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# **Joint Radio Resource Management in Heterogeneous Networks**

António João Nunes Serrador

Supervisor: Doctor Luís Manuel de Jesus Sousa Correia

Thesis approved in public session to obtain the PhD degree in  
Electrical and Computer Engineering

Jury final classification: Pass with Merit

Jury

Chairperson: Chairman of the IST Scientific Board

Members of the Committee:

Doctor Jordi Perez Romero  
Doctor Luís Manuel de Jesus Sousa Correia  
Doctor Rui Manuel Rodrigues Rocha  
Doctor Fernando José da Silva Velez  
Doctor António José Castelo Branco Rodrigues

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Doctor Luís Manuel de Jesus Sousa Correia, Professor Associado (com Agregação), Instituto Superior Técnico, da Universidade Técnica de Lisboa

Doctor Rui Manuel Rodrigues Rocha, Professor Associado, Instituto Superior Técnico, da Universidade Técnica de Lisboa

Doctor Fernando José da Silva Velez, Professor Auxiliar, da Universidade da Beira Interior

Doctor António José Castelo Branco Rodrigues, Professor Auxiliar, Instituto Superior Técnico, da Universidade Técnica de Lisboa

2012



*To my beloved son António Salvador*



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# Abstract

This thesis is devoted to exploring new management mechanisms required for heterogeneous mobile and wireless networks, taking advantage of their coverage superposition and management integration, allowing operators the opportunity to reduce installation and operational costs while offering high quality services to end users. One proposes an integrated solution for this multi-dimension problem, by defining a new set of models capable to provide mechanisms to manage modern heterogeneous networks, such as holistic cost functions where different networks performance metrics and key players (operators and users) are used, and combined to manage the complex heterogeneous environment. Furthermore, new analytical models are also proposed to evaluate heterogeneous integrated scenarios where the joint radio resource management policies performance are analysed. These models are developed and implemented in a simulation tool, where several capabilities and benefits of the proposed models are shown. Raging from service cost up to network energy efficiency, the proposed models show performance and management benefits. This work contributes to simplify joint radio resource management algorithms, generating additional gains at networks overall performance, by reducing the overall delay and blocking and maximising the overall bitrate experience by end users. The achieved performance gains range from 5% up to about 10 times.

## Keywords

Heterogeneous Networks, Joint Radio Resource Management, Cost Function, Simulation, Vertical Handover.

# Resumo

Esta dissertação explora novos mecanismos de gestão das redes heterogêneas sem fios, tirando partido da sua sobreposição de cobertura e capacidade de gestão integrada, permitindo aos operadores reduzir custos operacionais mantendo a qualidade de serviços aos utilizadores. São propostas soluções integradas para este problema de dimensões múltiplas, sendo definidos novos modelos capazes de oferecer mecanismos de avaliação das redes heterogêneas, como funções de custo holísticas que usam diferentes métricas de desempenho sentidas por operadores e utilizadores, combinando-as na gestão conjunta e complexa de redes heterogêneas. São ainda propostos modelos analíticos para avaliar o desempenho de diferentes políticas de gestão de recursos rádio integradas, aplicadas a cenários diferentes. Estes modelos são implementados e explorados no simulador desenvolvido, onde são apresentados os ganhos e perdas de capacidade dependendo das políticas de gestão. Desde os custos dos serviços até aos índices de eficiência energética, os modelos propostos apresentam benefícios de desempenho e gestão. Esta tese contribui para a simplificação dos algoritmos de gestão conjunta de recursos rádio, gerando ganhos adicionais ao nível do desempenho global, reduzindo o atraso e o bloqueio e maximizando o débito oferecido aos utilizadores. Os ganhos de desempenho obtidos variam entre 5 % até aproximadamente 10 vezes.

## Palavras-chave

Redes Heterogêneas, Gestão Comum de Recursos Rádio, Função de Custo, Simulação, *Handover* Vertical.

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# List of Acronyms

2G	2 <sup>nd</sup> Generation
3G	3 <sup>rd</sup> Generation
3GPP	3 <sup>rd</sup> Generation Partnership Project
3GPP2	3 <sup>rd</sup> Generation Partnership Project 2
4G	4 <sup>th</sup> Generation
8PSK	8-Phase Shift Keying
ABC	Always Best Connected
ACA	Admission Control Algorithm
ACK	ACKnowledgment
AI	Air Interface
AIFS	Arbitration Inter Frame Space
AP	Access Point
APC	Access Point Controller
ASM	Advanced Spectrum Management
BB	Base Band
BC	Base station Controller
BE	Best Effort
BER	Bit Error Rate
BHCA	Busy Hour Call Attempt
BK	BacKground
BO	Blocking Only
BPSK	Binary Phase Shift Keying
BrD	Bitrate and Delay
BrO	Bitrate Only
BrS	Bitrate and Service
BS	Base Station
BSC	Base Station Controller
CAC	Call Admission Control

## *List of Acronyms*

CBR	Constant Bit Rate
CCK	Complementary Code Keying
CD	Collision Avoidance
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CF	Cost Function
CN	Core Network
CO	COoling
COST	Co-operation in the field of Scientific and Technical Research
CQI	Channel Quality Indicator
CR	Capacity Region
CS	Circuit Switch
CSMA	Carrier Sense Multiple Access
DAC	Distributed Admission Control
DB	Delay and Blocking
DC	DC-DC power
DCF	Distributed Coordination Function
DL	DownLink
DNPM	Dynamic Network Planning and flexible network Management
DO	Delay Only
DS	Distribution System
EDAC	Enhanced Distributed Admission Control
EDACA	Enhanced Distributed Admission Control Algorithm
EDCA	Enhanced Distributed Channel Access
EDGE	Enhanced Data for GSM Evolution
EE	Energy Efficiency
EIA	Electronic Industries Association
ETSI	European Telecommunications Standard Institute
E-UTRA	Evolved-UMTS Terrestrial Radio Access
FDMA	Frequency Division Multiple Access
FF	Fittingness Factor
FP6	Sixth Framework Programme
FP7	Seventh Framework Programme
FTP	File Transfer Protocol
GERAN	GSM/EDGE Radio Access Network

