values for the profit, as the time pass, and the use of MBS evolves, the operator is able to choose different cell coverage distances, in order to sup-port a different number of users, whilst maximising the profit. The profit is higher for higher coverage distances, because few cells are used, and the costs are lower. Whereas in linear geometries (e.g., roads and highways) it will be easy to decrease the cell coverage distance to the half when the user demand increases (installing BSs in between the existing ones), it will not be so easy in urban geometries, further work on the optimisation of this evolution being needed. A first step will be to grasp what happens in regular urban geometries when one evolves from a sparse mesh of BSs to a denser one. The stringent design requirements associated with cost / revenue analysis shows that it is important to have accurate forecasts for user demand in each phase of MBS evolution, in order to avoid over-dimensioning, and thus avoid high investments (without immediate return) in an early phase.

Chapter 7

Conclusions and Future Research

7.1. Conclusions

Important aspects of cellular planning in Mobile Broadband Systems have been covered, and conclusions on the achieved re-use pattern, spectral efficiency and cost / revenues were obtained for the 40 and 60 GHz frequency bands, on several cellular geometries, corresponding to different deployment scenarios, supporting different types of terminal mobility.

On the one hand, all the analysis is based on a complete classification of MBS services and applications, their characterisation parameters and deployment scenarios. On the other, assuming the use of FDMA/TDMA, results for the cellular coverage and frequency re-use have been obtained, i.e., the coverage distance, the position of BSs (which is a relevant output in irregular urban geometries), and the re-use pattern.

In order to obtain the supported traffic and the spectral efficiency, one generalised the traditional telecommunications operator procedures of analysing and dimensioning single-service tele-traffic to multi-service. Inputs are the achieved coverage distance, the re-use pattern, the characteristics of the DSA++ MAC protocol, the channel structure, the service characterisation, the deployment scenarios, and the characteristics of traffic from mobility.

From the variation of the achieved spectral efficiency with the coverage distance, one evaluated the cost / revenue MBS performance in the different bands, and for various cellular geometries, taking the re-use pattern, the coverage distance, and some hypothetical cost / revenue parameters into account. This procedure allows for obtaining system optimisation, and establishing some strategies for the different phases of MBS deployment. The prices of the connections will strongly depend on the scenario, on the cellular geometry, and, in some way, on the frequency band.

In Chapter 2, a classification for mobile broadband services and applications was proposed, which distinguishes between interactive and distribution services, and also identifies the types of information supporting each one. A taxonomy was also proposed for applications characterisation parameters, divided into five different types: main ones, traffic and communications parameters, service components and operation environments as well. As the multi-service traffic analysis of MBS, with a given mixture of applications, requires the definition of their main operation environments, the respective deployment scenarios were defined. The usage of broadband applications (> 2 Mb/s) increases from the residential market (17%) to the business one (25%), corresponding to a decrease in the usage of wideband ([384, 2000] kb/s) ones (from 50 down to 42 %), and to a constant value for the usage of low-MBS ([128, 384] kb/s) ones (33%); slight differences exist from the business to the industrial market. The density factors were also proposed for each scenario.

Chapter 3 addressed the comparison of characteristics between the bands of 40 and 60 GHz, prospectively allocated for Mobile Broadband Communication Systems. The key difference between the two bands is the oxygen absorption, which is negligible at 40 GHz, but presents high values at 60 GHz, decreasing from 14 dB/km (at 62 GHz) down to approximately 1 dB/km (at 66 GHz). The impact of this excess absorption is two-fold: on the one hand it reduces the received signal power, but on the other it also reduces the co-channel interference. These two quantities may not suffer the same amount of reduction, hence, differences in the re-use pattern may result. The results showed that for the regular coverage geometries the difference in the re-use pattern obtained in both bands is not relevant, a value of 3 being achieved. However, differences exist in the range of maximum coverage distances values at 43.5 GHz being up to 20 % larger than at 66 GHz.

For irregular urban geometries, the results obtained from specific cellular layouts showed that the re-use pattern is the same for both bands (in the range 5-7) for the range of coverage distances where the system operation interference limited (say, for coverage distances less than 124 m). Again, larger coverage lengths can be achieved at 40 GHz, although with a higher associated re-use pattern. Because of the difference in the re-use pattern between the two urban geometries, the one-way bandwidth per cell is higher for the planar regular geometries, however not having, any practical difference between the bands of 40 and 60 GHz. For a total bandwidth assigned to the system of 2 GHz, the one-way bandwidth per cell is 333 MHz for the regular geometry and 200 MHz for the irregular urban one.

The highest values for the number of cells and for the re-use pattern in the irregular geometry result from the highest complexity of the urban environment, a higher number of cells being needed to overcome the difficulties in coverage resulting from urban obstacles. This originates a higher number of interference sources, coming from different directions – although obstructions from buildings to the interference exist. Therefore, the highest system capacity values for the planar regular geometry are explained by the lowest values of the re-use pattern.

In Chapter 4, models allowing the study of the influence of coverage distance and velocity on the supported traffic and on the new calls traffic linear density were examined, and results were obtained for typical scenarios in MBS with a linear coverage geometry. The blocking probabilities for both new and handover calls were assessed for configurations without guard channels for handover via the consideration of a Markov chain, which can be approximated by a model that allows the use of the theory from Jackson networks. For systems without guard channels for handover, for a fixed bounding value for the blocking probability, the new calls traffic linear density was analysed, increasing with the decrease of the maximum coverage distance, *R*, being upper limited by a value which depends on the characteristics of the mobility scenario.

However, call-dropping probability requirements also need to be fulfilled, leading to a new calls traffic density that only increases with the decrease of *R* down to an optimum value, and being lower for scenarios with higher mobility. These optimum values of *R* are higher for scenarios with higher and higher mobility, leading to limitations in system capacity, mainly for high mobility scenarios. In order to overtake these limitations, the use of guard channels for handover is studied, particularly for high mobility scenarios.

For these scenarios, one concludes that there is a degradation in system capacity, because in the case of short duration connections, for the coverage distances foreseen for MBS, higher optimum values for the new connections traffic linear density are obtained when using 2 guard channels; however, for the highways scenario, the corresponding coverage distances are larger than the foreseen cell lengths. It was also verified that there is degradation in system capacity, measured in Erlang/km, for higher and higher mobility scenarios. A comparison between the results for short and long duration calls was also presented, and one concluded that the use of guard channels for handover has only to be considered for the former. For long duration connections, the use of guard channels for handover has not shown to be advantageous.

In Chapter 5, an MMPP model was proposed for the modelling of the superimposition of MBS data and video IPP sources. Given the correspondence between applications and their bearer service components, an algorithm for the Bernoulli case of the Bernoulli-Poisson-Pascal model was used to compute the blocking probability. The mobility does not have to be considered in the blocking probability computation for each value of the fraction of active users (i.e., the algorithm does not suffer any change when mobility is considered), because the normalised activation rate does not depend on it. However, it affects the value of the maximum handover failure probability. By defining the different types of terminal mobility associated with each application, it is possible to compute the values of the total service rate of each component and, consequently, the values of the maximum handover failure probability corresponding to a given connection dropping probability threshold. In each scenario, the different values of the maximum handover failure probability are identified in this way, making the constraints associated with each deployment scenario available and ready to use. One started by obtaining results for fixed values of R, considering the distribution of resources according to this constraint. One studied the dependence of the supported fraction of active users, supported number of users per cell, and the spectral efficiency on the scenario and on the number of users per cell. One concluded that for the scenario where the maximum load per user is lower, i.e., the URB (urban) one, the number of supported users is higher. Comparing the cases of 288 and 384 channel/cell one also concludes that, although the number of channels is only 25 % lower, the supported number of users decreases 50 %.

High terminal mobility strongly degrades system performance. Only 81-82 % of the traffic is supported in the URB scenario relatively to the static case. In the ROA (roads) scenario, the influence is more drastic: only 28 % of the traffic is supported in the 384 channel/cell case relatively to the static case, and 21 % in the 288 channel/cell case. The variation of the supported traffic with the coverage distance was also studied, the case of balance between the links with the $P_{hf} = (P_{hf})_{max}$ constraint being considered (in opposition to the balance according to $P_b = 2$ %). This allowed us to choose a re-use factor of 3, $K = 3$, for the urban scenario, whereas $K = 2$ is needed in the BCC (business city centre) and ROA scenarios. $K = 3$ corresponds to the 40 GHz band and/or the upper 1 GHz sub-band of the 60 GHz band, while $K = 2$ corresponds to the lower 1 GHz sub-band of the 60 GHz band (and only a part of it in the case of the 'Manhattan grid' geometry, more precisely).

In Chapter 6, a cost/revenue performance prospective analysis of MBS was proposed given some assumptions for cost and revenues parameters. A 'net cost' model was presented for the design tradeoffs between reuse pattern, the coverage distance, and the spectral efficiency, which allows for optimising the cellular planning in linear and urban coverage geometries. As a working hypothesis, one considered that MBS will only be viable when the cost of deploying and operating the system will decrease to the order of magnitude of the costs associated with today's systems. The existence of profitable cell configurations for the system was seen to depend critically on the relation between the re-use pattern and the cluster revenue-to-cost ratio.

In order to achieve an annual 'net revenue' of 150 000 €/km, the revenue per basic channel, R_{384}, should be higher for the scenario with lower associated spectral efficiency, for a given value of R. For example, comparing the BCC, URB and ROA scenarios for $R = 100$ m and $K = 2$, whereas the spectral efficiency takes values of 39.5, 32.2 and 15.2, the revenue from each basic channel has to be $R_{384} = 0.00625$, 0.010 and 0.070 €/min, respectively, i.e., the prices in the ROA scenario (where the spectral efficiency is clearly the lowest) have to be around one order of magnitude higher than in the BCC scenario. An MBS 'hypothetical price list' was obtained from these results, applications with higher average data rate being the most expensive ones (also depending on their average duration). Different results arise for prices in different scenarios. As it is not foreseen that prices will depend on the deployment scenario, operators will have to compute each application price considering the relative weight of each scenario in the overall system, although the differentiation of prices could also be a possibility.

For the value of the net revenue one is assuming as a goal (150 000 €/km), a choice was done on a value of R that minimises the net cost whilst guaranteeing a given number of supported users per kilometre. In a medium term scenario, if one assumes that the number of foreseen users will be half of the mature MBS number of users, one concludes that they can be supported using cells with $R = 200$ m in the URB and ROA scenarios. However, the foreseen number of users for mature MBS can only be achieved with cells with $R = 100$ m. This solution has the advantage of corresponding to a higher profit (e.g., 72.5 against 53.3 % in the ROA scenario, or 68.4 against 52.1 % in the URB scenario, for one of the hypothesis). In the BCC scenario, however, some limitations exist because one cannot use cells with $R < 175$ m whilst considering $K = 2$, and the foreseen supported users can only be supported by at least three operators together (from the four one is considering).

Results for costs and revenues were also obtained for the irregular urban geometry (i.e., for BCC and URB scenarios), some differences existing, namely in the number of operators (2 instead of 4), and in the re-use pattern ($K = 5$ instead of 2-3).

One concludes the following for irregular geometries:

- In the BCC scenario, R_{384} is higher (associated with the lowest number of channel/cell, 345 against 432, and the lowest number of supported user/km, 97 against 166);
- In the URB scenario, R_{384} is lower (associated with the highest number of channel/cell, 345 against 288, and the highest number of supported user/km, 116 against 87).

Comparing the results for the profit with the ones for the regular urban geometry one concludes that the profit is typically higher in the irregular urban geometry for the BCC scenario (associated with higher values of R_{384}, and the lowest values of the number of resources per cell), and lower in the URB scenario (associated to lower values of R_{384}, and the highest values of the number of resources per cell).

Therefore, the overall conclusions of this thesis are the following. In regular coverage geometries, depending on the frequency band chosen for MBS operation, the 40 and the 60 GHz ones being prospectively allocated by ITU, the frequency re-use pattern will be 2 or 3, the lower value being only possible in the [62, 63] GHz sub-band (or only in a part of it, in the case of the planar regular geometry). In irregular coverage geometries, the minimum frequency re-use pattern is 5, this highest value resulting from the highest complexity of the urban environment, a higher number of cells being also needed to overcome the difficulties in coverage, resulting from urban obstacles. Thus, a higher system capacity can be achieved in regular geometries.

A complete classification of MBS services and applications, their characterisation parameters, and deployment scenarios were used as an input for the tele-traffic analysis, together with the achieved coverage distance, the re-use pattern, the characteristics of the DSA++ MAC protocol, the channel structure, and the characteristics of traffic from mobility. Assuming a balance between the up- and downlinks according to the maximum handover failure probability constraint in the URB and ROA scenarios (and according to the blocking probability in the BCC scenario), one achieved 137 supported user/km in the BCC scenario, 74 user/km in the URB scenario, and 50 user/km in the ROA scenario, for a cell coverage distance of 100 m, and a re-use pattern of 2, 3 and 2, respectively (corresponding to a total spectral efficiency of 39.5, 29.1 and 15.2 %, respectively). This means that MBS will be able to support an up- plus downlink data rate of 346, 168 and 127 Mb/s per operator in the BCC, URB and ROA scenarios (these values were obtained by multiplying the maximum load per user by the number of supported user/km). Thus, one concludes that high terminal mobility strongly degrades system performance. However, one has to remember that the models for the handover failure probability determination over-estimate it, this pessimistic approach being nevertheless acceptable form an engineering point of view. Further research has to be done in order to obtain more accurate results.

Although it is not necessary that future MBS will be based on ATM technology, one considered it, together with assuming the use of the DSA++ MAC protocol, which allows considering connection oriented communications. By allocating a so-called container, formed by a certain number of slots, a BS defines channels like in circuit-switched connections. Thus, the methodologies for circuit-switched network analysis supporting heterogeneous traffic can be applied, while the MAC protocol guarantees that the maximum delay is kept under values that do not affect the performance of applications, namely real-time ones. Following this approach, for non-real time applications, one assumes that a minimum data rate is guaranteed by the system e.g., in ABR (Available Bit Rate) applications, only this minimum being considered in traffic computations. The access to supplementary resources (if needed) is only possible if they are available, but it has not to be taken into account in the computations of the blocking probability, because it does not correspond to the worst-case situation.

From the economic analysis, one concludes that, although there are no optimum values for the profit, as time passes, and the use of MBS evolves, the operator is able to choose different cell coverage distances, in order to support a different number of users, whilst maximising the profit. The profit is higher for higher coverage distances, because few cells are used, and the costs are lower. Whereas in linear geometries (e.g., roads and highways) it will be easy to decrease the cell coverage distance to the half when the user demand increases (installing BSs in between the existing ones), it will not be so easy in urban geometries.

Because of the large demand foreseen for mobile multimedia services and applications, MBS will certainly be necessary, in the context of reconfigurable systems, supporting high data rate applications. Although there still are a lot of uncertainties, there certainly is a lot of work to be done, mainly after the UMTS standard being stable and closed.

7.2. Suggestions for Further Research

The suggestions for further work fall into two main categories. The first category consists of improving the knowledge about the characteristics of services and applications, and of deployment scenarios, owing to the nowadays lack of data for the usage and for the stochastic characterisation of duration of each application, for the respective service components they access to, and for the cost parameters as well. The second category encompasses the validation of some of the proposed models, namely the models for traffic from mobility and for multi-service traffic.

This work was based on the initial study of classification of services and applications, and their characterisation parameters form Chapter 2. However, this first approach is somehow limited by the lack of actual data for the parameters. Hence, further work is needed to fully reach the objective of having actual parameters for tele-traffic modelling, when the data becomes available. By now, one uses the estimations already available, and in some cases, one proposes some values (in order to enable a first approach to the cellular planning of MBS). Besides, actual values for the cost parameters will be used in the future, replacing the values one assumed in Chapter 6.

In the second category of suggestions, there are two aspects of importance. First, in relation to the model for traffic from mobility, one has been seeing that there is a high approximation error in handover failure probability computation in the considered high mobility scenarios, there being the need of improving the accuracy of the model. The generalisation of the analysis of traffic from mobility of Chapter 4 to other geometries, different from the linear coverage one, is also of importance. On the other hand, it is worthwhile to note that some limitations can be identified in the model from Chapter 5, and also in the approach itself. Regarding the model, although it is widely divulged, some kind of validation (in terms of simulation and/or the use of real data, i.e., traces for multimedia, Web applications, …) is needed, namely for the correspondence between service components and applications. In relation to the approach, one has to remind that the values for the parameters were proposed in this thesis, based in the characterisation of applications one has found in literature; hence, some changes can occur when real data becomes available. However, all the aspects of the proposed methodology will remain, and the algorithm will be run with the new values for the parameters. It is also worthwhile to note that, although one considered that the delay is kept under acceptable values using the DSA++ protocol, this assumption has to be properly evaluated for actual implementations of the algorithm.

Besides the main categories for further work mentioned before, one can also refer that, although the coverage and frequency re-use analysis from Chapter 3 was a very complete one indeed, one essential difference can occur in the future: if one considers a different multiple access scheme (e.g., OFDM), different assumptions and methodologies arise, and important changes will occur. Furthermore, regarding the evolution on cell dimensions that resulted from the cost / revenue optimisation from Chapter 6, whereas in linear geometries (e.g., roads and highways) it will be easy to decrease the cell coverage distance to the half when the user demand increases (installing BSs in between the existing ones), it will not be so easy in urban geometries, further work on the optimisation of this evolution being needed. A first step will be to grasp what happens in regular urban geometries when one evolves from a sparse mesh of BSs to a denser one. Finally, the stringency on design requirements associated with cost / revenue analysis shows that it is important to have accurate forecasts for user demand in each phase of MBS evolution, in order to avoid over-dimensioning the system, and thus avoid high investments (without immediate return) in early phases.

Appendix A

Applications - Presentation and Description

A detailed description of each MBS application is given, the references used for it being identified.

Table A.1 – Applications presentation and description.

No.	Application	Description	References
1	Tele-education	Remote learning and training based on audio-visual information.	[ITUT93a]
2	E-commerce	Remote shopping based on audio-visual catalogues allowing the users to choose goods and services and to do electronic payment.	[ITUT93a]
3	Tele-advertising	Interactive publicity based on the exchange of audio-visual information.	[ITUT93a]
4	Building Security	Surveillance of buildings by means of mobile or fixed cameras.	[ITUT93a]
5	Traffic Monitoring	Surveillance of main roads or avenues by means of mobile or fixed cameras. Besides its purpose, it differs from the previous application in data rates (associated to image resolution) and mobility.	[ITUT93a]
6	Mobile Video Surveillance	Application where the task provided is the localisation and communication with the person committed to monitoring the object of surveillance. a) Alarm Detection in Industrial Environment – this application is intended to be useful in industrial environments where men cannot be completely replaced, but their action is occasional and only in response to alarm conditions. The localisation and communication with the person committed to a particular industrial process is the task provided by this application. Multimedia information (video images, audio and data), related to the alarm condition, is transmitted as well as the data necessary to solve the problem that caused the alarm. b) Security Surveillance of Property – the same kind of purpose as before, but in a residential environment. House conditions and video/sound information available to a person while travelling, giving him/her the ability of self-surveillance.	[LoBe94, p. 8]
7	TV Signal Transfer	Transfer of television signals, e.g., from reporters in the field. It may be a life transmission.	[ITUT93a]
8	Video/Audio Dialogue	Conversational communication based on the exchange of audio and video (e.g., between two different studios from the same broadcaster, exchanging TV programmes or advertising material).	[ITUT93a]
9	Mobile HDTV Outside Broadcast	Sports, concerts, and news are of great importance to the broadcasting industry. At present, to produce a programme from, for example, a sports stadium, it requires a large amount of cable rigging to connect many cameras and microphones to the on-site mobile control room. MBS HDTV Outside Broadcast would reduce the cabling to that needed to set up the base stations, while allowing all cameras to have the freedom of wireless operation, not just one of two cameras as at present. Broadcasters, therefore, would like to have a transportable MBS which could be set up quickly as the need arises, or they even also could use the public MBS (e.g. to cover marathons or bicycle races). It is essentially an asymmetric application (e.g., one can use MPEG1 for feedback channel and MPEG2 in the uplink). It may be a life transmission.	[AZDS94, p. 15]
10	Journalist Contribution of Information	Journalists spread over a city or region access to a database where they can store multimedia documents (written articles, scanned images, photos, voice comments and video). The documents are analysed by the editor(s) to compose a newspaper(s) / magazine(s). During the editing process a journalist can be called to provide more information or comment on the proofs he can look at in his terminal.	[ITUT93a], [LoBe94, p. 7]
11	High Quality Voice	Program audio and high quality audio can be provided to users. Program sound allows the transmission of audio signals between 30 Hz and 7 kHz.	[PCMF99]

Table A.1 (cont.) – Applications presentation and description.

No.	Application	Description	References
12	Multi-lingual Commentary Channel	High quality voice providing the translation of speech to different languages.	[ITUT93a]
13	Multiple Programs Channel	A set of high quality voice or high fidelity audio channels (between 20 Hz and 20 kHz) with different programs with a quality up to the offered by compact disks.	[PCMF99]
14	High Speed data Transfer	Transfer of an information sequence of bits without changing its configuration (bit and sequence integrity). This service will have the same capabilities as ISDN bearer services. User rates should be adapted to theses for N-ISDN compatibility. Nevertheless, other alternatives could be used, e.g., packet based 10 Mb/s peak rate for burst transfer of larger objects such as images.	[PCMF99]
15	Wireless LAN Interconnection	Once a business has used a high-definition teleconferencing system based on, e.g., 34 Mb/s video coding, then it is difficult to see how they will be satisfied with anything less. The take up of MBS in business customer premises networks (CPNs), i.e., a combined wireless LAN and a PABX, could be quite rapid as businesses see its advantages over cabled CPNs or lower capacity wireless LANs. The high capacity of MBS will enable to be used in large open-plans offices. A CPN installation can be completely stand-alone, or it can be connected to the fixed IBCN (Integrated Broadband Communications Network).	[AZDS94, p. 13]
16	Transfer of Video Information	Exchange of files with videos.	[ITUT93a]
17	Transfer of Other Information	Exchange of unrestricted data information, other than video.	[ITUT93a]
18	Still Image Transfer	Exchange of files with still images.	[ITUT93a]
19	Multi-rate Interac-tive Computer	Communication with the purpose of using a remote computer via a/the network.	[ITUT93a]
20	Industrial Wireless LAN	Communications needed in the factories, e.g., around a petrol-chemical plant, or airport ancillary services (everything except the air traffic control). The high-quality video capability of MBS will be very useful for remote control of machines in hazardous environments, e.g., a nuclear power plant. Especially if the remote control of one machine is being carried out by another machine that incorporates vision recognition.	[AZDS94, p. 10]
21	CAD/CAM/CAE	Data communications for computer added design/manufacturing/ engineering.	[ITUT93a]
22	Business Communications	a) Banking, Insurance– this application provides the usual credit card and banking card services. In addition, other banking or insurance services, including the personal communication with the office should be provided. b) General– business communications for the mobile user includes high resolution fax transfer (including colour), advanced e-mail transfer (including voice, video, etc.) access to the company LAN, interactive library access, videoconferencing, tele-presence and video-telephony.	[LoBe94, p. 7], [AZDS94, p. 12]
23	Data File Transfer (FTP)	Application with usual ftp (file transfer protocol) functionalities.	[ITUT93a]

Table A.1 (cont.) – Applications presentation and description.

No.	Application	Description	References
24	Tele-software	Usual downloading of executable large files from WWW pages. It allows to obtain software from remote sites via the network.	[ITUT93a]
25	Real Time Control	Remote control applications provide users with the ability to control distant devices by sending and receiving control signals packets. These control signals are then translated so as to be usable by the device. High quality video/audio (MPEG-1 or MPEG-2, possibly multi-channel and/or stereo picture), control information and computer data may be required.	[PCMF99], [ETSI97, p. 21]
26	Telemetry	generally low bit rate services, i.e., 2 kb/s. which typically involve the transport of less than 2 kb per transaction. Transaction services will generally require quick response or confirmation. It may be provided either by a connection oriented or a connectionless network service.	[PCMF99]
27	Alarms	Industrial monitoring is a specific application in industrial environments. Examples are monitoring of oil pipelines or monitoring of production processes and resources like tanks in chemistry plants. Data is typically generated by a sensor. It is very short as well as specific. It has very stringent delay bound and variance. Normally, the bandwidth needed is low. However, in certain circumstances (e.g., fire or explosion) a very bursty and strongly correlated traffic can be generated by hundreds (thousands) of sensors which has to be handled by the network according to the QoS requirements.	[ETSI97, p. 21]
28	Remote Terminal	It is a two-way symmetric transmission, which gives to the user the ability to connect a host computer or another terminal.	[PCMF99]
29	High Speed Tele-fax	Very high-resolution facsimile or the transfer of mixed documents that might include text, facsimile images, voice, annotations and/or video components.	[ITUT93a]
30	Professional Images	Application for the exchange of images, e.g., from an engineering project.	[ITUT93a]
31	Medical Images	Transmission and storage of medical images (e.g. X-ray and MRI-CAT[1] Scan).	[ITUT93a]
32	Remote Games	Computer programs and games for entertainment purposes, which can be played simultaneously by different players over a network.	[ITUT93a]
33	Tele-robotics	Remote control of robots, e.g., in factories or hazardous environments.	[ITUT93a]
34	Web Browsing	It is one of the nowadays most popular multimedia applications, also with large future foreseen acceptance (e.g., Mobile Internet). The Internet has gained prominence far beyond the expectations expressed by experts only a few years ago. Today businesses of all kinds make extensive use of Internet and Intranet as a means to disseminate information about their products and services. Similarly, government institutions are getting ready to put their information on the Net. With the emergence of electronic payment the Net will become a commercial environment as well. For many international organisations the Net has become an indispensable tool. As a consequence users spend hours a day “surfing” the Net to find and exchange information. This information is typically not just text form but includes extensive graphics as well as, in some cases, video and audio sequences.	[ETSI97, p. 19]

[1] MRI-CAT Scan – Magnetic Resonance Imaging – Computerised Axial Tomography Scan.

Table A.1 (cont.) – Applications presentation and description.

No.	Application	Description	References
35	Multimedia Conference	High quality video/audio channels with multiparty data links for the transmission of still images or other types of computer data (normally in large video displays). According to [UMTS96], multimedia services include those in which the interchanged information consists of more than one type (e.g. video, data, voice and graphics). Multimedia services have multi-valued attributes, which distinguish them from traditional telecommunications services such as voice and data. A multimedia service may involve multiple parties, multiple connections, addition/deletion of resources and users within a single communication service.	[ETSI97, p. 18]
36	Interactive Multimedia	Application for co-operative work and also for the exchange of mixed documents but with high level of interactivity.	-
37	Real Time Des-ktop Multimedia	Exchange of real time mixed documents, e.g., with real time image or animations, e.g., for entertainment or advertisement purposes.	-
38	Mobile Emergency Services	At the scene of an accident, the emergency services (Fire, Police, Ambul-ance) could make use of a number of different communications services. The paramedics may need to send high definition video back to a hospital to obtain advice from a doctor (tele-presence), while fire fighters may need to obtain detailed plans of a building using multimedia library access.	[AZDS94, p. 14]
39	Mobile Repair Assistance	Service technicians may be repairing broken-down vehicles at the side of the road or carrying out on-site repairs, e.g., industrial machinery, and photocopiers. Access to a multimedia library would be useful for obtaining up-to-date manuals. The ability to support high definition video allows demonstration films shown on how to carry out the repair. Also, advice can be obtained from a remote expert (tele-presence).	[LoBe95, p.5]
40	Mobile Tele-working	Tele-working is working from home or from anywhere (public transportation, airport waiting rooms), and so it will need the applications outlined in the discussion of business communications. The main advantage of MBS is flexibility; the ability to rapidly set up an employee home for tele-working at a cost that would be less than that of a cabled solution. It may mean working at home but being in contact with colleagues at work and with customers through video/voice/data sessions. It also means collaboration between geographically separated persons, possibly a group of them. Here, too, the ability of telecommunications to deliver high quality video and sound as well as real time data allows users to avoid costly and time-consuming travel. Application developers have caught on to this opportunity. A variety of “screen sharing” tools is being developed that provide users with the means to work together in real time on the same electronic documents while being in eye and ear contact.	[AZDS94, p.13], [ETSI97, p. 19]

Table A.1 (cont.) – Applications presentation and description.

No.	Application	Description	References
41	Freight and Fleet Management	In the transport and distribution business customer requirements will become more demanding (quicker and just in time delivery). Potential customers need better delivery schedule and tariff information. Selecting the best means of transport based on time/quality/cost considerations and the best sequence to place goods into the means of conveyance, there will be pressures to increase the efficiency and reduce the price, and fast communications will play an important role. a) Freight and Logistic Management – Between terminal partners in the transport chain there are shippers, forwarders and carriers taking care of the transport orders. The activities covered by this application are: i) actions related to the planning, forecast of transport demand and transport resources and ii) activities based on status reporting from the vehicle to the fleet operator (expected time of arrival, shipment status in terms of load quality and quantity, confirmed delivery). b) Fleet Management – Here one considers the activities that are performed by the fleet operator, taking into consideration the information provided by all the vehicles. There is a planning stage based on transport order booking, updated road maps and statistical data traffic. A dynamic stage based on fleet monitoring (status of the load and unpredictable traffic situations) is then necessary.	[LoBe94, p. 5]
42	High Speed Trains	A full train contains a large mobile user community with commensurate demands for bandwidth. It poses specific problems for the design due to the potentially high rate of cell switching because of the speed of the train. Possibly, the first high-speed train systems will provide a service to fixed videophones, TVs (for entertainment), and cabled IBCN connection inside the trains. Later, when the air interface to hand-portable equipment is available, wireless connections could also be used internally.	[AZDS94, p. 15]
43	Document Storage System	Conversational transfer of mixed documents, facsimile images, voice, annotation, and/or video components, based on the mixed document service communications service, which provides document servers for the filing, update, and access of documents by a community of users.	[Stal99]
44	Paging	It is a short message service that consists in the one-way transmission of textual messages from a service centre to a mobile user.	[PCMF99]
45	Visual E-mail	Analogous to today's electronic mail (text/graphic mail) – with images attachments.	[Stal99]
46	Audio/Video Mailbox	It replaces the mailing of a video cassette.	[ITUT93a]
47	Electronic Mailbox Service for Voice	It replaces the mailing of an audio cassette. A common feature in today's telephony systems.	[Stal99]
48	Electronic Mailbox Service for Multimedia	It allows the transmission and storage of mixed documents containing text, graphics, voice and/or video components.	[ITUT93a]

Table A.1 (cont.) – Applications presentation and description.

No.	Application	Description	References
49	Videotex Including Moving Pictures and Sound	It is analogous to the Narrowband Videotex service, which is a general-purpose database retrieval system that can use the switched public network or an interactive metropolitan cable TV system. The Narrowband Videotex provider maintains a variety of databases on a central computer. Some of these are public databases provide by the Videotex system. Others are vendor-supplied services, such as stock market advisory. Information is provided in the form of pages of text and simple graphics. Broadband Videotex is an enhancement of this Videotex system. The user would be able to select sound passages, high resolution images of TV standard, and short video scenes, in addition to current text and simplified graphics. Examples of Broadband Videotex applications include the following: • Results of Quality Tests on Consumer Goods • Computer Supported Audio-visual Entries • Electronic Mail-order Catalogues and Travel Brochures (with the option of placing a direct order or making a direct booking) • Retrieve Encyclopaedia Entries	[Stal99]
50	E-newspaper	The newspapers are made available to users on their fixed/mobile terminal equipment. The news can be organised so that users navigate according to their own interests. Special services like personalised journals can be provided on demand for this type of application. It is in the form of short messages, sound or facsimile images of newspaper pages send to subscribers who had paid for the service.	[ITUT93a], [LoBe94, p. 7]
51	Multimedia Library	This application provides the users with access to video, audio and data libraries in the mobile environment. At the same time a user can communicate with others (videoconferencing) while having computer facilities available. Discussion and classes on specialised topics can be provided while users are travelling or just seated in a garden.	[LoBe94, p. 6]
52	Retrieve of Encyclopaedia Entries	It provides access to encyclopaedia entries in the form of a multimedia library.	[LoBe94, p.6]
53	Tourist Information	This application is addressed to tourism and holiday travel. The system would provide information in the form of multimedia documents (video, audio and data) to travellers arriving at a city or country. Special events as well as particular sites could be displayed so that a tourist would be able to choose his own path. Also, access to sophisticated booking/reservation systems would provide up-to-date information about hotels, restaurants and other entertainment places.	[LoBe94, p. 4]
54	MPEG-1 Video Retrieval Service (on demand) for Entertainment Purposes	Communication that allows the user could order full length MPEG-1 films or videos from a film/video library facility for entertainment purposes.	-
55	MPEG-1 Video Retrieval Service (on demand) for Remote Educational and Training Purposes	Communication that allows the user could order full length MPEG-1 pre-filmed lectures from a film/video library facility. It can be different from 54), e.g., in its typical average duration or in the maximum value allowable for BER.	-

Table A.1 (cont.) – Applications presentation and description.

No.	Application	Description	References
56	MPEG-2-4 Video Retrieval Service (on demand) for Entertainment Purposes	Communication that allows the user could order full-length MPEG-2-4 films or videos from a film/video library facility for entertainment purposes.	-
57	MPEG-2-4 Video Retrieval Service (on demand) for Remote Educational and Training Purposes	Communication that allows the user could order full-length MPEG-2-4 pre-filmed lectures from a film/video library facility. It can be different from 56), e.g., in its typical average duration or in the maximum value allowable for BER.	-
58	Video Browsing for Entertainment or Business Purposes	Communication that allows the user could order full length films or videos from a film/video library facility for entertainment or business purposes. Because the provider may have to satisfy many requests, bandwidth considerations dictate that only a small number of video transmissions can be supported at any one time. A realistic service would offer perhaps 500 movies/videos for each two-hour period. Using a 50 Mb/s video channel, this would require a manageable 25 Gb/s transmission capacity from video suppliers to distribution points. The user would be informed by the provider at what time the film will be available to be viewed or transmitted to the subscriber's video recorder.	-
59	High-resolution Image Retrieval Service for Entertainment Purposes	Communication that allows the user could retrieve high-resolution images, e.g., films or documentaries, for entertainment purposes. It is different from 58) be cause it can be a non-real rime application.	[ITUT93a]
60	High-resolution Image Retrieval Service for Remote Educational and Training	Communication that allows the user could retrieve high resolution images, e.g., pre-filmed lectures, for remote education and training. It differs from 59), e.g., in its average duration.	[Stal99, p. 380]
61	High-resolution Image Retrieval Service for Professional Image Communications Training	Communication that allows the user could retrieve professional high resolution images, e.g., photos or engineering projects.	[Stal99, p. 380], [ITUT93a]
62	High-resolution Image Retrieval Service for Medical Image Communications	Communication that allows the user could retrieve high resolution X-ray and magnetic resonance imaging / computerised axial tomography scan images (MRI-CAT).	[Stal99, p. 380], [ITUT93a]
63	Remote Educational and Training Data Retrieval Service	Retrieval of unrestricted data for remote education and training.	-
64	Remote Database Access	This application provides the users with access to unrestricted data libraries. It can be different from 63), e.g., in the values of transmission data rate or typical average duration.	-

Table A.1 (cont.) – Applications presentation and description.