GGSN	Gateway GPRS Support Node
GMSC	Gateway Mobile Switching Centre
GMSK	Gaussian Minimum Shift Keying
GMU	Global Management Unit
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
HBN	High Bitrate Networks
HCCA	Hybrid Coordination Function Controlled Channel Access
HCF	Hybrid Coordination Function
HCS	Hierarchical Cell Structure
HHO	Horizontal HandOver
HM	High Mobility
HMC	Heterogeneous Media Convergence
HSDPA	High-Speed Downlink Packet Access
HSPA	High Speed Packet Access
HSPA+	High Speed Packet Access Plus
HSUA	Hot Spot in Urban Area
HSUPA	High-Speed Uplink Packet Access
HT	High Traffic
HTTP	Hyper Text Transfer Protocol
HUD	High Users Density
ICT	Information and Communication Technologies
IEEE	Institute of Electrical and Electronics Engineers
IMT-2000	International Mobile Telecommunications-2000
IP	Internet Protocol
ITMU	Interface Traffic Monitoring Unit
JCAC	Joint Call Admission Control
JRRM	Joint Radio Resource Management
KPI	Key Performance Indicator
LB	Load Balancing
LBF	Load Balancing Factor
LBN	Low Bitrate Networks
LCD	Long Constrained Delay
LLC	Logical Link Control
LM	Low Mobility

## *List of Acronyms*

LS	Location Server
LT	Low Traffic
LTE	Long Term Evolution
LTE-A	Long Term Evolution–Advanced
LUD	Low Users Density
M2M	Machine to Machine
MAC	Medium Access Control
MBN	Medium Bitrate Networks
MBWA	Mobile Broadband Wireless Access
MeT	Medium Traffic
MIMO	Multiple Input Multiple Output
MM	Medium Mobility
MME	Mobility Management Entity
MSC	Mobile Switching Centre
MT	Mobile Terminal
MUD	Medium Users Density
NICT	National Institute of Information and Communications Technology
NLoS	Non Line of Sight
NoCF	Non Cost Function
NRT	Not Real Time
O&M	Operation and Maintenance
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
OVSF	Orthogonal Variable Spreading Factor
PA	Power Amplifier
PCF	Point Coordination Function
PDF	Probability Density Function
PF	Proportional Fair
PHY	PHYsical
PS	Packet Switch
PSu	AC-DC Power Supply
PSK	Phase-Shift Keying
PSTN	Public Switching Telephone Network
QAM	Quaternary Amplitude Modulation

QoS	Quality of Service
QPSK	Quaternary Phase Shift Key
RAT	Radio Access Technology
RF	Radio Frequency
RLC	Radio Link Control
RMG	Relative MIMO Gain
RMU	Resource Management Unit
RNC	Radio Network Controller
RR	Round Robin
RRM	Radio Resource Management
RT	Real Time
RTP	Real Time Protocol
SC	Switching Centre
SD	Standard Deviation
SGSN	Serving GPRS Support Node
S-GW	Serving Gateway
SHO	Soft HandOver
SINR	Signal-to-Interference-plus-Noise Ratio
SISO	Single Input Single Output
SOHO	Small Office Home Office
TC	Traffic Class
TCP	Transmission Control Protocol
TDMA	Time Division Multiple Access
TIA	Telecommunications Industry Association
ToS	Type of Service
TOT	Total Occupation Time
TRX	Transceiver
TTB	Transmission Time Budget
TTI	Transmission Time Interval
TVD	Time or Volume Dependent
UE	User Priorities
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UTRAN	UMTS Terrestrial Radio Access Network
VBR	Variable Bit Rate

## *List of Acronyms*

VHO	Vertical HandOver
WCDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity
WiMAX	Worldwide Interoperability for Microwave Access
WLAN	Wireless Local Area Network
WWW	World Wide Web



# List of Symbols

$\alpha$	BS orthogonal factor (CDMA environments)
$\alpha_i$	Video model autoregressive process coefficient
$\alpha_p$	Pareto distribution shape
$\beta_k$	Weibull probability distribution shape parameter
$\Delta t$	Time interval
$\eta_{DT}$	System or network data efficiency
$\eta_{HHOr}$	Horizontal handover cell crossing rate
$\eta_{PT}$	System or network power efficiency
$\eta_{VHO r}$	VHO crossing rate
$\lambda_b$	HHO calls average arrival rate
$\lambda_k$	Weibull probability distribution scale parameter
$\lambda_{sp}$	Call arriving rate from other RAT
$\lambda_{vb}$	VHO calls average arrival rate
$\mu$	Lognormal mean
$\rho_{AU}$	Active users capacity density
$\rho_l$	Signal to interference ratio in downlink
$\sigma$	Lognormal variance
$\tau_{Ce}$	Expected JRRM delay
$\tau_{d,r}$	RAT $r$ delay
$\overline{\tau_{JRRM}}$	JRRM average delay
$\tau_k$	Voice model burst duration
$\tau_s$	Service $s$ average duration
$\Psi$	Street orientation angle

## List of Symbols

$\psi_{i,p,s,r}$	Fittingness factor
$A_{cov,r}$	BS coverage area
$A_v$	VHO traffic between RATs
$B\alpha$	Shape correction parameter
$C_{bs,r}$	BS capacity
$C_{MT,n}$	$n^{th}$ MT cost
$C_{NT}$	Network Total Cost
$C\theta_r$	Operator's total cost for given RAT $r$
$C\theta_{r,b}$	Operator's cost for each BS $b$ , RAT $r$
$C_U$	Total power cost required to transmit $V_D$
$d$	Distance between BS and MT
$D\alpha$	Correction parameter
$d_B$	Building separation
$D_s$	Data volume for a given service $s$
$f$	Frequency
$F_{BS}$	BS receiver noise figure
$F_{HHO}$	HHO failure rate
$F_{VHO}$	VHO failure rate
$G(\phi, \varphi)$	Antenna diagram for each sector (vertical and horizontal)
$G_{BS}$	BS antenna gain
$g_i(n)$	Gaussian random variable of $n$ state
$h_B$	Building height
$h_{BS}$	BS antenna height
$h_{MT}$	MT height
$i$	User $i$
$I_{inter}$	Interference generated by other cells
$I_{intra}$	Interference generated inside a cell
$J_{id}$	JRRM Instantaneous delay
$K$	Voice model state
$k_{b,i}$	Normalised value of each KPI

$k u_i$	User $i$ KPI
$L_0$	Free Space attenuation
$L_B$	Building loss
$L_{BF}$	Load balancing factor
$L_C$	Cable loss
$L_{msd}$	Multi-screen diffraction loss
$L_{ori}$	Attenuation caused by street orientation in relation to radio path
$L_p$	Propagation model average path loss
$\overline{L_r}$	Average load in RAT $r$
$L_{rts}$	Roof-to-street diffraction and scatter loss
$L_{UB}$	User body loss
$M_{CH}$	BS total available channels
$m_i$	Video transmission speed average value
$m_k$	Voice model mean burst duration
$N_0$	Noise spectral density
$N_{AU}$	Number of active users in JRRM
$N_{AU-D}$	Number of active data users
$N_{AUr}$	Number of active users attached to a given RAT
$N_{AUr,b}$	Number of Active Users in a BS/AP $b$ and RAT $r$
$N_{AU-V}$	Number of voice and video active users
$N_{Bco}$	Number of blocked calls due to channels
$N_{Bpo}$	Number of blocked calls due to load
$N_{BS}$	Number of BSs
$\overline{N_{BSMT}}$	JRRM average number of BS/APs reachable by all active MTs
$N_{BSMT,i}$	Number of BS/APs reachable by each active MT $i$
$N_{BSr}$	Total number of BSs for a given RAT $r$
$N_C$	Total number of calls
$N_{CorU}$	Number of covered users
$N_{FFVH}$	Number of VHOs triggered by the FF algorithm
$N_{Hf}$	Number of unsuccessful HHOs