No.	Application	Description	References
65	Large Files Download from a Database	Retrieval of files, e.g., from a site in World Wide Web, via FTP.	-
66	Mixed Media Documents Retrieval	It provides access to files with mixed media documents.	-
67	Remote Procedure Call	Remote execution of computer programs for several purposes.	-
68	Urban Guidance (Public Transport Information)	It is intended to serve both the public transportation company and its users. Multimedia information could be provided to a scheduling centre on the public transport company. A traffic forecasting service could also be included in this application. The user of the public transportation has access to exact timetables of buses or trains as well as alternative routes to reach a specific location (including the estimated vehicle occupation).	[LoBe94, p. 4]
69	Assistance in Travel	a) City Guidance – a person who does not know a city can have assistance to meet a given location through this application, choosing the best path to meet a location and informing him/her the average time it takes to get there. Alternatively he/she can ask for alternative paths with some tourist attractions, and the application has the ability to show some images on them, besides providing him/her with the detailed maps where the location of the car is pointed out. b) Traffic Advice and Road Conditions – this application is intended to provide user-oriented information (data, video and audio comments) about the traffic conditions. A user can decide on the more convenient road to reach a specific destination, get information about parking, traffic flow and traffic forecast.	[LoBe94, p. 5]
70	Distribution of Unrestricted Data	Broadcast of data without any pre-specified format.	[ITUT93a]
71	Distribution of Audio/Video Signals	Broadcast of advertising films, mini-documentaries or any TV or radio programme.	[ITUT93a]
72	TV Programme Distribution	This service provides a continuous flow of information, which is distributed from a central source to an unlimited number of authorised receivers connected to the network. Each user can access this flow of information but has no control over it. In particular, the user cannot control the starting time or order of the presentation of the broadcasted information. All users simply tap into the flow of information.	[ITUT93a]
73	Full Channel Broadcast Videography for Remote Educational and Training Purposes	Cyclical communication of text, graphics, sound and still images with user ability to individually access the cyclical distributed information with cyclical repetition for remote education and training.	[ITUT93a]
74	News Distribution	Application that allows the distribution of news to an audience, including sound (it is different from e-newspaper owing to the possibility of supporting sound).	-
75	In House Information Systems for Trade Fairs, Hotels and Hospitals Cabletext	Enhancement of nowadays teletext to B-ISDN.	[ITUT93a]

Appendix B

Other Types of Classification for Service and Applications

Other possible approaches for the classification of services/applications are presented in order to highlight the advantages of the approach based on the ITU-T Recommendation, which, in a certain way, aggregates the different ways of classification, in conjunction with the respective characterisation parameters.

1) Main Service Classes

The market for UMTS comprises a wide area of applications that can be converted into six main service classes: Speech, Simple Messaging, Switched Data, Medium Multimedia, High Multimedia and High Interactive Multimedia, Table B.1. In a certain way, this classification is equivalent to the one of types of information described before.

The first three classes of services are seen as logical extensions of second generation mobile market, being supported by circuit switching, and the last three are addressing the new mobile UMTS multimedia market, being supported by packet switching, except High Interactive Multimedia, which is also supported by circuit-switching.

Table B.1 – UMTS Main Service Classes [UMTS98].

Service Class	Symmetry	Applications
Speech (16 kb/s)	Asy	• Simple one-to-one and one-to-many voice services (teleconferencing) • Voicemail
Simple Messaging (14 kb/s)	Sym/Asy	• SMS (short message delivery) and paging • E-mail delivery • Broadcast and public information messaging • Ordering/payment (for simple electronic commerce)
Switched Data (14 kb/s)	Asy	• Low speed dial-up LAN access • Internet/Intranet access • Fax
Medium Multimedia (384 kb/s)	Asy	Asymmetric services which tend to be 'bursty' in nature, require moderate data rates, and are characterised by a typical file size of 0.5 Mbytes, with a tolerance to a range of delays. They are classed as packet switched services. • LAN and Intranet/Internet access • Application sharing (collaborative working) • Interactive games • Lottery and betting services • Sophisticated broadcast and public information messaging • Simple online shopping and banking (electronic commerce) services
High Multimedia (2 Mb/s)	Asy	Asymmetric services, which tend to be 'bursty' in nature, require high data rates. These are characterised by a typical file size of 10 Mbytes, with a tolerance to a range of delays. They are classed as packet switched services. Applications include: • Fast LAN and Intranet/Internet access • Video clips on demand • Audio clips on demand • Online shopping
High Interactive Multimedia (128 kb/s)	Sym	Symmetric services which require reasonably continuous and high-speed data rates with a minimum of delay. Applications include: • Videotelephony and Videoconferencing • Collaborative working and tele-presence

* Legacy services – mainly using radio modems such as PCMCIA cards, are not expected to be very significant by 2005.

2) Purpose of Services / Applications

Services on demand will be common in UMTS. High quality entertainment services, down-loading of large files or on-line surfing are possible services in this context. Examples of new or enhanced services and applications are presented in Table B.2, which will be supported by UMTS, classified according to their nature. Some of these mass-market services have already been applied in the fixed network or in GSM, and will be improved with the advent of GSM based High Speed Circuit Switched Data (HSCSD) as well as General Packet Radio Service (GPRS) and even Enhanced Data Rates for GSM Evolution (EDGE). However, UMTS will offer significant improvements both in service provision and delivery performance.

Table B.2 – Purpose of UMTS Services/Applications [UMTS98].

Purpose	Applications
Information	Public information services such as • Browsing the WWW • Interactive shopping • On-line equivalents of printed media • On-line translations • Location based broadcasting services • Intelligent search and filtering facilities
Education	• Virtual school • On-line science labs • On-line library • On-line language labs • Training
Entertainment	• Audio on demand (as an alternative to CDs, tapes or radio) • Games on demand • Video clips • Virtual sightseeing
Community services	• Emergency services • Government procedures
Business information	• Mobile office • Narrowcast business TV • Virtual work-groups
Communication services	Person-to-person services such as • Videotelephony • Videoconferencing • Voice response and recognition • Personal location
Business and financial services	• Virtual banking • On-line billing • Universal SIM-card and Credit card
Road transport telematics	• Toll ticket • Fleet management • Car security

3) Distinction between Business and Residential Services/Applications

Another way of organising the services supported by fixed B-ISDN, instead of the ITU-T I.211 Recommendation, is to group them by their nature, into business and residential categories, as it is presented in Table B.3.

Table B.3 – Nature of B-ISDN Applications [Stal99].

(a) Business	**(b) Residential**
High-speed Image Networking • Design automation (CAD/CAM/CAE) • Medical imaging/consultation • Photographic editing • Scientific visualisation • High-resolution graphics/image rendering Interactive multimedia • Interactive tele-training • Work-at-home/telecommuting • Print/publishing collaboration • Subject-matter-expert consultation • Virtual reality • Multimedia telephony Wide Area Network distributed Computing • LAN backbone/interconnect • Host-to-host channel networking • Disaster recovery/information vaulting • Load sharing	Distribution video • Broadcast TV/HDTV • Broadcast distance learning • Enhanced pay-per-view (near video-on-demand) • Video-on-demand • Video catalogue/advertising • Tele-shopping Interactive Multimedia • Multimedia electronic mail • Multimedia 700, 800 and 900 services • Sports event simulcasting/tele-wagering • Interactive distance learning • Multimedia videotext/”Yellow Pages” • Interactive TV/games • Multimedia telephony and virtual reality

In the business world, the changes in both organisational structure and degree of reliance on high capacity suggest an increasing demand for high-capacity broadband communications. In particular, in many organisations, some or all of the following factors will come into play:

- increasing of use of applications involving high volume of data, including high-resolution graphics and image processing;
- a distributed client/server architecture, with communication across Internet;
- increasing reliance on multiple-LAN, multi-site configuration.

In the residential category, non-business consumers want more advanced telecommunications services that build on their familiarity with telephone and cable TV services. Entertainment and “useful” applications, at the right price, will dominate this market.

Appendix C

Main Characteristics

The main characteristics of interactive services are presented (for conversational, message and retrieval services, respectively), as well as of distribution services (for broadcast and cyclical services, respectively). The cases of lack of data are identified by blank spaces. In the column for the asymmetry of connections, UL and DL refer to up- and downlink, respectively. These values correspond to main characteristics parameters of the applications defined in Tables 2.7-2.11. Its detailed description was presented in Section 2.2.1.

Table C.1 – Main Characteristics of Interactive Services – Conversational.

Type of Information	Examples of Broadband Services	Applications	Intrinsic time dependency	Delivery requirements	Symmetry of connections	Directionality	Interactivity	Number of parties
Moving Pictures and Sound	Broadband Videotelephony - High definition	1) Tele-education 2) E-commerce 3) Tele-advertising			Sym/Asy	Bid		One-to-one
	Broadband VideoConference	1) Tele-education 2) E-commerce 3) Tele-advertising			Sym/Asy **1UL-3DL** [ETSI97]	Bid		Multi-party
	ISDN-Videoconference	1) Tele-education 2) E-commerce 3) Tele-advertising	TB	RT	Sym/Asy	Bid	Yes	Multi-party
	Video Surveillance	4) Building Security 5) Traffic Monitoring 6) Mobile Video Surveillance			Asy **5UL-1E3DL** [UMTS98] **1UL-10DL** [ETSI97]	Und or Bid		One-to-one
	Video/audio Information Transmission Service	7) TV Signal Transfer 8) Video/Audio Dialogue 9) Mobile HDTV Outside Broadcast 10) Journalist Contribution of Information			Asy **5UL-1E3DL** Asy **4UL-1DL** **5UL-1E3DL**	Bid		One-to-one
Sound	Multiple Sound Programme Signals	11) High Quality Voice 12) Multi-lingual Commentary Channel 13) Multiple Programs Channel	TB	RT	Sym [UMTS98]	Bid	Yes	One-to-one
Data	High-speed Unrestricted Information Transmission Service	14) High Speed Data Transfer - LAN Interconnection - MAN Interconnection - Computer-computer interconnection 15) Wireless LAN Interconnection 16) Transfer of Video Information 17) Transfer of Other Information Types 18) Still Image Transfer 19) Multi-rate Interactive Computer 20) Industrial Wireless LAN 21) CAD/CAM/CAE 22) Business Communications	NTB TB NTB	NRT/RT	Asy **the ratio varies from case to case**	Bid	Yes	One-to-one

Table C.1 (cont.) – Main Characteristics of Interactive Services – Conversational.

Type of Information	Examples of Broadband Services	Applications	Intrinsic time dependency	Delivery requirements	Symmetry of connections	Directionality	Interactivity	Number of parties
Data	High Volume File Transfer Service - FTP	23) Data File Transfer (ftp) 24) Program Downloading	NTB	RT	Asy [Kwok97] **4-10UL – 100DL**	Bid	Yes	One-to-one
	High-speed Tele-action	25) Real Time Control 26) Telemetry 27) Alarms 28) Remote Terminal	TB	RT	Asy **the ratio varies from case to case**	Bid	Yes	One-to-one
Document (multimedia)	High-speed Tele-fax	29) User-to-user Transfer of Text, Images, Drawing, etc.	TB	NRT	Sym [UMTS98]	Bid	Yes	One-to-one
	High Resolution Image Communication Service	30) Professional Images 31) Medical Images 32) Remote Games (network) 33) Tele-robotics	TB/ NTB	RT	Asy **26UL – 1000DL** [UMTS98]			
	Mixed Document Communications Service	34) Desktop Multimedia (e.g. Web browsing) 35) Multimedia Conferencing 36) Interactive Multimedia 37) *Real time* Desktop Multimedia 38) Document Storage System	TB	RT	Asy **3-10UL – 100DL** [ETSI97] **1UL-5DL** [Kwok97]			
		39) Mobile Emergency Services 40) Mobile Repair Assistance 41) Mobile Tele-working 42) Freight and Fleet Management 43) High speed Trains			Sym			

Table C.2 – Main Characteristics of Interactive Services – Messaging.

Type of Information	Examples of Broadband Services	Applications	Intrinsic time dependency	Delivery requirements	Symmetry of connections	Directionality	Interactivity	Number of parties
Data	Electronic Mail/Paging	44) Paging 45) Visual E-mail (with attachments …)	NTB	RT	Asy **4-10UL – 100DL** [Kwok97]	Bid	Yes	One-to-one
Moving Pictures (video) and Sound	Video/image Mail	46) Audio / Video Mailbox	TB	NRT				
Voice (sound)	Voice Mail	47) Electronic Mailbox Service for Voice	TB	NRT				
Mixed Document	Multimedia Mail	48) Electronic Mailbox Service for Multimedia	TB	NRT	Asy			

Table C.3 – Main Characteristics of Interactive Services – Retrieval.

Type of Information	Examples of Broadband Services	Applications	Intrinsic time dependency	Delivery requirements	Symmetry of connections	Directionality	Interactivity	Number of parties
Text, Data, Graphics, Sound, Still Image, Moving Pictures	Broadband Videotex	49) Videotex Including Moving Pictures 1) Tele-education	TB	RT	Asy **5UL-1E3DL** [UMTS98]	Bid .	Yes	One-to-many
		24) Tele-software	NTB					
		2) E-commerce 3) Tele-advertising 50) News Retrieval 51) Multimedia Library 52) Retrieve of Encyclopaedia Entries	TB					
		53) Tourist Information	NTB					
	Video Retrieval Service On Demand (MPEG1)	54) Entertainment Purpose 55) Remote Educational and Training	TB	RT / NRT (for file download)				
	Video Retrieval Service On Demand (MPEG2-4)	56) Entertainment Purpose 57) Remote Educational and Training	TB					
	Video Browsing	58) Entertainment or Business Purposes	TB	RT				
	High-resolution Image Retrieval Service	59) Entertainment Purposes 60) Remote Educational and Training 61) Professional Image Communications 62) Medical Image Communications	NTB	NRT / RT				
	Data Retrieval Service	24) Tele-software 63) Remote Educational and Training 64) Remote Database Access 65) Large File Download 66) Mixed Media Documents 67) Remote Procedure Call	NTB	NRT/ RT	Asy **4-10UL-100DL** [Kwok97]			
	Multimedia Retrieval Service	68) Urban Guidance-Public Trans. Inf. 69) Assistance in Travel (Vehicular)	TB	NRT/RT	Asy **5UL-1E3DL** [UMTS98]			

Table C.4 – Main Characteristics of Distribution Services – Broadcast.

Type of Information	Exs. of Broadband Servs.	Applications	Intrinsic time dependency	Delivery requirements	Symmetry of connections	Directionality	Interactivity	Number of parties
Data	High-speed Unrestricted Digital Information Distribution Services	70) Distribution of Unrestricted Data	NTB	NRT	–	Und	No	One-to-many
Text, graphics, still images	Document Distribution Service	50) Electronic Newspaper 10) Electronic Publishing	NTB	NRT				
Moving pictures and sound	Broadband Video Information Distribution Service	71) Distribution of Video/audio Signals	TB	RT				
Video	Existing Quality TV Distribution Service (NTSC, PAL, SECAM)	72) TV Programme Distribution	TB	RT				
	Extended Quality TV Distribution Service (enhanced and high quality TV distribution)	72) TV Programme Distribution	TB	RT				
	HDTV Service (non-MPEG)	72) TV Programme Distribution	TB	RT				
	MPEG2-4 Service	72) TV Programme Distribution	TB	RT				
	Pay TV (pay-per-view, pay-per-channel)	72) TV Programme Distribution	TB	RT				

Table C.5 – Main Characteristics of Distribution Services – Cyclical.

Type of Information	Exs. of Broadband Servs.	Applications	Intrinsic time dependency	Delivery requirements	Symmetry of connections	Directionality	Interactivity	Number of parties
Text, Graphics, Sound, Still images	Full Channel Broadcast Videography	73) Remote Educational and Training 3) Tele-advertising 74) News Distribution 24) Tele-software 50) E-newspaper	TB NTB TB	NRT	Asy **0.005UL-1DL** [UMTS98]	Und **commands in the reverse channel**	Yes	One-to-many
	Cabletext (timely and frequently requested information)	50) E-newspaper 75) In House Information Systems for Trade Fairs, Hotels and Hospitals	NTB TB/NTB	NRT (low delay)				

Appendix D

Traffic Characteristics

Traffic characteristics of interactive services are presented (for conversational, message and retrieval services, respectively), as well as of distribution services (for broadcast and cyclical services, respectively). The cases of lack of data are identified by blank spaces. These values correspond to traffic characteristics parameters of the applications defined in Tables 2.7-2.11. Its detailed description was presented in Section 2.3.

Table D.1 – Traffic Characteristics of Interactive Services – Conversational.

Type of Information	Examples of Broadband Services	Applications	Average Duration	Transmission Rate	Latency/ delay
Moving Pictures and Sound	Broadband Videotele-phony - High definition	1) Tele-education 2) E-commerce 3) Tele-advertising	**3 min** [SDD]-[MBS94]	**64 kb/s- 2 Mb/s** [PCMF99] weaker than videoconference	**200 ms** [ACCORD]
	Broadband VideoConfe-rence	1) Tele-education 2) E-commerce 3) Tele-advertising	**30-45 min** usual duration for a business meeting	**2-8 Mb/s** with MPEG2 **14 Mb/s** [Stal99] UL **0.75 Mb/s** DL **2.25 Mb/s** [ETSI97]	**200 ms**
	ISDN-Videoconference	1) Tele-education 2) E-commerce 3) Tele-advertising	**30-45 min** usual duration for a business meeting	**(*k*·64) kb/s,** *k*=1. . 30 H.261,H.263 (mobile commns) [PCMF99] **> 384 kb/s** [Stal99]	**200 ms** [ACCORD]
	Video Surveillance	4) Building Security 5) Traffic Monitoring 1/2 day of work of a policeman → 6) Mobile Video Surveillance	**Several hours** **3-4 h** **120 min** [RoSc94]	UL **0.75 Mb/s** DL **6.4 kb/s** [ETSI97] **2 Mb/s** [PCMF99] **14 Mb/s** [RoSc97] **0.75-2.25 Mb/s** video multi-point monitoring	**200 ms**
	Video/audio Information Transmission Service	7) TV Signal Transfer 8) Video/Audio Dialogue 9) Mobile HDTV Outside Broadcast 10) Contribution of Information	**50 min** [RoSc94]	**2-10 Mb/s** with MPEG2 **Up to 34 Mb/s** without MPEG2 [PCMF99] UL **0.75 Mb/s** DL **2.25 Mb/s** [ETSI97]	**500 ms**
Sound	Multiple Sound Program-me signals	11) High Quality Voice 12) Multi-lingual Commentary Channel 13) Multiple Programmes Channel		High quality voice **128 kb/s or 3.07 Mbit/s (8 channels)** [PCMF99] Hi-fi Stereo **384 kb/s** [HIPERLAN] **940 kb/s-1.5 Mb/s** [Stal99]	**< 500 ms** [ACCORD] – not telephony
Data	High-speed Unrestricted Information Transmission Service	14) High Speed Data Transfer			**1 s** [ACCORD] [PCMF99]
		- LAN Interconnection	**15 min** [SDD]	**1.5-100 Mb/s** [Stal99]	
		- MAN Interconnection			
		- Computer-computer interconnection		**64 kb/s-1.5 Mb/s** [Stal99]	
		15) Wireless LAN Interconnection	**15 min** [RoSc94,Vele99]	**128kb/s-155 Mb/s**	
		16) Transfer of Video Information 17) Transfer of Other Information Types 18) Still image Transfer 19) Multi-rate Interactive Computer 20) Industrial Wireless LAN 21) CAD/CAM/CAE		**25 Mb/s** [ETSI97]	
		22) Business Communications	**15 min** [RoSc94]	**1.5-100 Mb/s** [Stal99]	

Table D.1 (cont.) – Traffic Characteristics of Interactive Services – Conversational.

Type of Information	Examples of Broadband Services	Applications	Average Duration	Transmission Rate	Latency/ delay
Data	High Volume File Transfer Service FTP	23) Data file Transfer (ftp) 24) Program Downloading	Few seconds	**64 kb/s-1.5 Mb/s** [Stal99] **2 Mb/s** [ETSI97]	**1 s** [PCMF99]
	High-speed Tele-action	25) Real Time Control 26) Telemetry 27) Alarms 28) Remote Terminal		**21 Mb/s** Up/down [ETSI97] **2 kb/s** **20 kb/s** up/down	**1 s** [PCMF99]
Document (multimedia)	High-speed Tele-fax	29) User-to-user Transfer of Text, Images, Drawing, etc.	**20 s** [Onvu94]	**64 kb/s**	**~5 s** [Stal99]
	High Resolution Image Communication Service	30) Professional Images 31) Medical Images 32) Remote Games (network) 33) Tele-robotics	**6-10 min** [Onvu94] **20 min** [RoSc94]	**10 Mb/s** **1.5-10 Mb/s / 10-100 Mb/s** [Stal99]	**1 s**
	Mixed Document Communications Service	34) Desktop Multimedia 35) Multimedia Conferencing 36) Interactive Multimedia 37) *Real Time* Desktop Multimedia 38) Document Storage System	**1-10 min** [UMTS98]	UL **2.4** DL **100 kb/s** **1-2 Mb/s** [Stal99]	*Not real time*
		39) Mobile Emergency Services	**20-45 min** [CaBr98]	**2-8 Mb/s** [AZDS94]	**200 ms** [PCMF99]
		40) Mobile Repair Assistance	**20-40 min**	**2-8 Mb/s** [AZDS94]	**200 ms** [PCMF99]
		41) Mobile Tele-working	**15-20 min**	**2-8 Mb/s** [AZDS94]	**500 ms** [PCMF99]
		42) Freight and fleet management	**2-5 min**	**2-8 Mb/s** [AZDS94] or UL**100**-DL**500 kb/s**	**200 ms** [PCMF99] like videotelephony
		43) High speed trains			

Table D.2 – Traffic Characteristics of Interactive Services – Messaging.

Type of Information	Examples of Broadband Services	Applications	Average Duration	Transmission Rate	Latency/ delay
Data	Electronic Mail/Paging	44) Paging 45) Visual E-mail (with attachments …)	**0.1-3 min** (data)	**9.6 kb/s-1.5 Mb/s** [Stal99] **50 kb/s** [ETSI97]	**5 mn** [PCMF99]
Moving Pictures (video) and Sound	Video/image Mail	46) Audio / Video Mailbox		**1-4 Mb/s**	**5 mn** with a cell delay tolerance of 1-5 s
Voice (sound)	Voice Mail	47) Electronic Mailbox Service for Voice		**16-64 kb/s** [Stal99]	**5 mn**
Mixed Document	Multimedia Mail	48) Electronic Mailbox Service for Multimedia		**1-4 Mb/s**	**5mn** with a cell delay tolerance of 1-5 s

Table D.3 – Traffic Characteristics of Interactive Services – Retrieval.

Type of Information	Examples of Broadband Services	Applications	Average Duration	Transmission Rate	Latency/ delay
Text, Data, Graphics, Sound, Still Image, Moving Pictures	Broadband Videotex	49) Videotex Including Moving Pictures 1) Tele-education 24) Tele-software 2) E-commerce 3) Tele-advertising 50) News Retrieval 51) Multimedia Library	-	**64 kb/s-10 Mb/s** [Stal99]	**500 ms** [PCMF99]
		52) Retrieve of Encyclopaedia Entries	**20 min** [RoSC94]		
		53) Tourist Information	**15 min** [RoSC94]		
	Video Retrieval Service – on demand (MPEG1)	54) Entertainment Purpose 55) Remote Educational and Training	**8-15 min** [Onvu94]	**1-2 Mb/s** [PCMF99]-[Kwok95]	**500 ms** [PCMF99] Much higher if it consists on a file download
	Video Retrieval Service - on demand (MPEG2-4)	56) Entertainment Purpose 57) Remote Educational and Training	**10-20 min** [Onvu94]	**4- 10 Mb/s** [PCMF99], [Gall91]	
	Video Browsing	58) Entertainment or Business Purposes	**3-5 min** [UMTS98]	**2-40 Mb/s** [Stal99]	**500 ms** [PCMF99]
	High-Resolution Image Retrieval Service	59) Entertainment Purposes 60) Remote Educational and Training 61) Professional Image Communications 62) Medical Image Communications	**3-5 min** [UMTS5] High multimedia	**100 Mb/s-10 Gb/s**	**500 ms** [PCMF99]
	Data Retrieval Service	24) Tele-software 63) Remote Educational and Training 64) Remote Database Access 65) Large File Download 66) Mixed Media Document 67) Remote Procedure Call		**<10 Mb/s** (burst transfer of large files, e.g. with image) [PCMF99] **64 kb/s** [PCMF99] **1.5-2 Mb/s** [Stal99] **400 kb/s** [ETSI97]	**500 ms**
	Multimedia Retrieval Service	68) Urban Guidance-Public Trans. Inf.	**5-10 min**	**2-4 Mb/s** [AZDS94], [Vele99]	**500 ms**
		69) Assistance in Travel (Vehicular)	**20min-3h** [RoSC94]		

Table D.4 – Traffic Characteristics of Distribution Services – Broadcast.

Type of Information	Exs. of Broadband Servs.	Applications	Average Duration	Transmission Rate	Latency/ delay
Data	High-speed Unrestricted Digital Information Distribution Services	70) Distribution of Unrestricted Data		**1-150 Mb/s** [Stal99]	**1 s** [PCMF94]
Text, graphics, still images	Document Distribution Service	50) Electronic Newspaper 10) Electronic Publishing	**20 min** [RoSc94]	**1-10 Mb/s** [Stal99]	**500 ms** [PCMF94]
Moving pictures and sound	Broadband Video Information Distribution Service	71) Distribution of Video/audio Signals		**2-40 Mb/s** [Stal99]	**500 ms** [PCMF94]
Video	Existing Quality TV Distribution Service (NTSC, PAL, SECAM)	72) TV Programme Distribution	**30-90 min**	With compression **3-10 Mb/s** Without compression **15-44 Mb/s**	**~100 ms** (for old standards)
	Extended Quality TV Distribution Service (enhanced and high quality TV distribution)	72) TV Programme Distribution	**30-90 min**	**> 15 Mb/s** [Stal99]	**500 ms**
	HDTV Service (non-MPEG)	72) TV Programme Distribution	**30-90 min**	**~20 Mb/s** [Peta96]	**500 ms**
	MPEG2-4 Service	72) TV Programme Distribution	**30-90 min**	**2-10 Mb/s** [PCMF94]	**500 ms**
	Pay TV (pay-per-view, pay-per-channel)	72) TV Programme Distribution	**30-90 min**	**3-40 Mb/s** [PCMF94]	**100 –500 ms** (100 ms for old standards)

Table D.5 – Traffic Characteristics of Distribution Services – Cyclical.

Type of Information	Exs. of Broadband Servs.	Applications	Average Duration	Transmission Rate	Latency/ delay
Text, Graphics, Sound, Still images	Full Channel Broadcast Videography	73) Remote Educational and Training 3) Tele-advertising 74) News Distribution 24) Tele-software 50) E-newspaper	**20 min** [RoSc94] multimedia library	**2-34 Mb/s**	**500 ms** (video)
	Cabletext (timely and frequently requested information)	50) E-newspaper 75) In House Information Systems for Trade Fairs, Hotels and Hospitals		**2-34 Mb/s**	**500 ms** (video)

Appendix E

Communications Characteristics

The communications characteristics of interactive services are presented (for conversational, message and retrieval services, respectively), as well as of distribution services (for broadcast and cyclical services, respectively). The cases of lack of data are identified by blank spaces. These values correspond to communications characteristics parameters of the applications defined in Tables 2.7-2.11. Its detailed description is presented in Section 2.3.

Table E.1 – Communications Characteristics of Interactive Services – Conversational.

Type of Information	Examples of Broadband Services	Applications	Burstiness	Service class	BER
Moving Pictures and Sound	Broadband Videotele-phony - High definition	1) Tele-education 2) E-commerce 3) Tele-advertising	**1-5** [HäAS95]	**ISO& CBR/RT-VBR** [Stal99]	**10^{-6}** [PCMF94]
	Broadband VideoConfe-rence	1) Tele-education 2) E-commerce 3) Tele-advertising			
	ISDN-Videoconference	1) Tele-education 2) E-commerce 3) Tele-advertising			
	Video Surveillance	4) Building Security 5) Traffic Monitoring 6) Mobile Video Surveillance			
	Video/Audio Information Transmission Service	7) TV Signal Transfer 8) Video/Audio Dialogue 9) Mobile HDTV Outside Broadcast 10) Journalist Contribution of Information	**1** [HäAS95]	**ISO & CBR** [PCMF94]	**10^{-10}-10^{-9}** [PCMF94]
Sound	Multiple Sound Program-me Signals	11) High Quality Voice 12) Multi-lingual Commentary Channel 13) Multiple Programs Channel	**1** [Onvu94]	**ISO&CBR** [Stal99]	**10^{-6}** [PCMF94] **10^{-4}** – High quality voice
Data	High-speed Unrestricted Information Transmission Service	14) High speed Data Transfer - LAN Interconnection - MAN Interconnection - Computer-computer interconnection 15) Wireless LAN Interconnection 16) Transfer of Video Information 17) Transfer of Other Information Types 18) Still Image Transfer 19) Multi-rate Interactive Computer 20) Industrial Wireless LAN 21) CAD/CAM/CAE 22) Business Communications	**1-50**	**NISO & UBR**	**10^{-6}** [PCMF94]

Table E.1 (cont.) – Communications Characteristics of Interactive Services – Conversational.

Type of Information	Examples of Broadband Services	Applications	Burstiness	Service class	BER
Data	High Volume File Transfer Service FTP	23) Data File Transfer (ftp) 24) Tele-software	**1-50**	**NISO & UBR**	**10^{-6}** [PCMF94]
	High-speed Tele-action	25) Real Time Control 26) Telemetry 27) Alarms 28) Remote Terminal	**1-50**	**NISO & UBR**	**10^{-6}** [PCMF94]
Document (multimedia)	High-speed Tele-fax	29) User-to-user Transfer of Text, Images, Drawing, etc.	**1** [Onvu 94]	**ISO&CBR**	**10^{-6}**
	High Resolution Image Communication Service	30) Professional Images 31) Medical Images 32) Remote Games (network) 33) Tele-robotics	**1-20** [HäAS95]	**ISO & CBR(VBR)**	**10^{-7}-10^{-6}** [PCMF94]
	Mixed Document Communications Service	34) Desktop Multimedia	**1-20** [HäAS95]	**ISO&RT-VBR**	**10^{-6}** [PCMF94]
		35) Multimedia Conferencing 36) Interactive Multimedia 37) *Real Time* Desktop Multimedia		**ISO & RT-VBR**	
		38) Document Storage System			
		39) Mobile Emergency Services	**1-5** [HäAS95]	**ISO&CBR(VBR)**	**10^{-6}** [PCMF94]
		40) Mobile Repair Assistance	**1-5** [HäAS95]	**ISO&CBR(VBR)**	
		41) Mobile Tele-working	**1-20** [HäAS95]	**ISO&CBR(VBR)**	
		42) Freight and Fleet Management	**1- 5** [HäAS95]	**ISO&CBR(VBR)**	
		43) High Speed Trains			

Table E.2 – Communications Characteristics of Interactive Services – Messaging.

Type of Information	Examples of Broadband Services	Applications	Burstiness	Service class	BER
Data	Electronic Mail/Paging	44) Paging 45) Visual E-mail (with attachments …)	**1**	**NISO & UBR**	**10^{-6}-10^{-4}**
Moving Pictures (video) and Sound	Video/image Mail	46) Audio/Video Mailbox	**1-20** [HäAS95]	**NISO & UBR** [PCMF94]	**10^{-6}** [PCMF94]
Voice (sound)	Voice Mail	47) Electronic Mailbox Service for Voice	**1**	**ISO&CBR** [PCMF94]	**10^{-6}** [PCMF94]
Mixed Document	Multimedia Mail	48) Electronic Mailbox Service for Multimedia	**1-20** [HäAS95]	**NISO&UBR**	**10^{-6}** [PCMF94]

Table E.3 – Communications Characteristics of Interactive Services – Retrieval.

Type of Information	Examples of Broadband Services	Applications	Burstiness	Service class	BER
Text, Data, Graphics, Sound, Still Image, Moving Pictures	Broadband Videotex	49) Videotex Including Moving Pictures 1) Tele-education 24) Tele-software 2) E-commerce 3) Tele-advertising 50) News Retrieval 51) Multimedia Library 52) Retrieve of Encyclopaedia Entries 53) Tourist Information	**1-20** [Stal99]	**ISO&RT-VBR** [HäAS95]	**10^{-6}**
	Video Retrieval Service On demand (MPEG1)	54) Entertainment Purpose 55) Remote Educational and Training	**1** [PCMF94]	**ISO&CBR** [PCMF94] ABR for file download	**10^{-10}-10^{-9}**
	Video Retrieval Service On demand (MPEG2-4)	56) Entertainment Purpose 57) Remote Educational and Training			
	Video Browsing	58) Entertainment or Business Purposes	**1-20** [HäAS95]	**NISO & UBR**	
	High-resolution Image Retrieval Service	59) Entertainment Purposes 60) Remote Educational and Training 61) Professional Image Communications 62) Medical Image Communications	**1-20**	**NISO&UBR**	**10^{-6}-10^{-4}** [PCMF94]
	Data Retrieval Service	24) Tele-software 63) Remote Educational and Training 64) Remote Database Access 65) Large File Download 66) Mixed media Documents 67) Remote Procedure Call	**1-50**	**NISO&ABR**	**10^{-6}-10^{-4}** [PCMF94]
	Multimedia Retrieval Service	68) Urban Guidance-Public Trans. Inf. 69) Assistance in Travel (Vehicular)	**1-5** [PCMF94]	**ISO&CBR/ RT-VBR**	**10^{-6}** [PCMF94]

Table E.4 – Communications Characteristics of Distribution Services – Broadcast.