## *List of Symbols*

$N_{HHO}$	Total number of HHOs computed by the simulator
$N_{HHOr}$	Number of HHOs given by the model for RAT $r$
$N_{KPIr}$	Total number of KPIs of a given RAT $r$
$N_{KPIu}$	Total number of KPIs for users
$N_{MT}$	Number of MTs
$N_{MTact,s}$	Number of active MTs using a service $s$
$N_p$	Total number of packets
$N_{RAT}$	Number of existing RATs
$N_{Vf}$	Number of unsuccessful VHOs
$N_{VHO_r}$	Number of VHOs estimated by the theoretical model
$N_{VHOsim}$	Number of VHOs computed by the simulator
$P_{B,r}$	RAT blocking probability
$P_{Be}$	Expected JRRM blocking probability
$P_{bJRRM}$	JRRM blocking
$P_{BSp}$	BS pilot Tx power
$P_{BSI}$	BS total power
$P_{CHr}$	RAT traffic distribution percentage defined at JRRM level
$P_{CVr}$	JRRM distribution of VHOs to RAT $r$
$P_D$	Power required to transmit the user information
$P_{FMT}$	Percentage of fast MTs
$P_H$	HHO probability
$P_{HF}$	HHO failure probability
$P_{Init,r}$	Initial traffic percentage for a given RAT $r$
$P_k$	Packet probability of being $S_k$ size
$P_O$	Power required to transmit the overhead information
$P_{rt}$	Packet Retransmission Time
$P_{SMT}$	Percentage of slow MTs
$P_{Sps}$	Service penetration probability
$P_T$	The total power required to transmit information
$P_{TX max}^{MT,r}$	MT maximum Tx power for a RAT $r$

$P_{VD}$	VHO drop probability
$P_{VH}$	VHO probability
$P_{VHF}$	VHO failure probability
$P_{VHO}$	VHO Percentage
$Q_k$	Voice model new state probability
$RAT_r$	BS type (RAT type $r$ )
$\overline{R_{b,i}}$	Average bit rate per user $i$
$\overline{R_{bJRRM}}$	JRRM average bit rate
$\overline{R_{b,s}}$	Average bit rate per service $s$
$\overline{R_{bt}}$	Total JRRM average bit rate
$R_i(n)$	Video transmission speed at $n$ state
$R_{NO}$	Receiver noise density
$R_r$	Cell radius
$R_{rc}$	RAT cluster approximated radius
$S_a$	Service area
$Sbr_{r,b,s}$	Service $s$ bitrate for BS/AP $b$ and RAT $r$
$S_k$	Voice model packet size
$S_O$	Sector 1, 2, 3 orientation
$S_{Rp}$	Services priority table (services priorities mapped into RATs)
$S_p$	Simulator version
$T_{\rho N}$	Overall traffic density
$T_{\rho N, r}$	Multi-service traffic generation density for each RAT
$T_{AN}$	Total generated traffic
$T_{CN}$	Overall network capacity density
$T_{CN, r}$	Network capacity density for each RAT
$U_t$	Urban type
$V_D$	Information volume only related to real user data
$V_{MTFmax}$	Maximum speed for fast MTs
$V_{MTFmin}$	Minimum speed for fast MTs
$V_{MTSmax}$	Maximum speed for slow MTs

## *List of Symbols*

$V_{MTSmin}$	Minimum speed for slow MTs
$V_o$	Information volume related to overhead and signalling
$\overline{v_r}$	Average speed
$V_T$	The total information volume
$w$	Street width
$w_i$	Weight of each user KPI
$w_o$	Operator's weight
$w_{o_r}$	Operator's weight for each RAT $r$
$w_{r,i}$	The weight of each $i$ KPI
$w_u$	User's weights
$X_{BS}$	BS location $x$
$x_m$	Pareto distribution scale
$Y_{BS}$	BS location $y$

# List of Programs

JRRMSim	JRRMSim is the thesis simulator, developed in Visual C++, and used to evaluate the majority of the proposed models.
MS Excel 2007	Excel is used to implement simple analytical models and to process results produced by JRRMSim.
Matlab	Matlab is used to validate some statistical functions and models developed in the simulator JRRMSim.
MS Word 2007	Word is used to edit this thesis and all associated documents such publications.
MS Visio 2003	Visio is used to edit several figures presented in this thesis.





# Chapter 1

## Introduction

This chapter provides the thesis overview, presenting, in Section 1.1, a brief history of the cellular evolution in the last two decades, and in Section 1.2 key aspects of the thesis motivation and objectives. Section 1.3 highlights the novelty aspects and concepts explored in the thesis. Section 1.4 provides an overview on the pursuit research strategy, where projects contributions and published work are highlighted. Finally, the dissertation contents are defined in Section 1.5.

## 1.1 Brief History

In the last two decades, mobile and cellular networks experienced an extraordinary evolution, mobile operators (some based on fixed networks and others from relevant economic groups) worldwide have gained billions of users into their continuous innovative networks, capabilities and services. This global industry has a tremendous impact on worldwide population daily lives, because users look at Mobile Terminals (MTs) as a functional link to their multi-relations with the rest of the world (families, colleagues, friends, Internet services, health care, emergency services, etc.). Today, MTs represent a “digital interface” for each person, connecting each individual to a communications network anywhere, any time, at a very acceptable cost.

The modern communications adventure started in 1980s with analogue first cellular generation systems, being very limited in coverage, cost and portability. The big boom started when digital 2<sup>nd</sup> Generation (2G) systems, promoted by the European Telecommunications Standard Institute (ETSI), were deployed in Europe, the Global System for Mobile Communications (GSM). GSM uses a combination of Frequency Division Multiple Access (FDMA) and Time Division Multiple Access (TDMA), being the first dedicated to voice and data over circuit switching. Figure 1.1 represents the commercial deployment of this evolution, starting from the 1990s up to today. 2G systems made considerable progress, because for the very first time they established a logical link between terminals and users implemented by SIM cards, leading to the personal communications concept. Furthermore, they allowed users to cross countries frontiers, using the same mobile device and operator account to communicate. This was a key feature for the global 2G success, leaving other regional systems behind, while attracting new operators and users to GSM networks. Later, packet switching services were integrated when General Packet Radio Service (GPRS) was deployed. This was also a very important step, because circuit and packet switch services converged to a single network/terminal in a mobile communications environment. The Enhanced Data for GSM Evolution (EDGE) was the following 2G step towards 3<sup>rd</sup> Generation (3G) systems, pushing GSM to its limits, increasing the bit rate by optimising the way that radio resources are used.

Universal Mobile Telecommunications System (UMTS) was announced in 2000 to be a revolutionary system, overcoming the 2G success, leading networks and users' experience to the next level, by increasing services bit rates and allowing better Internet access, and video calls, among others. 3G MTs started to be very much data consumers and generators, because MTs

started to be equipped with video/photo cameras, colour screens and audio players, among other gadgets, like keyboards or touch displays. Also, memory and new software processing capacity in MTs contributed to a new dimension in mobile communications, the multimedia one. At the radio interface, a key aspect to increment a generation was the new disruptive air interface technique, the Wideband Code Division Multiple Access (WCDMA), defined by 3rd Generation Partnership Project (3GPP), to multiplex users based on an orthogonal code, sharing the same band, proving operators new cellular planning concepts and flexibility. 3G also introduced a less mentioned, however relevant, factor, i.e., the capacity to integrate legacy generations (GSM). This meant that, for the first time, heterogeneous networks shared a common switching core (circuits and packets), databases and users account centres, keeping independent only the base station sub-system, although co-located.

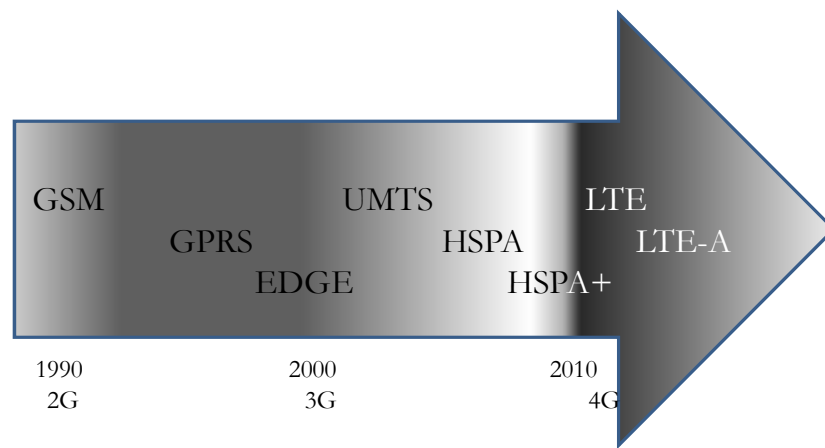


Figure 1.1 – ETSI/3GPP cellular evolution in the last two decades.

Furthermore, 3G systems keep evolving to new versions, mainly at the radio interface, new modulation techniques, packets scheduling, channel encoders, antennas systems/processing like Multiple Input Multiple Output (MIMO), etc. These new improvements are known as High Speed Packet Access (HSPA) and High Speed Packet Access Plus (HSPA+), UMTS releases 5, 6 and 7, allowing the efficient combination of voice, video and data services. Furthermore, with these new optimised air interfaces, data reached high throughputs at a low cost, comparing to cable costs and mobility limitations. This aspect, associated to flat rates offered by operators, led data traffic to an exponential growth worldwide; also, it is via a 3G MT that new millions of users in developing countries access Internet applications. One should also mention the Machine to Machine paradigm and associated applications, with strong and rising contribution to data traffic.

In the last few years, industry made the next relevant step, and moved to the 4<sup>th</sup> Generation (4G), the so called Long Term Evolution (LTE), Releases 8 and 9, and Long Term Evolution–Advanced (LTE-A), Release 10. This generation increment also brings new features to mobile

operators, and naturally to end users, besides introducing a more modern multiple access air interface, the Orthogonal Frequency Division Multiple Access (OFDMA), enabling higher bit rates. LTE introduces the latest findings from research groups, by increasing the mobility experience to end users, like top mobility speeds, very low latencies even during handovers, retro compatibility to legacy systems, power savings, a relevant set of radio resource management possibilities and optimisation, larger bands, and packet scheduling to users in an opportunistic manner, based on radio channel variations experience by each individual MT.

## **1.2 Thesis Motivation and Objectives**

Currently, in wireless cellular networks, convergence is mainly considered at the core network level, with the use of Internet Protocol (IP) as the universal networks “glue”. However, not much attention has been given to how the various wireless standards can be converged at the MT, if multiple wireless standards are available to the user from a common core network. Under this context, important issues arise, like determining how services map onto certain standards (or even split between standards), and how can this be made seamless or transparent to MTs. Another important issue, still to be analysed, is the impact of convergence on the several access networks performance (and vice-versa) and the consequences to users’ experience. Based on this “environment”, new challenges arise, namely the radio resource management schemes and associated methodologies, and the way that these algorithms/management policies will handle the new, and rising, network parameters in a balanced and controlled way.

This thesis is precisely motivated by this vision of future wireless communication systems, where there will be a convergence of wireless standards, leading to new enhancements in networks and users experience.

In a future wireless mobile heterogeneous network environment, Radio Resource Management (RRM) and Joint RRM (JRRM) entities, and their corresponding functionalities and algorithms, must perform important decisions, based on a huge amount of spatial-temporal data. This important information frequently consists of counters and network performance indicators, mainly generated by cellular Base Stations (BSs) at the radio interface. Moreover, in a heterogeneous environment, these BSs belong to different Radio Access Technologies (RATs), which intrinsically have different Key Performance Indicators (KPIs). Since the number of these parameters is increasing in current and future systems, and JRRM requires a high level view of

network performance, a common and integrated solution to this problem should be identified. Additionally, the solution to this problem should handle mainly radio resources evaluation and network conditions, enabling, in a flexible manner, the implementation of different network management policies.

The thesis dominant objective (Figure 1.2) is to propose a set of reasonable simple models to be implemented by future heterogeneous networks entities, which will manage radio resources at low and high levels, RRM and JRRM entities, respectively. These models should be capable to handle a wide range of networks indicators (including future and unpredictable ones), especially capable of including multiple cellular networks. Besides driving the networks parameters set, models should also provide mechanisms to evaluate and predict networks capacity and performance for any scenario. These objectives should be demonstrated by a multi-system simulation tool platform developed throughout this thesis, where different studies are developed to evaluate the overall network performance, obtained for different scenarios, using different approaches, namely:

- analysis of the impact of users traffic variations;
- analysis of the impact of users' services on specific reference scenarios corresponding to different available access technologies;
- evaluation of the expected benefits by having convergence and a central management entity;
- analysis of the impact of different centralised policies on the overall networks performance;
- comparison of different centralised algorithms and management policies;
- introduction of energy efficiency awareness into RRM issues;
- the development of simple analytical models to compare with simulations results.