Type of Information	Examples of Broadband Services	Applications	Burstiness	Service class	BER
Data	High-speed Unrestricted Digital Information Distribution Services	70) Distribution of Unrestricted Data	**1-50** [HäAS95]	**NISO&A/ UBR**	**10^{-6}**
Text, graphics, still images	Document Distribution Service	50) Electronic Newspaper 10) Electronic Publishing	**1-20** [HäAS95]	**NISO&UBR**	
Moving pictures and sound	Broadband Video Information Distribution Service	71) Distribution of Video/audio Signals	**1** [HäAS95]	**ISO&CBR**	**10^{-6}**
Video	Existing Quality TV Distribution Service (NTSC, PAL, SECAM)	72) TV Programme Distribution	**1** [HäAS95]	**ISO&CBR**	**10^{-10}-10^{-9}** [PCMF94]
	Extended Quality TV Distribution Service (enhanced and high quality TV distribution)	72) TV Programme Distribution			**10^{-10}-10^{-9}** [PCMF94]
	HDTV Service (non-MPEG)	72) TV Programme Distribution			**10^{-6}** [PCMF94]
	MPEG2-4 Service	72) TV Programme Distribution			**10^{-6}** [PCMF94]
	Pay TV (pay-per-view, pay-per-channel)	72) TV Programme Distribution			**10^{-9}** [PCMF94]

Table E.5 – Communications Characteristics of Distribution Services – Cyclical.

Type of Information	Exs. of Broadband Servs.	Applications	Burstiness	Service class	BER
Text, Graphics, Sound, Still images	Full Channel Broadcast Videography	73) Remote Educational and Training 3) Tele-advertising 74) News Distribution 24) Tele-software 50) E-newspaper	**1**	**ISO & CBR**	**10^{-6}**
	Cabletext (timely and frequently requested information)	50) E-newspaper 75) In House Information Systems for Trade Fairs, Hotels and Hospitals			

Appendix F

Operation Environments

The operation environments of interactive services are presented (for conversational, message and retrieval services, respectively), as well as of distribution services (for broadcast and cyclical services, respectively). The cases of lack of data are identified by blank spaces. Note that the mobility scenario is identified by ‘All’ when the applications can be supported in all of them, i.e., ST, PD, UB, MR and HW. These values correspond to the operation environments parameters of the applications defined in Tables 2.7-2.11. Its detailed description is presented in Section 2.3, and in Section 2.5 as well, for the details concerning the deployment scenarios.

Table F.1 – Operation Environments for Interactive Services – Conversational.

Type of Information	Examples of Broadband Services	Applications	Frame-work	Nature	Environment	Mobility scenario	Service Provision	Deployment Scenarios
Moving Pictures and Sound	Broadband Videotele-phony - High definition	1) Tele-education 2) E-commerce 3) Tele-advertising	BCC, URB, ROA, COM, transports, **EMER-GENCY**	BUS/ FAM	Ind, Outd, TRA	All	PUB	All
	Broadband VideoConfe-rence	1) Tele-education 2) E-commerce 3) Tele-advertising		BUS/ FAM	Ind, Outd, TRA	ST/HW	PUB	TRA, COM, OFF, IND
	ISDN-Videoconference	1) Tele-education 2) E-commerce 3) Tele-advertising		BUS/ FAM	Ind, Outd, TRA	ST/HW	PUB	All
	Video Surveillance	4) Building Security	BCC, URB, ROA COM transports, **TV, OFF, IND**	BUS	Ind, Outd	ST	PUB/ PRIV	All
		5) Traffic Monitoring				ST		BCC,URB, ROA, TRA
		6) Mobile Video Surveillance				All		All
	Video/Audio Information Transmission Service	7) TV Signal Transfer	BCC, URB, ROA COM transports, **TV**	BUS	Ind	ST	PUB/ PRIV	ROA, TRA, COM, OFF, IND, HOM
		8) Video/Audio Dialogue			Ind	ST		
		9) Mobile HDTV Outside Broadcast			Ind, Outd	All		All
		10) Journalist Contribution of Information			Ind	ST		
Sound	Multiple Sound Program-me Signals	11) High Quality Voice 12) Multi-lingual Commentary Channel 13) Multiple Programs Channel	BCC, URB, ROA, COM, transports, **TV, OFF, IND**	BUS/ FAM	Ind, Outd, TRA	All	PUB	All
Data	High-speed Unrestricted Information Transmission Service	14) High Speed Data Transfer			Ind, Outd, TRA			
		- LAN Interconnection - MAN Interconnection - Computer-computer interconnection	COM, **OFF, IND,** transports	BUS		ST	PUB/ PRIV	TRA, COM, OFF, IND
		15) Wireless LAN Interconnection				ST,UB,MR,HW		All
		16) Transfer of Video Information 17) Transfer of Other Information Types 18) Still Image Transfer 19) Multi-rate Interactive Computer	BCC, URB, ROA, COM, transports, **OFF, TV**	BUS/ FAM		All		All
		20) Industrial Wireless LAN	**OFF, Industry**				PRIV	OFF, IND
		21) CAD/CAM/CAE	**OFF, IND, COM**	BUS		ST	PUB/ PRIV	COM, OFF, IND
		22) Business Communications	BCC, COM, transp, **OFF**				PRIV	TRA, COM, OFF, IND

Table F.1 (cont.) – Operation Environments for Interactive Services – Conversational.

<table>
<tr><th>Type of Information</th><th>Examples of Broadband Services</th><th>Applications</th><th>Frame-work</th><th>Nature</th><th>Environment</th><th>Mobility scenario</th><th>Service Provision</th><th>Deployment Scenarios</th></tr>
<tr><td rowspan="5">Data</td><td rowspan="2">High Volume File Transfer Service FTP</td><td rowspan="2">23) Data File Transfer (ftp)
24) Tele-software</td><td rowspan="2">Transports, TV, OFF, IND</td><td rowspan="2">BUS/ FAM</td><td rowspan="2">Outd (transp), Ind, TRA</td><td rowspan="2">All</td><td rowspan="2">PUB/ PRIV</td><td>All</td></tr>
<tr><td>TRA, COM, OFF, IND, HOM</td></tr>
<tr><td rowspan="3">High-speed Tele-action</td><td rowspan="3">25) Real Time Control
26) Telemetry
27) Alarms
28) Remote Terminal</td><td>COM, OFF, IND</td><td rowspan="3">BUS</td><td rowspan="3">Ind, Outd</td><td rowspan="3">ST</td><td rowspan="3">PRIV</td><td>COM, OFF, IND, HOM</td></tr>
<tr><td>IND, transp</td><td>TRA, IND</td></tr>
<tr><td>COM, OFF, IND</td><td>COM, OFF, IND, HOM</td></tr>
<tr><td rowspan="11">Document (multimedia)</td><td>High-speed Tele-fax</td><td>29) User-to-user Transfer of Text, Images, Drawing, etc.</td><td>BCC, URB, ROA, COM, transps., EMERG., TV, OFF, IND</td><td>BUS/ FAM</td><td>Ind, Outd</td><td>All</td><td>PUB/ PRIV</td><td>All</td></tr>
<tr><td rowspan="4">High Resolution Image Communication Service</td><td rowspan="4">30) Professional Images
31) Medical Images
32) Remote Games (network)
33) Tele-robotics</td><td>BCC, URB, COM, ROA, transps, TV, OFF, IND.</td><td>BUS</td><td>Ind, Outd</td><td rowspan="4">All</td><td rowspan="4">PUB/ PRIV</td><td>All</td></tr>
<tr><td>EMER-GENCY</td><td>BUS/ FAM</td><td>Ind</td><td>BCC, URB, ROA, COM</td></tr>
<tr><td>BCC, URB, COM, ROA, transports</td><td>BUS/ FAM</td><td>Outd</td><td>All</td></tr>
<tr><td>COM, TV/IND</td><td>BUS</td><td>Ind, Outd</td><td>COM, OFF, IND</td></tr>
<tr><td rowspan="6">Mixed Document Com-munications Service</td><td rowspan="6">34) Desktop Multimedia
35) Multimedia Conferencing
36) Interactive Multimedia
37) Real time Desktop Multimedia
38) Document Storage System
39) Mobile Emergency Services
40) Mobile Repair Assistance
41) Mobile Tele-working
42) Freight and Fleet Management
43) High Speed Trains</td><td>BCC, URB, ROA, transp, COM, TV, OFF, IND</td><td>BUS/ FAM</td><td>Ind, Outd</td><td>All</td><td>PUB/ PRIV</td><td>All</td></tr>
<tr><td>EMERG.</td><td>BUS</td><td>Outd</td><td>ST,UB,MR,HW</td><td>PUB/ PRIV</td><td>BCC, URB, ROA</td></tr>
<tr><td>COM, EMERG.</td><td>BUS</td><td>Outd</td><td>ST,PD,UB</td><td>PUB/ PRIV</td><td>BCC, URB, ROA, COM, HOM</td></tr>
<tr><td>BCC, ROA, COM, transp.,</td><td>BUS/ FAM</td><td>Ind, Outd, TRA</td><td>MR, HW</td><td>PUB</td><td rowspan="2">All</td></tr>
<tr><td>EMERG.,TV, OFF, IND</td><td>BUS</td><td>Outd</td><td>ST,UB,MR,HW</td><td>PUB</td></tr>
<tr><td>Transports</td><td>BUS/ FAM</td><td>TRA</td><td></td><td>PUB</td><td>TRA</td></tr>
</table>

Table F.2 – Operation Environments for Interactive Services – Messaging.

Type of Information	Examples of Broadband Services	Applications	Frame-work	Nature	Environment	Mobility scenario	Service Provision	Deployment Scenarios
Data	Electronic Mail/Paging	44) Paging 45) Visual E-mail (with attachments …)	BCC, ROA, COM, transps, **TV, OFF, IND**	BUS/ FAM	Ind, Outd, TRA	All	PUB/ PRIV	All
Moving Pictures (video) and Sound	Video/image Mail	46) Electronic Mailbox Service for the Transfer of Moving Pictures and Sound		BUS/ FAM	Ind, Outd, TRA	All	PUB/ PRIV	
Voice (sound)	Voice Mail	47) Electronic Mailbox Service for Voice		BUS/ FAM	Ind, Outd, TRA	All	PUB/ PRIV	
Mixed Document	Multimedia Mail	48) Electronic Mailbox Service for Multimedia		BUS/ FAM	Ind, Outd, TRA	All	PUB/ PRIV	

Table F.3 – Operation Environments for Interactive Services – Retrieval.

Type of Information	Examples of Broadband Services	Applications	Framework	Nature	Environment	Mobility scenario	Service Provision	Deployment Scenarios
Text, Data, Graphics, Sound, Still Image, Moving Pictures	Broadband Videotex	49) Videotex Including Moving Pictures 1) Tele-education 24) Tele-software 2) E-commerce 3) Tele-advertising 50) News Retrieval 51) Multimedia Library 52) Retrieve of Encyclopaedia Entries 53) Tourist Information	BCC, URB, ROA, COM; transp., **TV, OFF, IND**	BUS/ FAM	Ind, Outd, TRA	All	PUB/ PRIV	All
	Video Retrieval Service – on Demand (MPEG1)	54) Entertainment Purpose 55) Remote Educational and Training	BCC, URB, ROA, COM transp., **TV, OFF, IND**	BUS/ FAM	Ind, Outd, TRA	All	PUB/ PRIV	
	Video Retrieval Service - on Demand (MPEG2-4)	56) Entertainment Purpose 57) Remote Educational and Training	BCC, URB, ROA, COM, transp., **TV, OFF, IND**	BUS/ FAM	Ind, Outd, TRA	All	PUB/ PRIV	
	Video Browsing	58) Entertainment or Business Purposes	BCC, URB, ROA, COM, transp., **TV, OFF, IND**	BUS/ FAM	Ind, Outd, TRA	All	PUB/ PRIV	
	High-resolution Image Retrieval Service	59) Entertainment Purposes 60) Remote Educational and Training 61) Professional Image Communications 62) Medical Image Communications	BCC, URB ROA, COM, transp., **TV, OFF, IND.**	BUS/ FAM	Ind, Outd, TRA	All	PUB/ PRIV	
	Data retrieval Service	24) Tele-software 63) Remote Educational and Training 64) Remote Database Access 65) Large File Download 66) Mixed Media Documents 67) Remote Procedure Call	BCC, URB, ROA, COM, transp., **TV, OFF, IND.**	BUS/ FAM	Ind, Outd, TRA	All	PUB/ PRIV	
	Multimedia Retrieval Service	68) Urban Guidance-Public Trans. Inf. 69) Assistance in Travel (Vehicular)	BCC, URB, ROA, COM, OFF, transp.	BUS/ FAM	Ind, Outd, TRA	All	PUB	BCC, URB, ROA, TRA, COM, OFF, HOM

Appendix G

Service Components Characterisation for a Different Basic Data Rate

If one considered different values for the data rate of the basic service component (512, 1 024 or 2 048 kb/s), the respective service components would be the ones from Annex G where, in some cases, the only possibility is having higher data rates for the service components, like the approach used for UMTS in [Garc00], [GaVC01], some waste existing.

Table G.1 – Resulting service components for a basic data rate of 512 kb/s.

Original		Resulting		
Service component	Data rate [kb/s]	Service component	R_{bsj} [kb/s]	a_j
BAS	384	FBAS	512	1
MD1	1152	FMD1	1536	3
MD2	1536			
MD3	1920	FMD3	2048	8
HDV	8064	FHDV	8192	16
HID	31 862	FHID	32256	63

Table G.2 – Resulting service components for a basic data rate of 1 024 kb/s.

Original		Resulting		
Service component	Data rate [kb/s]	Service component	R_{bsj} [kb/s]	a_j
BAS	384	TBAS	1024	1
MD1	1152	TMD1	2048	2
MD2	1536			
MD3	1920			
HDV	8064	THDV	8 192	8
HID	31 862	THID	32 768	32

Table G.3 – Resulting service components for a basic data rate of 2 048 kb/s.

Original		Resulting		
Service component	Data rate [kb/s]	Service component	R_{bsj} [kb/s]	a_j
BAS	384	DMD3	2048	1
MD1	1152			
MD2	1536			
MD3	1920			
HDV	8064	DHDV	8192	4
HID	31 862	DHID	32768	16

However, the only alternative viable choice for this mixture of applications service and respective components characterisation is the use of a basic data rate of 512 kb/s, although some waste exists.

Otherwise, form Tables 5.7-5.10 one can conclude that, as the choices of basic data rate for the service components of 1024 or 2048 kb/s cannot discriminate between the MD1 (1 152 kb/s) and the MD3 (1 920 kb/s) components when they are used simultaneously, this option is not feasible at all. Examples of applications that use the MD1 and MD3 components simultaneously are MES, MRA, MTW, FFM, UGD or ATR. Thus, henceforth one is only going to consider the use of 384 or 512 kb/s basic data rates.

Appendix H

Discussion on MBS Maximum User Data Rates versus Mobility

Regarding the maximum coverage distance allowed, one can relate each of the cases (A, B and C), associated to a given value of the GBR, with each of the deployment scenarios.

- ✓ Case A, R < 350 m, may correspond to the ROA scenario. Higher maximum coverage distances can be seen as agreeing with higher mobility [VeCo99b]. Although the total bit rate per carrier is the lowest, the foreseen user density will not certainly exceed the values for the BCC and the URB scenarios.
- ✓ Case B, R < 180 m, may correspond to the URB scenario. Lower coverage distances agree with lower mobility [VeCo99b]. The total bit rate per carrier is higher (twice the value of case A), and applications up to 36 Mb/s can be supported by a single carrier.
- ✓ Case C, R < 60 m, may correspond to the BCC scenario. The highest possible user bit rate per carrier allows the use of services components with higher associated bit rates. In cases where a higher cell coverage distance is needed, one also could associate the case B to the BCC scenario, although that approach will not be followed here.

From the user point of view, one can suppose that MBS can be used in the context of re-configurable mobile systems, like UMTS, and thus the system will be sufficiently smart to change its frame structure from one case to another, in order to achieve a higher capacity per carrier, while the user roam through the system, from one scenario to the other.

From this analysis one can therefore propose an indicative staircase boundary for the foreseen maximum user data rates in MBS when the OQPSK type of modulation is used, Fig. H.1.

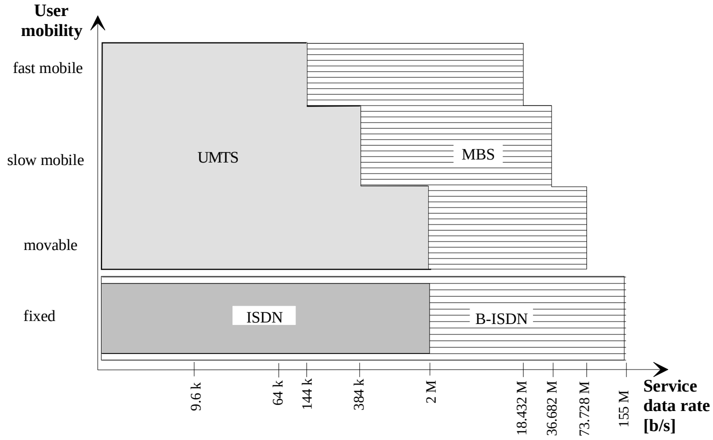


Fig. H.1 – MBS maximum user data rates versus mobility with the OQPSK type of modulation.