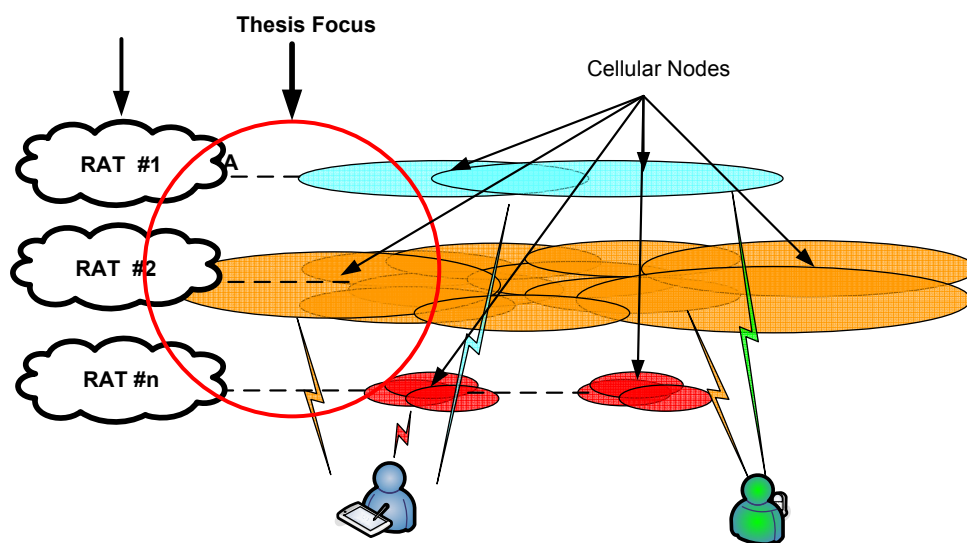


Figure 1.2 - Thesis focus identification.

Summarising, the key goal of this work is to propose a flexible solution to manage heterogeneous networks, assuming a high level of integration among them. In order to illustrate the focal point of the thesis, a red circle in Figure 1.2 presents the JRRM area, where different types of cellular networks coexist. This relevant characteristic should be handled opportunistically, since the jointly management of these different wireless access nodes, will enhance the overall user experience and the network operator management efficiency indicator, from the network capacity up to their energy efficiency gains.

### **1.3 Novelty**

Cellular heterogeneous networks are converging to present a single view to end users, which is possible because network cores are continuously being simplified by emerging simple integrated architectures and centralised networks implementation. However, they present new areas for research, namely management of radio resources of different systems in an integrated manner to handle new problems and management opportunities. Therefore, new perspectives are required to simplify the rising complexity, when different cellular networks specifications need to be handled by a single supervisor, with the power to change any of the radio resources available.

Based on the previous environment, this thesis claims novelty when some new ideas and models are proposed to manage heterogeneous networks. In the telecommunications industry, operators and users are key stakeholders. Nevertheless, operators' decisions usually do not take users demands and profiles into account, thus, this thesis also explores and proposes the inclusion of users' interests into the management decisions board, by measuring their relevant metrics. The innovative mechanism for this relevant characteristic is that it should be "implementable", otherwise, systems vendors do not show any interest, hence, it should be simple and provide results in real time.

Another novel requirement is that future changes in management should present simple ways to add new key parameters or remove old ones, or even be capable to include new management policies criteria. Furthermore, it should allow for the inclusion of future network systems managed under the JRRM domain.

Additionally, this thesis claims another innovative aspect, the RRM/JRRM theoretical model. This model is capable of including, in a simple and relatively realistic manner, several relevant network issues that are hard to find (in literature) modelled by simple analytical approaches. It

enables a mobile operator to use the model in order to estimate Quality of Service (QoS) at RRM and JRRM levels, when deploying heterogeneous networks in different multi-service traffic densities/mobility and multi RAT coverage scenarios.

Finally, this thesis also addresses RAT's energy efficiency by proposing fundamental metrics, focussed on the way that networks radio protocol overhead and useful data are related, and can be analysed from the energy efficiency viewpoint. This matter is very important for current network operational costs, having also significant impacts on the environment.

## **1.4 Research Strategy and Impact**

The work developed in this thesis was done within different research European frameworks and projects, such as the Sixth Framework Programme (FP6), the Seventh Framework Programme (FP7), and also in the Co-operation in the field of Scientific and Technical Research (COST), namely IST-AROMA, ICT-4WARD, COST2100, ICT-EARTH, and ICT-NEWCOM++. Although all these projects had a considerable work overhead beyond this thesis, they enabled the contact with many senior researchers from many other international institutions, namely networks vendors, cellular operators, research centres and universities, by sharing knowledge, experiences, publishing joint work, and being aware of different visions from the so called “real world or industry”. Thus, in the development of this thesis, these projects naturally have a considerable influence over many decisions taken.

Technological groups were defined, allowing simple abstractions from the system standards detailed implementation, therefore, extending the developed models and algorithms applicability in time, keeping relevant systems characteristics into consideration, like coverage, bit rate, channel bandwidth and radio management fundamental techniques.

Since the focus is RRM and JRRM supporting models and algorithms, relevant reference scenarios were defined in order to explore key points touched by all these models, demonstrating the flexibility and performance gains provided by them. In this research area/environment framework, it is hard to select key scenarios and corresponding results, since the number of possible combinations are literally infinite, thus, only some of examples are shown to evaluate system trends, and in some cases system limits.

Finally, another important strategy is the definition of analytical models, enabling relevant comparison capabilities with other models under simulation. These models present a simple

mathematical approach, being less complex than the ones implemented in simulation; they also allow network designers to extract a network performance prediction.

Some concepts and ideas explored by this thesis have impact on different aspects of wireless communications networks, especially in wireless heterogeneous network environments. When these networks work in a cooperative manner, they require less energy or radio resources to provide a high quality experience to end users. Thus, this thesis has impact on the environment itself, by reducing energy consumption at radio interface equipments, or in the number of access systems, since different wireless networks can work together in a more efficient way, contributing to the green wireless strategy. Another important impact of this thesis is on the network architecture, since it requires at least one more relevant module, which is the JRRM entity that will process the algorithm, by implementing overall management policies.

The work presented in this thesis was already disseminated in several papers that were published or submitted to various conferences and journals:

- International Journals:
  - Ferreira,L., Serrador,A., and Correia,L.M., “Concepts of Simultaneous Use in Mobile and Wireless Communications”, *Wireless Personal Communications*, DOI: 10.1007/s11277-006-9045-6, Vol. 37, No. 3, May 2006, pp. 317-328.
  - Serrador,A. and Correia,L.M., “A Cost Function Model for CRRM over Heterogeneous”, *Wireless Personal Communications*, DOI 10.1007/s11277-010-9919-5, Vol. 59, No.2, July 2011, pp 313-329.
  - Cardoso,F., Correia,L.M., Mannersalo,P. Fanti,T. Serrador,A., Nunzi,G., Genay,N., and Le Rouzic,E., “Physical Layer Aware Network Architecture for the Future Internet”, accepted for publication in *IEEE Communications Magazine*, 2011.
  - Serrador,A. and Correia,L.M., “An Analytical Model to Evaluate JRRM QoS Parameters”, submitted to *Wireless Personal Communications*, Sep. 2011.
- International Conferences:
  - Serrador,A., Galvano,G., Ferreira,L. and Correia,L.M., “Parameters for the Definition of Scenarios for CRRM Performance Evaluation”, in *Proc. of MELECON 2006, - 13<sup>th</sup> IEEE Mediterranean Electrotechnical Conference*, Málaga, Spain, May 2006 (<http://www.melecon2006.etsit.uma.es>).
  - Serrador,A. and Correia,L.M., “A Cost Function for Heterogeneous Networks Performance Evaluation Based on Different Perspectives”, in *Proc. of 16<sup>th</sup> IST Mobile and Wireless Communications Summit*, Budapest, Hungary, July 2007 (<http://www.mobilesummit2007.org>).



- Serrador,A. and Correia,L.M., “Policies For a Cost Function For Heterogeneous Networks Performance Evaluation”, in *Proc. of PIMRC’07 – The 18<sup>th</sup> Annual IEEE International Symposium on Personal Indoor and Mobile Radio Communications*, Athens, Greece, Sep. 2007 (<http://www.pimrc2007.org>).
- Serrador,A. and Correia,L.M., “*A Cost Function for Heterogeneous Networks Performance Evaluation*”, in *Proc. of ConfTele’2007 – 6<sup>th</sup> Conference on Telecommunications*, Peniche, Portugal, May 2007 (<http://www.co.it.pt/conftele2007>).
- Serrador,A., Kuipers,M. and Correia,L.M., “Impact of MIMO Systems on CRRM in Heterogeneous Networks”, in *Proc. of IEEE- WCNC08 - Wireless Communication Networking Conference*, Las Vegas, NV, EUA, Mar.-Apr. 2008 (<http://www.ieee-wcnc.org/2008>).
- Serrador,A. and Correia,L.M., “*A Model for Heterogeneous Networks Management and Performance Evaluation*”, in *Proc. of NOMS’08 - IEEE/IFIP Network Operations and Management Symposium*, Salvador, Brazil, Apr. 2008 (<http://www2.dcc.ufmg.br/eventos/noms2008>).
- Serrador,A., Kuipers,M. and Correia,L.M., “*MIMO Capacity Influence on JRRM*”, in *Proc. of WPMC 2008 - Wireless Personal Multimedia Communications*, Lapland, Finland, Sep. 2008 ([www.wpmc2008.org](http://www.wpmc2008.org)).
- Caeiro,L., Serrador,A., Cadoso,F.D., and Correia,L.M., “Radio Resource Management in Multiple Virtual Networks”, in *Proc. of FUNEMS’10 – Future Network & Mobile Summit 2010*, Florence, Italy, June 2010 (<http://www.futurenetworksummit.eu/2010>).
- Serrador,A. and Correia,L.M., “*A Model to Evaluate Vertical Handovers on JRRM*”, in *Proc. of PIMRC 2010 - IEEE 21<sup>st</sup> Annual International Symposium on Personal, Indoor and Mobile Radio Communications*, Istanbul, Turkey, Sep. 2010 (<http://www.ieee-pimrc.org/2010>).
- Serrador,A. and Correia,L.M., “*Energy Efficiency Gains Using VHOs in Heterogeneous Networks*”, in *Proc. of IFIP 2012 - 11<sup>st</sup> International Conferences on Networking*, Prague, Czech Republic, May 2012 (<http://networking2012.cvut.cz>).

Also, contributions were made within the European research projects as follows:

- Advanced Resource Management Solutions for Future All IP Heterogeneous Mobile Radio Environments (IST-AROMA), [AROM09]:
  - Target Scenarios specification: vision at project stage 1, [Ljung06].
  - Simulation tools: inherited features and newly implemented capabilities, [Serr06b].
  - First report on AROMA algorithms and simulation results, [Sall06].

- Simulation tools: final version capabilities and features, [Serr07].
- Intermediate report on AROMA algorithms and simulation results, [Sall07].
- Final report on AROMA algorithms and simulation results, [Rome07].
- Architecture and Design for the Future Internet (ICT-4WARD), [4WAR10]:
  - Virtualisation Approach: Concepts, [BaGo09].
  - Physical Layer Awareness, [CCMF10b].
- Energy Aware Radio and neTwork tecHnologies (ICT-EARTH), [EART11]:
  - Most Promising Tracks of Green Network Technologies, [Godo11].
- The FP7 European network of excellence in Wireless Communications (ICT-NEWCOM++), [NEWC10]:
  - Identification of relevant scenarios, use cases and initial studies on JRRM and ASM strategies, [Serr08].
  - Definition and evaluation of JRRM and ASM algorithms, [Srok09].
  - Final report of the JRRM and ASM activities, [Rome10].

Additionally, most of the relevant work was presented in regular meetings of the COST Action 2100 (COST2100) [COST10].

## 1.5 Contents

This thesis is organised in 8 chapters, including this one. In Chapter 2, some basic wireless radio families systems are briefly described, oriented to basic common characteristics, like systems architectures, radio interface, systems characterisation, mobility and throughput, coverage and capacity. Chapter 3 presents the state of the art on models and algorithms related to RRM in current and future wireless systems, and also an approach to 4G management policies, entities and concepts. Chapter 4 describes and proposes new JRRM models and algorithms, being the novelty in this thesis. In Chapter 5, some simulations aspects, decisions, approaches and implementation aspects are addressed. In Chapter 6, reference scenarios and corresponding variation are proposed; based on these scenarios, and on developed analytical models, theoretical results are presented and discussed. Relevant simulation results are presented in Chapter 7, including a brief comparison with theoretical ones. Finally, in Chapter 8, significant conclusions are summarised and future research work lines are also proposed. Further detailed information can be found in Annexes, i.e., in Annex A details about mobility models are provided. In Annex B, the adopted propagation models are described. In Annex C, the used traffic source models for

traffic generation are presented. In Annex D, models validation procedures and evaluation are shown. To conclude, in Annex E, extra results obtained from one particular JRRM algorithm are shown.