In a similar way, the respective boundary if the 16-OQAM type of modulation was used would be the one from Fig. H.2, the data rates being twice of the previous ones.

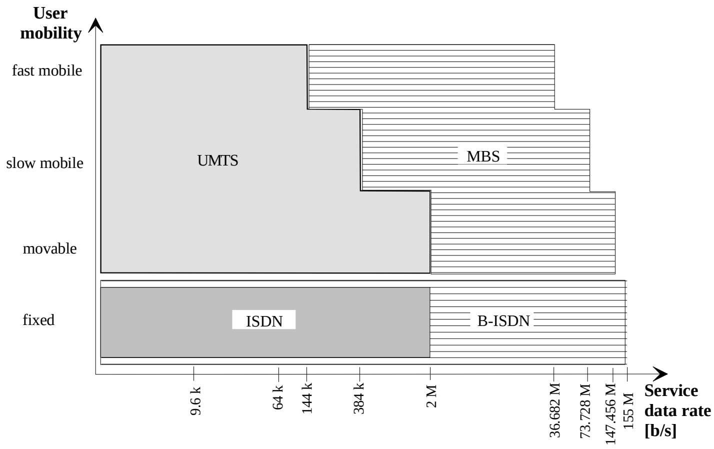


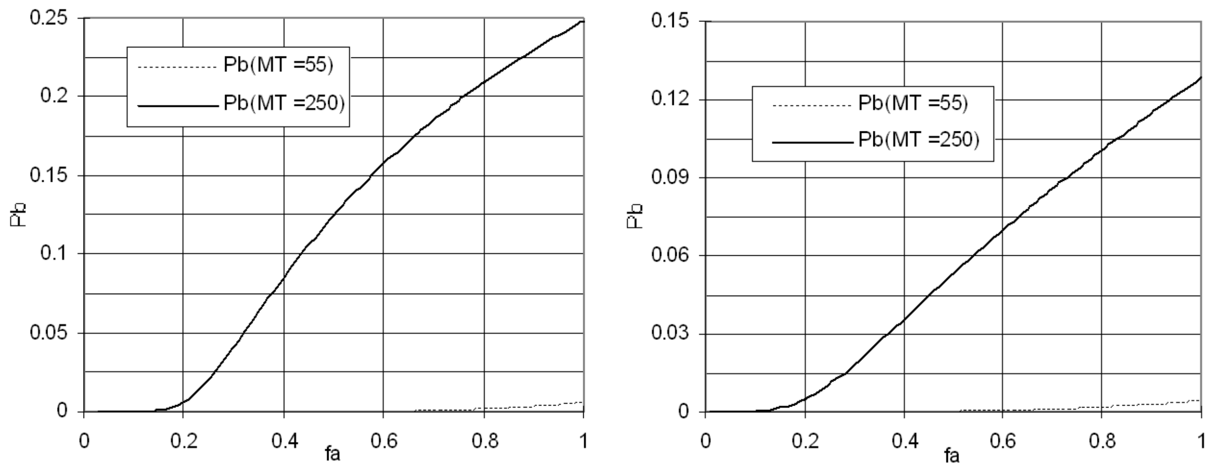
Fig. H.2 – MBS maximum user data rates versus mobility with the 16-OQAM type of modulation.

However, one should remember that the 16-OQAM case option of each burst payload containing the information contents of two basic data blocks, instead of a single one, is not well accepted (because two ATM cells are included in the same slot).

Appendix I

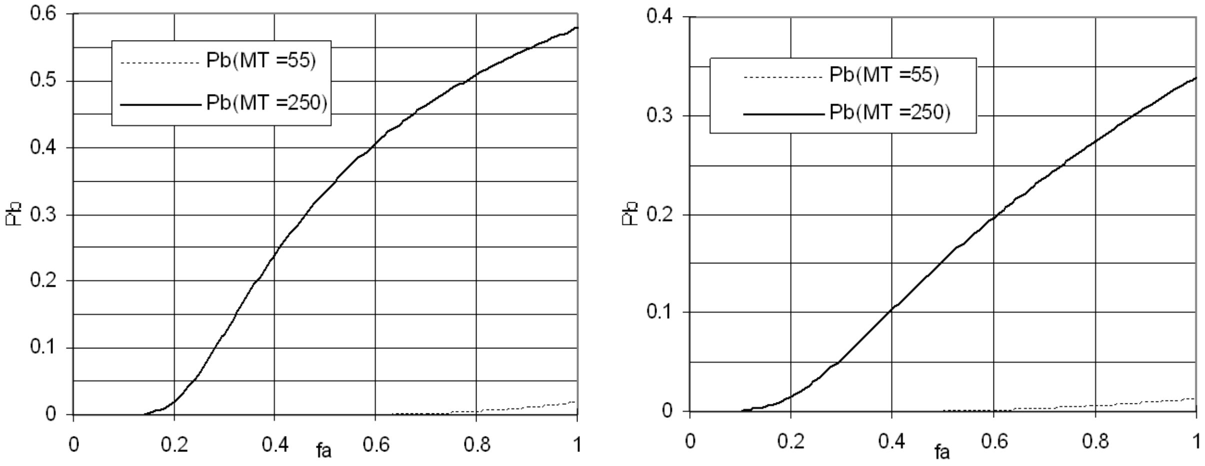
Blocking Probability for the BAS, MD1, MD2 and MD3 Components

In this Annex, some supplementary results for the blocking probability as a function of f_a are presented for the BAS, MD1, MD2 and MD3 service components for the BCC scenario.



a) Uplink b) Downlink

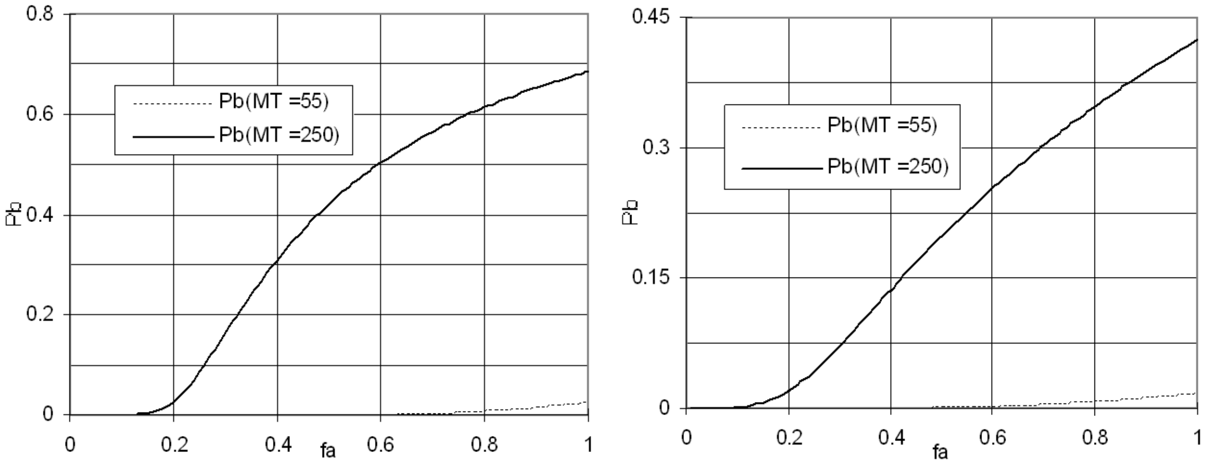
Fig. I.1 – Blocking probability as a function of f_a for the BAS component, 384 resource/cell.



a) Uplink

b) Downlink

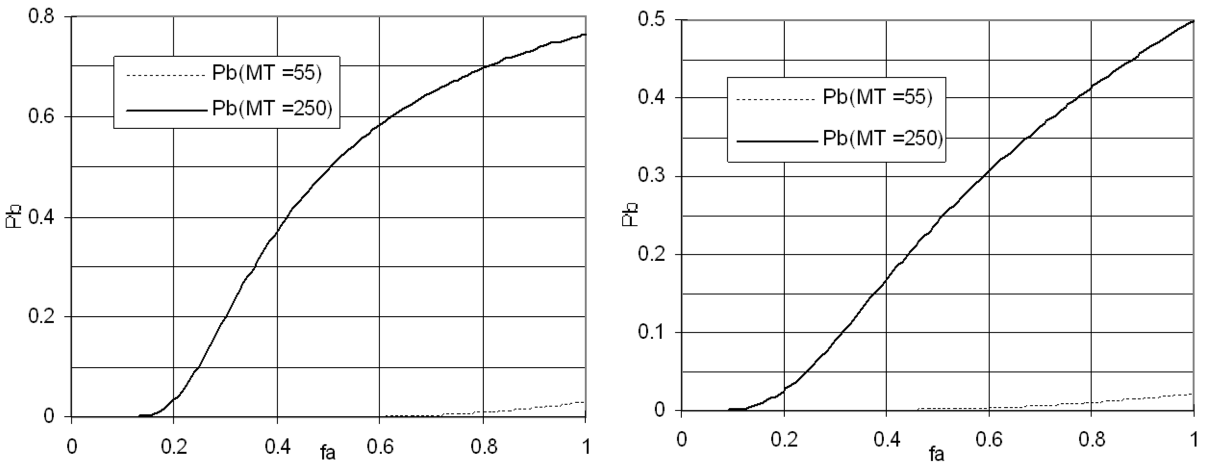
Fig. I.2 – Blocking probability as a function of f_a for the MD1 component, 384 resource/cell.



a) Uplink

b) Downlink

Fig. I.3 – Blocking probability as a function of f_a for the MD2 component, 384 resource/cell.



a) Uplink

b) Downlink

Fig. I.4 – Blocking probability as a function of f_a for the MD3 component, 384 resource/cell.

Appendix J

Results for $M_T = M_{max\_load}$ in the Presence of Mobility

In this Appendix one presents results for the supported fraction of active users and the supported number of users per cell for $M_T = M_{max\_load}$, in the presence of mobility.

For the $M_T = M_{max\_load}$ case, the results for the supported f_a are the ones from Tables J.1-J.2, where the best situation for design purposes is identified in bold.

Table J.1 – Supported f_a for $P_{hf} = (P_{hf})_{max}$ with 384 Channel/Cell and Presence of Mobility, $M_T = M_{max\_load}$.

$f_{a\,[\%]}$			Original case	Change 1	Change 2
M_{ENV} =250	BCC	UL	60.2	38.4	**43.2**
		DL	35.0	41.1	**39.6**
M_{ENV} =100	URB	UL	**37.5**	29.6	25.3
		DL	**46.4***	49.5	51.4
M_{ENV} =100	ROA	UL	36.9	**21.5**	-
		DL	6.3	**9.9**	-

* In this case the limitation by P_b = 2% from Table 5.31 leads to $f_{a[\%]}$ = 39.1. However it does not affect the dimensioning of the system, as it is the uplink that does limit the system.

Table J.2 – Supported f_a for $P_{hf} = (P_{hf})_{max}$ with 288 Channel/Cell and Presence of Mobility, $M_T = M_{max\_load}$.

$f_{a\,[\%]}$			Original case	Change 1	Change 2
M_{ENV} =250	BCC	UL	47.2	**31.8**	-
		DL	22.0	**26.0**	-
M_{ENV} =100	URB	UL	**25.5**	15.3	-
		DL	**35.8***	40.2	-
M_{ENV} =100	ROA	UL	25.0	15.9	**10.4**
		DL	2.8	4.2	**5.1**

* In this case the limitation by P_b = 2% from Table 5.32 leads to $f_{a[\%]}$ = 26.1. However it does not affect the dimensioning of the system as it is the uplink that does limit the system.

These results correspond to the number of supported users and the spectral efficiency from Tables J.3-J.4 obtained for the best combination in Tables 5.39 and 5.40.

Table J.3 – Supported Number of Users and Spectral Efficiency with 384 Channel/Cell and Presence of Mobility, $M_T = M_{max\_load}$.

			N_{SU}	S_{ef}	Worst case S_{ef}
M_{ENV} = 250	BCC	UL	23.8	0.51	0.46
		DL	21.8	0.37	0.37
M_{ENV} = 100	URB	UL	22.5	0.33	0.33
		DL	28.3	0.44	0.35
M_{ENV} = 100	ROA	UL	11.8	0.27	0.13
		DL	5.9	0.10	0.10

Table J.4 – Supported Number of Users and Spectral Efficiency with 288 Channel/Cell and Presence of Mobility, $M_T = M_{max\_load}$.

			N_{SU}	S_{ef}	Worst case S_{ef}
M_{ENV} = 250	BCC	UL	13.0	0.37	0.30
		DL	10.6	0.24	0.24
M_{ENV} = 100	URB	UL	11.5	0.23	0.23
		DL	16.5	0.35	0.24
M_{ENV} = 100	ROA	UL	4.3	0.14	0.07
		DL	2.3	0.05	0.05

The comparison between these values and the ones without mobility leads to the values of Table J.5.

Table J.5 – Comparison between the Cases of Absence and Presence of Mobility, $M_T = M_{max\_load}$.

		$f_{a[\%]}$		$f_{a-with} / f_{a-without}$
		Without mobility	With mobility	
384 resource/cell	BCC	39.6	39.6	1
	URB	44.1	37.5	0.85
	ROA	36.2	9.9	0.27
288 resource/cell	BCC	26.0	26.0	1
	URB	30.2	25.5	0.84
	ROA	24.3	5.1	0.21

One concludes that the terminal mobility has a similar effect for $M_T = M_{ENV}$ and $M_T = M_{max\_load}$.

Appendix L

Results for Traffic for *K* = 2

In this Appendix, one presents the dependence on R of the supported fraction of active users, the spectral efficiency and the number of supported users per kilometre for $K = 2$. In these figures, while UP and DOWN designate the up- and downlinks, TOT refers to the total spectral efficiency.

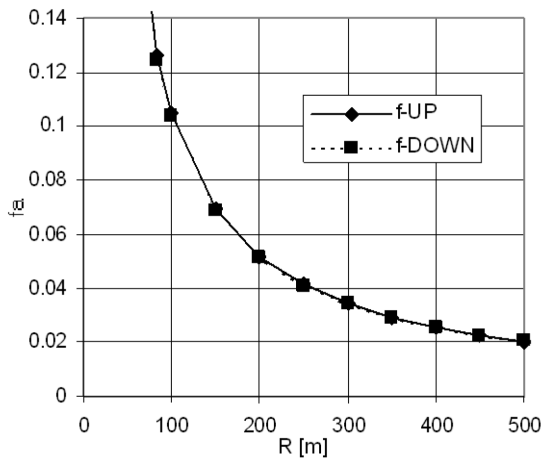
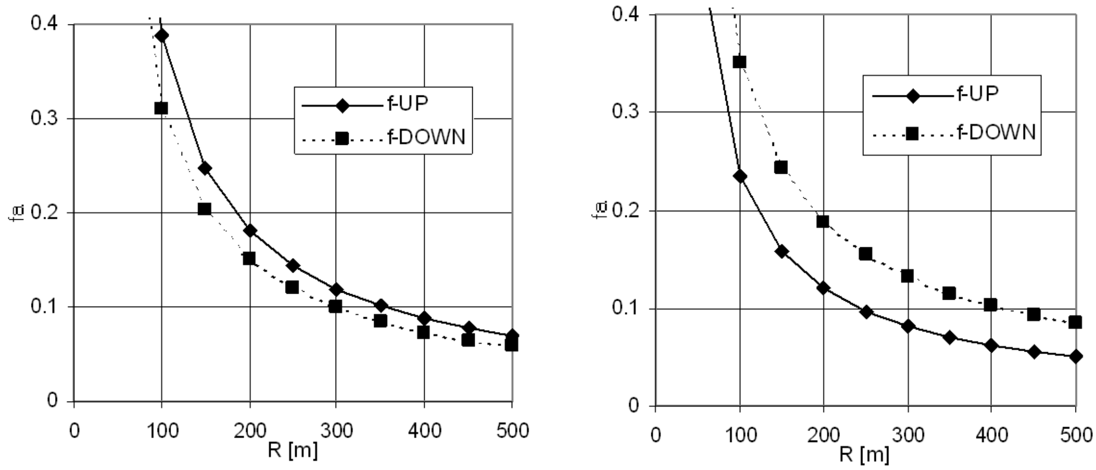


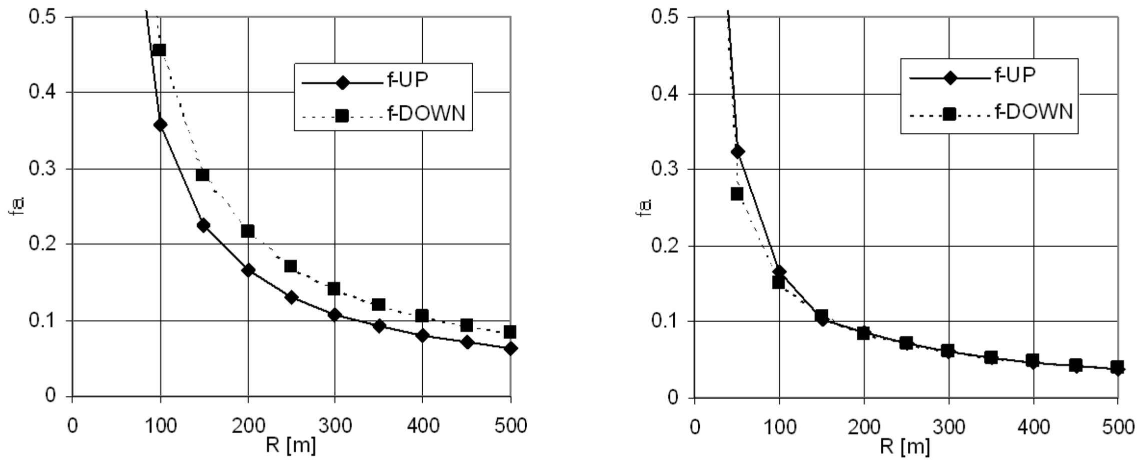
Fig. L.1 – Supported fraction of active users as a function of *R* for the BCC scenario, both in absence and presence of mobility, *K* = 2.



a) Absence of mobility

b) Presence of mobility

Fig. L.2 – Supported fraction of active users as a function of *R* for the URB scenario, *K* = 2.



a) Absence of mobility

b) Presence of mobility

Fig. L.3 – Supported fraction of active users as a function of *R* for the ROA scenario, *K* = 2.