# Chapter 2

## Systems Overview

This chapter presents the current state of the art of different kinds of mobile and wireless technologies, the radio interface being the main focus. In order to contextualise the usage of the different wireless technologies, Section 2.1 provides a simple approach to services-applications and scenarios. The following Sections 2.2 and 2.3 present common systems characteristics, current systems and other aspects namely the future ones. At the end, in Section 2.4, a comparison is proposed to discuss solutions associated to different scenarios.

## 2.1 Services, Applications and Scenarios

In this section, an overview on services, applications and scenarios is presented. Since this thesis deals with RRM in heterogeneous networks, a simple characterisation of these topics is required. Voice is the most widely used service by humans. However, humans and machines (mobile or fixed ones) are using data services more and more, therefore, an overall characterisation of different classes of services and applications should be taken into account.

3GPP [3GPP06] has classified services as shown in Table 2.1, where one may find four main service classes: Conversational, Streaming, Interactive, and Background.

Table 2.1 - 3GPP service classes classification.

		Traffic class			
		Conversational	Streaming	Interactive	Background
Fundamental characteristics	Connection delay (main attribute)	Minimum fixed	Minimum variable	Moderate variable	High variable
	Buffering	No	Allowed		
	Bandwidth	Guaranteed bit rate		No guaranteed bit rate	
	General Characteristics	Symmetric traffic, delay sensitive, low emphasis on signal quality	Asymmetric traffic, delay variation sensitive, not sensitive to transmission errors	Asymmetric “request-response” traffic, low round trip delay, high signal quality required	Asymmetric, non-real time traffic, high signal quality required
	Real Time	Yes		No	
	Typical Applications	Voice, video telephony, interactive games	Audio streaming, video on demand	Voice messaging, FTP, Web browsing	E-mail, SMS, MMS, FAX

With the growth of UMTS High-Speed Downlink Packet Access (HSDPA) and High-Speed Uplink Packet Access (HSUPA) networks, which allow the efficient combination of voice, video and data services, a lot of studies have been conducted, and the resulting literature is widely available regarding the modelling of the services and applications that can be carried on these networks. However, as far as Worldwide Interoperability for Microwave Access (WiMAX) is concerned, the same type of studies is not yet available in large scale. WiMAX is flexible enough

so that different QoS profiles can be set almost on a per application basis, as long as the higher layers, such as Transmission Control Protocol (TCP)/IP, can somehow differentiate the different packets generated by the different applications. A wide range of different applications are addressed by Institute of Electrical and Electronics Engineers (IEEE) 802.16e, Table 2.2.

Table 2.2 -WiMAX Services Classes (extracted from [WiMa05]).

Class Description	Application Type	Real Time	Data Rate
Interactive Gaming	Interactive Gaming	Yes	50-85 kbps
VoIP, Video	VoIP		4-64kbps
Conference	Video Phone		32-284kbps
Streaming Media	Music/Speech		5-128 kbps
	Video Clips		20-384 kbps
	Movies Streaming		> 2 Mbps
Information Technology	Instant Messaging	No	< 250 Bytes /message
	Web Browsing		> 500 kbps
	e-mail		> 1 Mbps
Media Content Download (Store and Forward)	Movie FTP		> 500 kbps
	Peer-to-Peer		> 500 kbps

The classification of services by 3GPP, [3GPP06], is mainly directed to cellular networks. The characteristics of a Wireless Local Area Network (WLAN) are somehow different, but even so, that classification can be used as a starting point to analyse their fundamental differences.

In the 802.11d standard [IEEE04], another type of traffic differentiation is proposed, some new traffic types being defined, representing different kinds of traffic that can be present in a given network. Having a distinction between traffic types allows latency and throughput guarantees to be supported by the network. This classification was proposed for wired LANs, but it is used also by the 802.11e [IEEE05] standard for QoS in WLANs. Seven traffic types are defined in IEEE 802.11d, as follows:

- Network Control – the most important traffic that must have priority over the rest;
- Voice – very stringent regarding delay, the maximum delay being as low as possible;
- Video – with some limitations regarding the maximum delay, but not as severe as Voice;
- Controlled Load – having important applications subject to admission control and with controlled throughput;
- Excellent Effort – a best effort traffic with higher priority than the lower classes;
- Best Effort Traffic – the normal LAN traffic;
- Background – traffic that is allowed on the network, but that should not interfere with the traffic from any of the other classes.

In some scenarios, e.g., 802.11e networks, [IEEE05], a different number of Traffic Classes (TCs) can be available on a given network, and, sometimes, some of the defined traffic types must be grouped together into a single class. This problem is also addressed in the standard, some possible solutions being proposed, depending on the number of classes available within the network. A mapping between various TCs and the traffic types defined (including a spare type) is also identified in the standard, Table 2.3. According to the standard, the spare type is to be used for scenarios where it may be advantageous to have an additional traffic type, similar to best effort, to support bandwidth sharing management for bursty data applications.

Table 2.3 - Mapping between User Priority and traffic types (extracted from [IEEE04]).

User Priority/Traffic	Classes Designation	Traffic type
1	BK	Background
2	-	Spare
0 (Default)	BE	Best Effort
3	EE	Excellent Effort
4	CL	Controlled Load
5	VI	Video
6	VO	Voice
7	NC	Network Control

In most cases, a scenario depends on systems availability and usage profiles taken by users. For example, in a modern and busy airport, many (if not all) wireless systems may be deployed; in this scenario, it is also possible to identify different user profiles, like mass market, Small Office Home Office (SOHO), business users, tourists, or even airport staff personal. Since systems usage is constrained by the scenario itself, a set of typical scenarios must be defined and characterised, highlighting the thesis problem: networks heterogeneity. This must be done combining both human and machine data communications.

Scenarios like airports, shopping centres and urban business hot spot areas can/should be analysed, to evaluate the use of different RRM policies. In the presence of these different scenarios, services and user profiles, different wireless systems can be combined in such a way that the more suitable system is used for a given service and user profile. In a scenario where different wireless systems are present, each one should be characterised by its intrinsic capabilities, like services, coverage areas, capacity, throughput, QoS, mobility, information distribution capabilities (uni-, multi-, and/or broad-cast), traffic generation densities, users profiles combination, and network and service costs, among others.