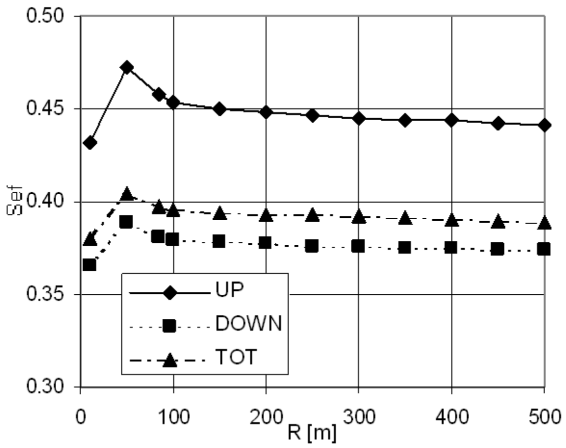
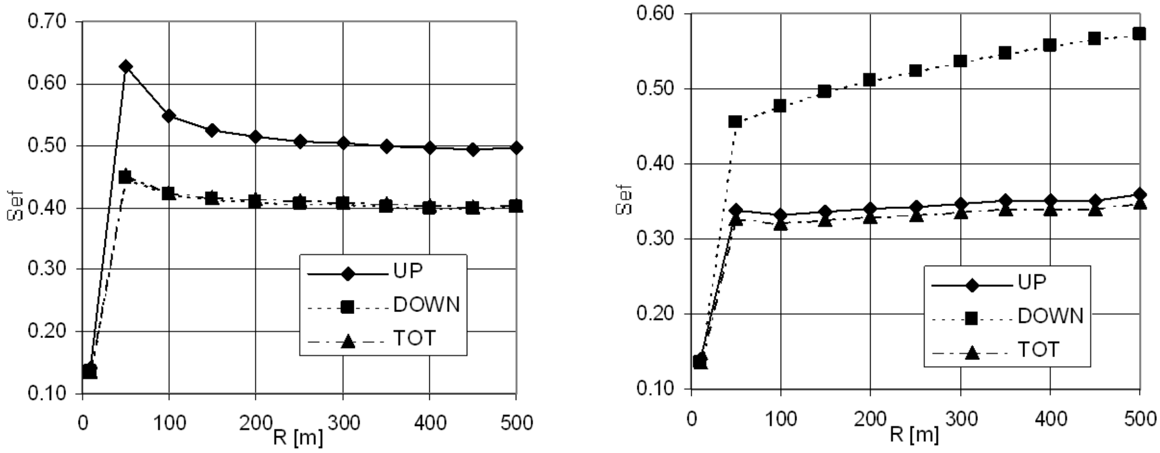


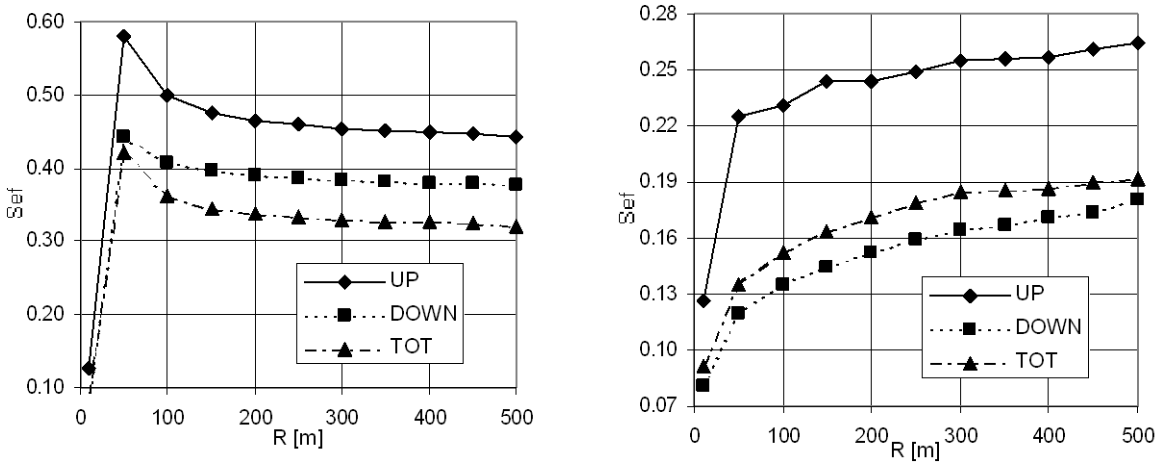
Fig. L.4 – Spectral efficiency as a function of *R* for the BCC scenario, both in absence and presence of mobility, *K* = 2.



a) Absence of mobility

b) Presence of mobility

Fig. L.5 – Spectral efficiency as a function of *R* for the URB scenario, *K* = 2.



a) Absence of mobility

b) Presence of mobility

Fig. L.6 – Spectral efficiency as a function of *R* for the ROA scenario, *K* = 2.

Appendix M

Supported Number of Users per Kilometre

In this Appendix, one presents the dependence on R of the supported number of users per kilometre. In these figures, UP and DOWN designate the up- and downlinks.

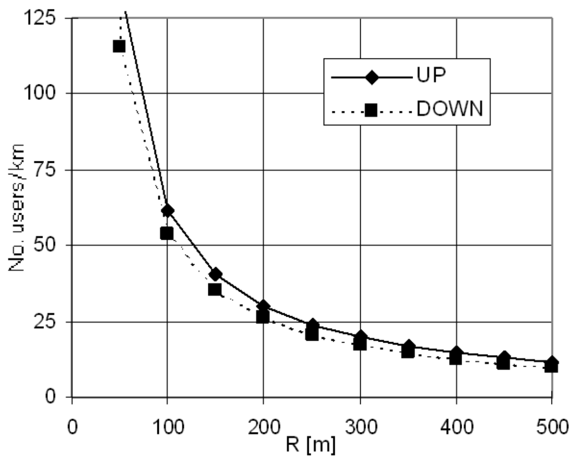
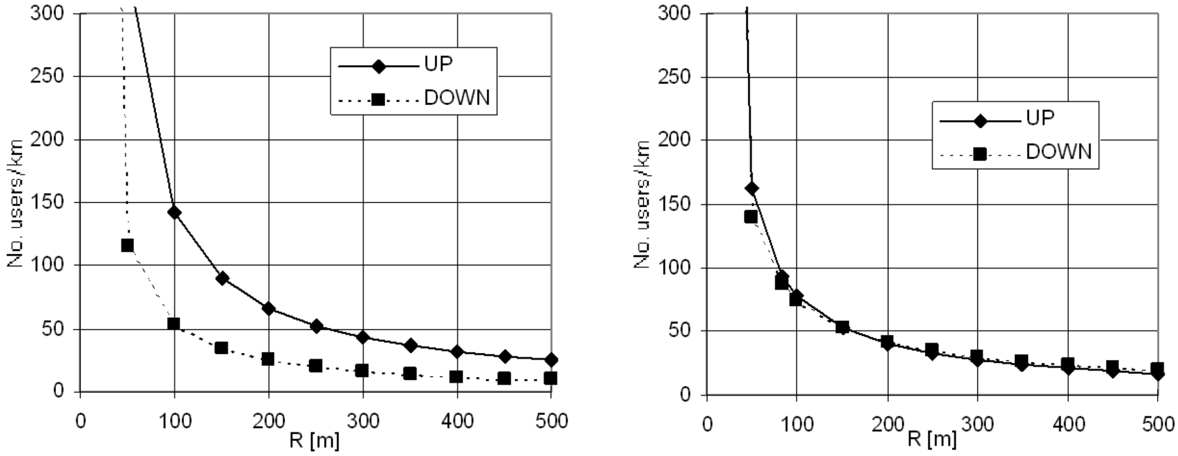


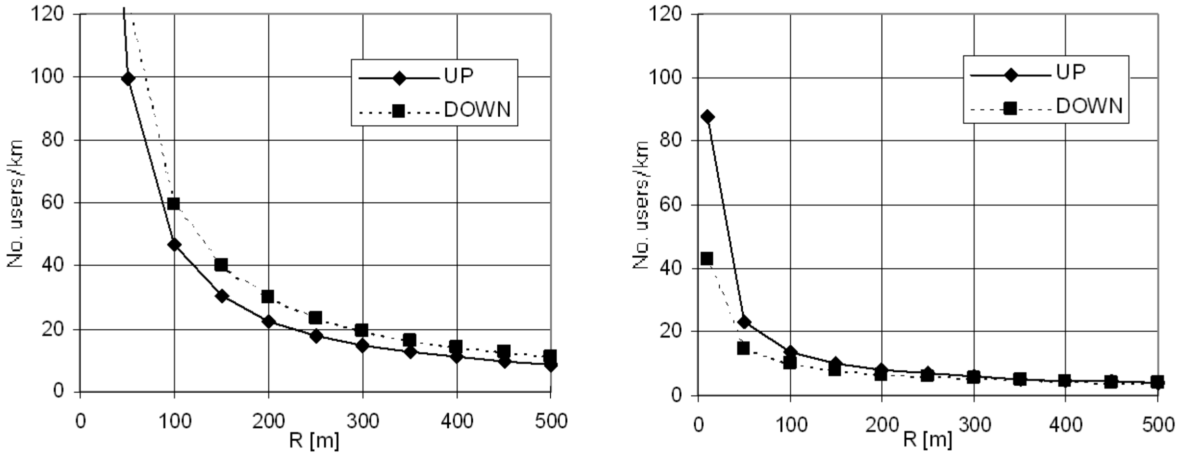
Fig. M.1 - Supported number of users per kilometre as a function of *R* for the BCC scenario, *K* = 3.



a) Absence of mobility

b) Presence of mobility

Fig. M.2 - Supported number of users per kilometre as a function of *R* for the URB scenario, *K* = 3.



a) Absence of mobility

b) Presence of mobility

Fig. M.3 - Supported number of users per kilometre as a function of *R* for the ROA scenario, *K* = 3.

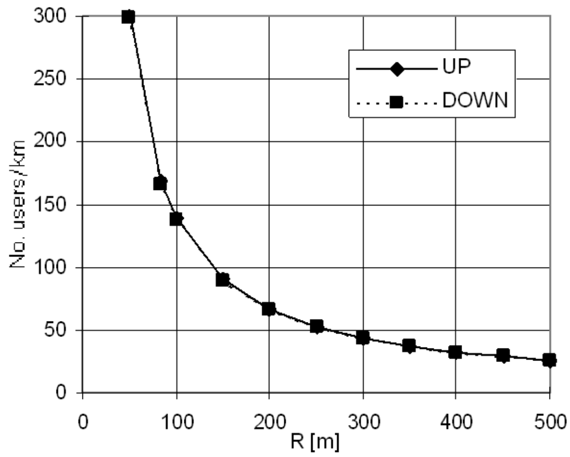
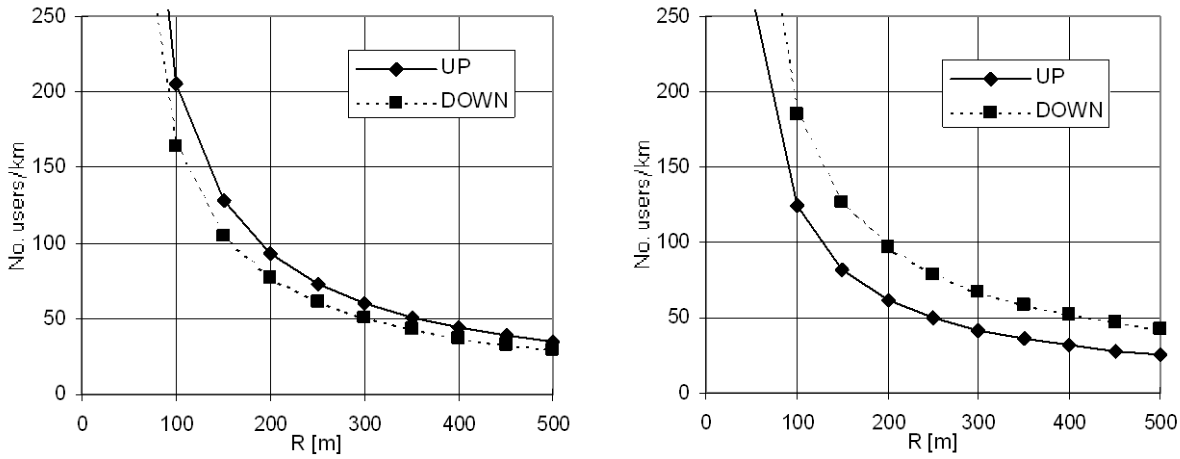


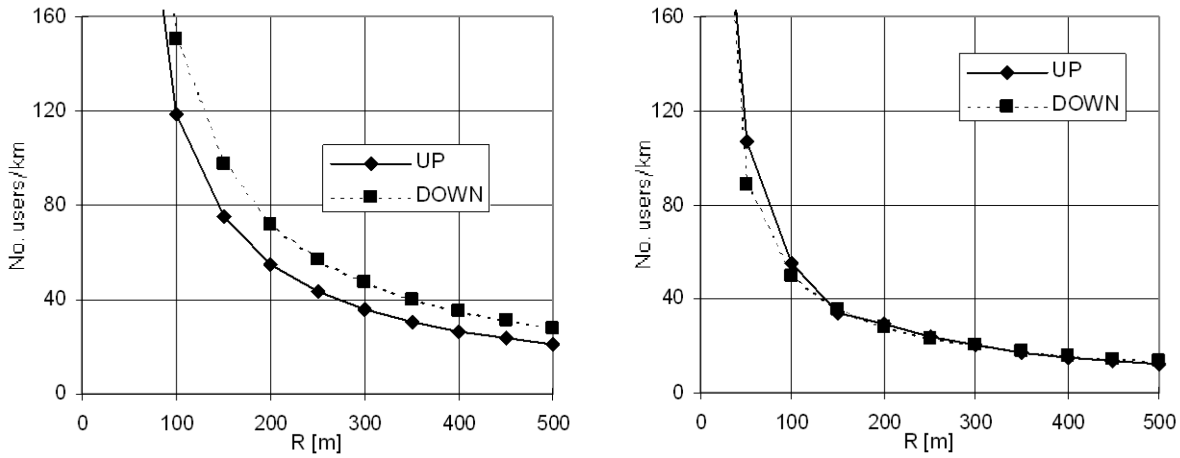
Fig. M.4 - Supported number of users per kilometre as a function of *R* for the BCC scenario, both in absence and presence of mobility, *K* = 2.



a) Absence of mobility

b) Presence of mobility

Fig. M.5 - Supported number of users per kilometre as a function of *R* for the URB scenario, *K* = 2.



a) Absence of mobility

b) Presence of mobility

Fig. M.6 - Supported number of users per kilometre as a function of *R* for the ROA scenario, *K* = 2.

Appendix N

Assumptions for the Revenues per Slot

In this Appendix, one presents the assumptions for the revenues per slot, R_{384}, in €/min, for eight different cases (A, B, C, …, H), which will label the graphs with results. The values of C_{fb} and C_{384} are only presented in the first Table to avoid redundancy (otherwise, it will be repeated in the cases presented next Tables).

Table N.1 – Assumptions for *K* = 3 (288 channel/cell) in the BCC scenario (both in the presence and absence of mobility), and in the URB and ROA scenarios (in the absence of mobility).

HYP.	C_{fb} [€/year]	C_{1920} [€/year]	R_{384} [€/min]							
			A	B	C	D	E	F	G	H
7	13000	600	0.005	0.0075	0.01	0.0125	0.015	0.0175	0.02	0.0225
5	6500	300	0.0025	0.00375	0.005	0.00625	0.0075	0.00875	0.01	0.01125
4	30000	300	0.005	0.0075	0.01	0.0125	0.015	0.0175	0.02	0.0225

Table N.2 – Assumptions for *K* = 3 (288 channel/cell) in the ROA scenario (in the presence of mobility).

HYP.	R_{384} [€/min]							
	A	B	C	D	E	F	G	H
7	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11
5	0.02	0.025	0.03	0.035	0.04	0.045	0.05	0.055
4	0.04	0.05	0.06	0.07	0.08	0.09	0.10	0.11

Table N.3 – Assumptions for *K* = 2 (432 channel/cell) in the BCC and URB scenarios (both in the presence and absence of mobility), and in the ROA scenario (in the absence of mobility).

HYP.	R_{384} [€/min]							
	A	B	C	D	E	F	G	H
7	0.0025	0.00375	0.005	0.00625	0.0075	0.00875	0.01	0.01125
5	0.00125	0.001875	0.0025	0.003125	0.00375	0.004375	0.005	0.005625
4	0.0025	0.00375	0.005	0.00625	0.0075	0.00875	0.01	0.01125

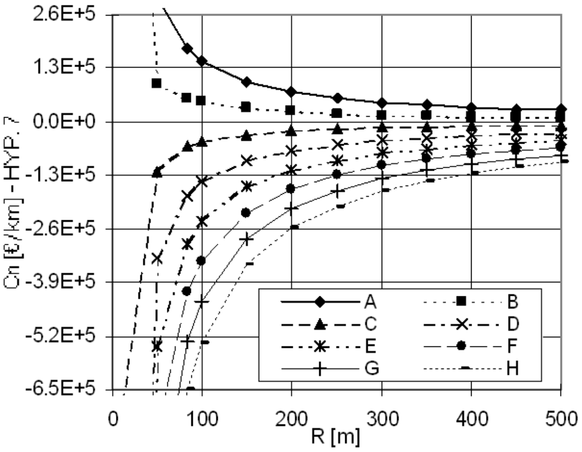
Table N.4 – Assumptions for *K* = 2 (432 channel/cell) in the ROA scenario (in the presence of mobility).

HYP.	R_{384} [€/min]							
	A	B	C	D	E	F	G	H
7	0.01	0.0125	0.015	0.0175	0.02	0.0225	0.025	0.0275
5	0.005	0.00625	0.0075	0.00875	0.01	0.01125	0.0125	0.01375
4	0.01	0.0125	0.015	0.0175	0.02	0.0225	0.025	0.0275

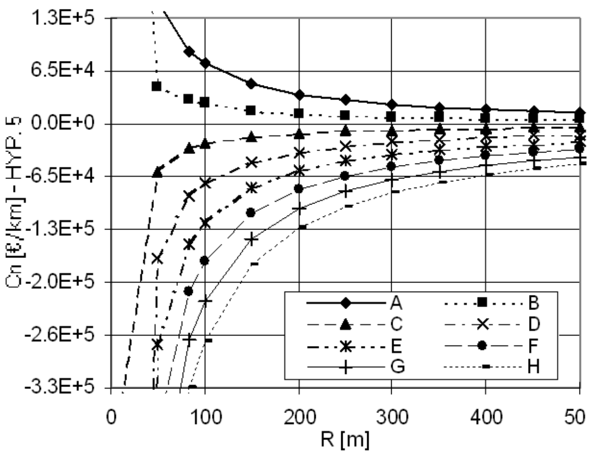
Appendix O

Net Costs

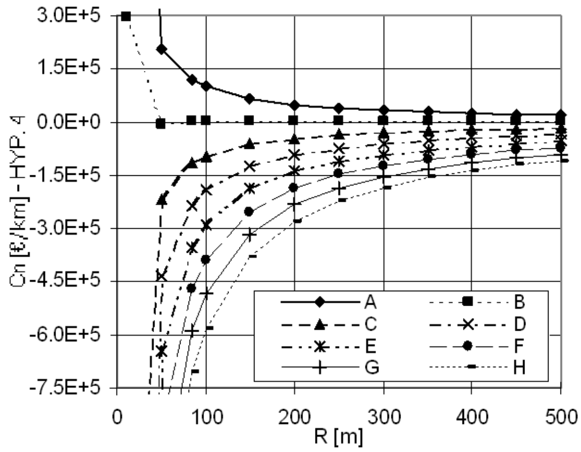
In this Appendix, one presents the dependence on *R* of the 'net costs' for the BCC and the ROA scenarios.



a) HYP. 7

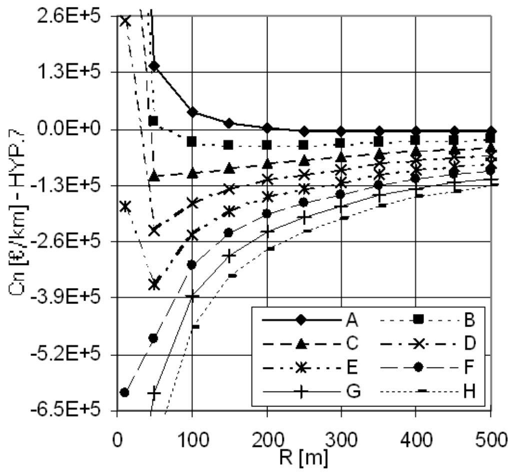


b) HYP. 5

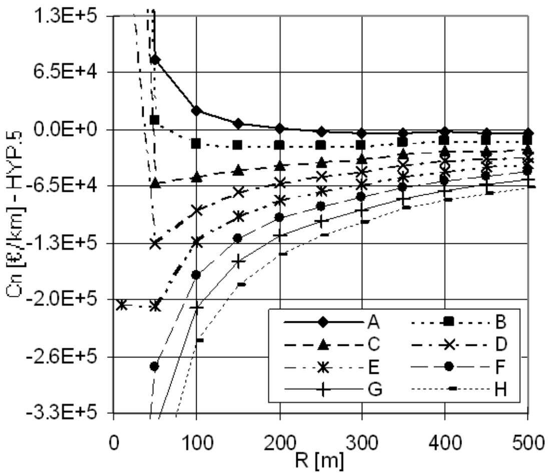


c) HYP. 4

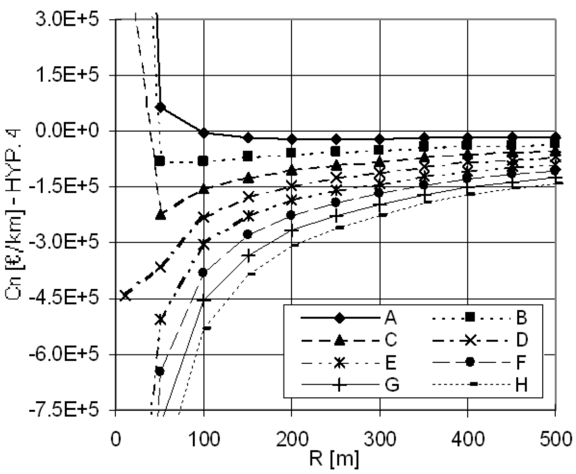
Fig. O.1 – Net cost as a function of *R* in the BCC scenario, *K* = 2.



a) HYP. 7



b) HYP. 5



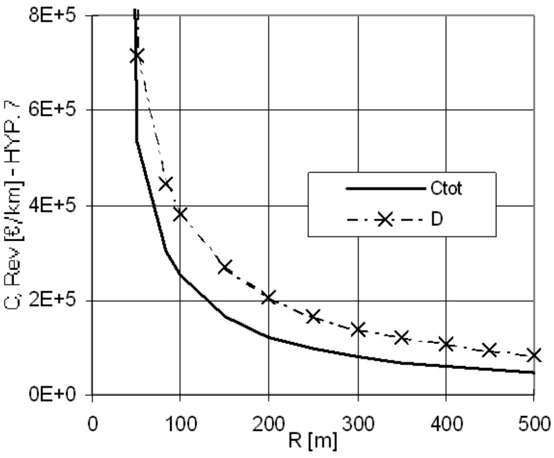
c) HYP. 4

Fig. O.2 – Net cost as a function of *R* in the ROA scenario, *K* = 2.

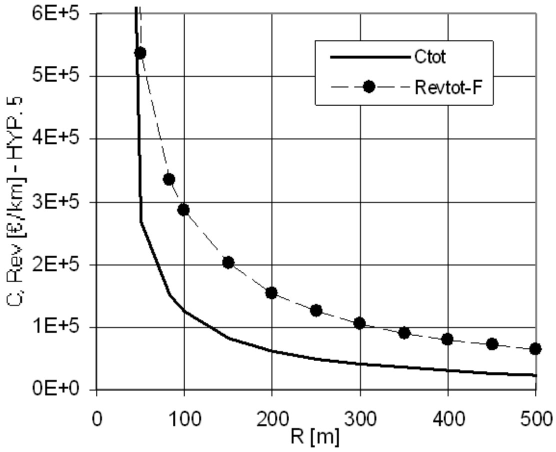
Appendix P

Total Cost and Revenue

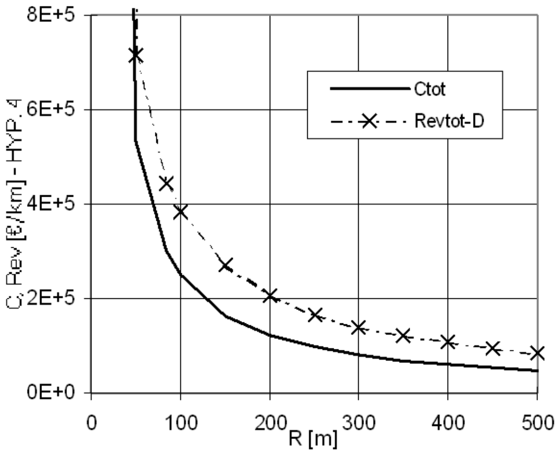
In this Appendix, one presents the dependence on R of the 'net costs' for the BCC and the ROA scenarios.



a) HYP. 7

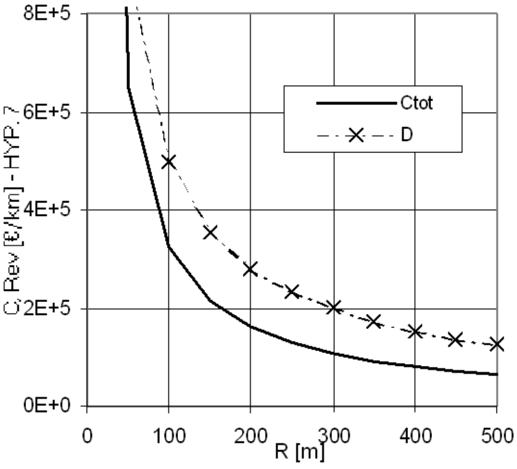


a) HYP. 5

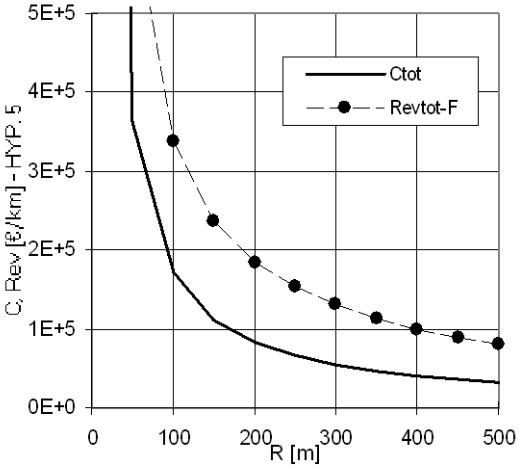


c) HYP. 4

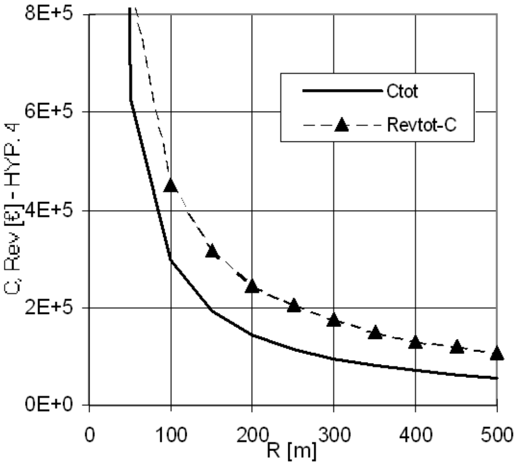
Fig. P.1 – Total cost and revenue for the URB scenario.



a) Hypothesis 7 (the chosen case is D)



a) Hypothesis 5



c) Hypothesis 4

Fig. P.2 – Total cost and revenue for the ROA scenario.

Appendix Q

Example of Prices in Irregular Geometries

In this Appendix, one presents an example of prices in irregular geometries.

Table Q.1 – MBS price list, in €/min, for the irregular urban geometry, BCC scenario.

Application	b_k [kb/s]		$\bar{\tau}$ [min]	HYP. 7		HYP. 5		HYP. 4	
	Uplink	Downlink		Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
1. HVT	1920	1920	3	0.03875	0.03875	0.02413	0.02413	0.03625	0.03625
2. IVC	384	384	30	0.00775	0.00775	0.00483	0.00483	0.00725	0.00725
3. MVS	1920	0.8	120	0.03875	0.00002	0.02413	0.00001	0.03625	0.00002
4. HOB	8067.8	1923.8	50	0.16283	0.03883	0.10137	0.02417	0.15232	0.03632
5. WLI	145.8	4031.8	15	0.00294	0.08137	0.00183	0.05066	0.00275	0.07612
6. FTP	19.1	384	0.33	0.00039	0.00775	0.00024	0.00483	0.00036	0.00725
7. PIM	384	8064	10	0.00775	0.16275	0.00483	0.10133	0.00725	0.15225
8. DMM	63.4	48.6	5	0.00128	0.00098	0.00080	0.00061	0.00120	0.00092
9. MES	2731.1	2731.2	20	0.05512	0.05512	0.03432	0.03432	0.05157	0.05157
10. MRA	2328.0	2373.0	40	0.04698	0.04698	0.02925	0.02925	0.04395	0.04395
11. MTW	1929.6	1929.6	20	0.03894	0.03894	0.02425	0.02425	0.03643	0.03643
12. FFM	2736.0	2736.0	5	0.05522	0.05522	0.03438	0.03438	0.05166	0.05166
13. EMB	63.4	1536	1	0.00128	0.03100	0.00080	0.01930	0.00120	0.02900
14. ECO	15.9	48.6	5	0.00032	0.00098	0.00020	0.00061	0.00030	0.00092
15. MML	4.8	2328.0	40	0.00010	0.04698	0.00006	0.02925	0.00009	0.04395
16. TIN	76.5	242.9	15	0.00154	0.00490	0.00096	0.00305	0.00144	0.00459
17. RPC	9.6	194.3	5	0.00019	0.00392	0.00012	0.00244	0.00018	0.00367
18. UGD	1935.3	1935.3	5	0.03906	0.03906	0.02432	0.02432	0.03654	0.03654
19. ATR	1935.3	1935.3	20	0.03906	0.03906	0.02432	0.02432	0.03654	0.03654
20. TVD	0	8064	90	0.00000	0.16275	0.00000	0.10133	0.00000	0.15225
21. ENP	0.8	242.9	20	0.00002	0.00490	0.00001	0.00305	0.00002	0.00459

Table Q.2 – MBS price list, in €/min, for the irregular urban geometry, URB scenario.

Application	b_k [kb/s]		$\bar{\tau}$ [min]	HYP. 7		HYP. 5		HYP. 4	
	Uplink	Downlink		Uplink	Downlink	Uplink	Downlink	Uplink	Downlink
1. HVT	1920	1920	3	0.03575	0.03575	0.02188	0.02188	0.02500	0.02500
2. IVC	384	384	30	0.00715	0.00715	0.00438	0.00438	0.00500	0.00500
3. MVS	1920	0.8	120	0.03575	0.00001	0.02188	0.00001	0.02500	0.00001
4. HOB	8067.8	1923.8	50	0.15022	0.03582	0.09192	0.02192	0.10505	0.02505
5. WLI	145.8	4031.8	15	0.00271	0.07507	0.00166	0.04594	0.00190	0.05250
6. FTP	19.1	384	0.33	0.00036	0.00715	0.00022	0.00438	0.00025	0.00500
7. PIM	384	8064	10	0.00715	0.15015	0.00438	0.09188	0.00500	0.10500
8. DMM	63.4	48.6	5	0.00118	0.00090	0.00072	0.00055	0.00083	0.00063
9. MES	2731.1	2731.2	20	0.05085	0.05085	0.03112	0.03112	0.03556	0.03556
10. MRA	2328.0	2373.0	40	0.04335	0.04335	0.02652	0.02652	0.03031	0.03031
11. MTW	1929.6	1929.6	20	0.03593	0.03593	0.02198	0.02198	0.02512	0.02512
12. FFM	2736.0	2736.0	5	0.05094	0.05094	0.03117	0.03117	0.03562	0.03562
13. EMB	63.4	1536	1	0.00118	0.02860	0.00072	0.01750	0.00083	0.02000
14. ECO	15.9	48.6	5	0.00030	0.00090	0.00018	0.00055	0.00021	0.00063
15. MML	4.8	2328.0	40	0.00009	0.04335	0.00005	0.02652	0.00006	0.03031
16. TIN	76.5	242.9	15	0.00142	0.00452	0.00087	0.00277	0.00100	0.00316
17. RPC	9.6	194.3	5	0.00018	0.00362	0.00011	0.00221	0.00012	0.00253
18. UGD	1935.3	1935.3	5	0.03603	0.03603	0.02205	0.02205	0.02520	0.02520
19. ATR	1935.3	1935.3	20	0.03603	0.03603	0.02205	0.02205	0.02520	0.02520
20. TVD	0	8064	90	0.00000	0.15015	0.00000	0.09188	0.00000	0.10500
21. ENP	0.8	242.9	20	0.00001	0.00452	0.00001	0.00277	0.00001	0.00316

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