Using appropriate RRM strategies in each wireless system, and simultaneously using JRRM as a way of having different wireless systems cooperating together, will increase the general offered



QoS. These management policies will naturally take advantage of the individual systems characteristics, in order to provide the best quality to a given service or application. For example, if a service requires an Internet access (with high mobility), most probably the best system will be a high capacity cellular network, but if the user is static, perhaps a WLAN will be the best option. Nevertheless, the odds can be different at dynamic and complex scenarios, where wireless systems can experience heavy traffic loads, therefore, not being available at a given point in time.

In order to meet the previous concept, in the following sections each type of network is discussed and its main characteristics are highlighted, the combination of different wireless systems being the main focus, in order to increase the overall service provided to end users.

A key aspect when defining scenarios in cellular networks is the offered traffic, which is independent of the networks. But the user's behaviour is closely dependent on network billing policies and performance, thus, in the presence of a heterogeneous scenario, users will generate traffic based on the average performance and cost (billing).

Traffic is mostly dependent on user's densities, number of connections per time interval, and finally on connection average time or information volume transferred. These basic parameters can be defined in relatively complex models, since these parameters can be classified in different categories like user types (Business, Mass Market, etc.), operational environments (City Centre, Urban, Sub-urban, Rural, etc.), services differentiation (conversational, streaming, etc.), their combination being a complex set of traffic layers [FCSC02]. In any case, traffic generated by each service can be defined by their Busy Hour Call Attempt (BHCA).

## **2.2 Wireless Local Area Networks**

### **2.2.1 Network Architecture**

When WLANs were designed, the main goal was to produce a wireless version of the current fixed computer networks, the so called LANs. For this reason, the WLAN main characteristics are quite similar to the LAN ones, namely stack layers protocols and supported services, therefore, being classified in this thesis as High Bitrate Networks (HBN). The HBN concept in this thesis is assumed to be a family of wireless networks that can offer bitrates above 40 Mbps.

WLANs architecture may be divided in two operating modes: infra-structured and ad hoc.

- Infra-structured, is the most popular and important mode, basically supporting a wireless Physical (PHY) layer and a Medium Access Control (MAC) one, these two layers being transparent to the wired LAN upper layers, which enables access to the wired network and interfaces to the logical data link and management layers. Besides this, it can also provide additional functionalities, like terminal mobility among the different Access Points (APs), Figure 2.1, supported by a Distribution System (DS) architecture.

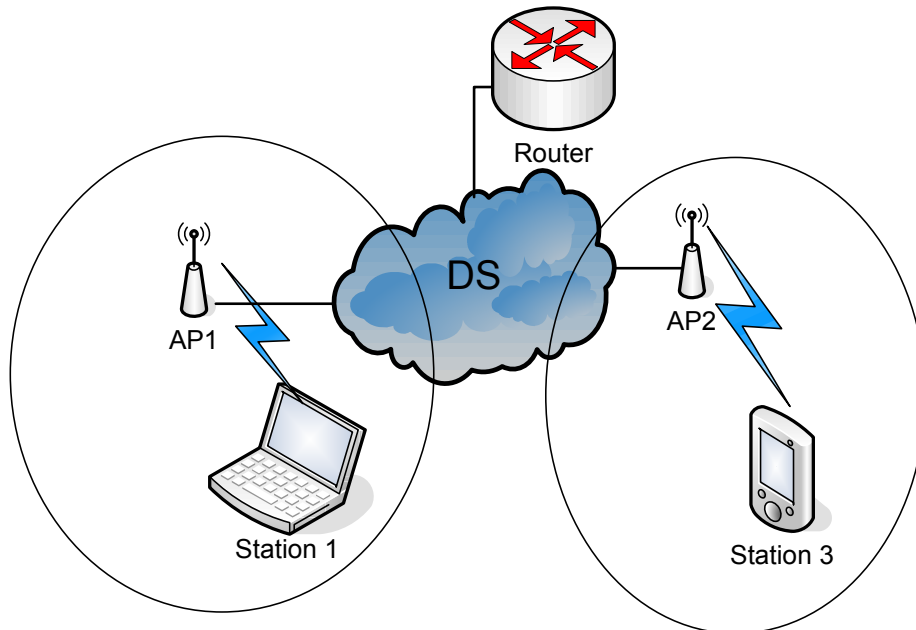


Figure 2.1 – Infra-structured architecture.

- The ad hoc architecture allows MTs to establish direct links, transferring data without additional equipment, being useful for data transfer among closely located users, enabling many network applications. In this environment, an important feature can be established, i.e., coverage extension, which can be accomplished by having an MT connected to the outside world (infra-structured), and at the same time being in ad-hoc mode with other MTs. The bearer service is basically data, however, voice, video, and Real Time (RT) applications in general, are being used more often; they are now supported over data networks due to the high capacity in data transmission, which reduces delay to acceptable levels, QoS being based typically on throughput and packet delay. Issues like security, mobility management, channel access procedures, channel interference, network planning, network access control, and physical resources management, are different from the wired world.

The deployment of these networks is made mainly in indoor environments, which intrinsically reduces the network coverage; moreover, the standardised transmitted power levels are quite low, being typically set to be less than 100mW, thus, coverage is also limited by this factor. But, this

potential drawback is very useful to maintain the covered users by a given AP above a minimum QoS in a crowded network.

WLANs have a very large capacity compared to others types of wireless networks; however, this characteristic is accomplished by sacrificing other aspects, like coverage. This high capacity is quite related to the channel throughput (tens of Mbps), which is supported on a wideband channel (tens of MHz).

In order to guarantee users mobility, the network coverage must be homogenous, therefore, in large networks, frequency reuse factor techniques are applied. WLANs at their “natural environment” are currently the “best” RATs enabling all types of applications, which can be supported over IP. Currently, other types of networks are taking advantage of this high performance, when a user (of a given operator) detects the presence of a WLAN (enabled by the same operator), it will probably handover to the WLAN, providing the user an expected higher QoS. However, this principle cannot be applied to all situations, namely intermediate or high user mobility scenarios; users usually operate their MTs in a quasi-stationary manner.

Another typical characteristic of a WLAN is that user throughput decreases when the distance between a user and an AP increases, leading to a non-uniform throughput coverage. Therefore, WLANs deployment should be carefully designed, in order to maintain user satisfaction in all areas assumed to be covered.

WLANs have an advantage compared to other systems, which is the overall low cost, at both the operational/maintenance and deployment levels. The infrastructure equipment cost is very low compared to other wireless access networks, or even in some particular case to wired ones. Thus, a WLAN is an important competitive technology in low mobility hot spot areas.

In these networks, billing can have different strategies, depending on the network deployment entity, which can be private or public. In private WLANs, installed essentially in company’s buildings, university campus, or even users homes, billing is absent, users’ authentication and data security being the main concern. In public WLANs, installed mainly in hot spot areas (e.g., airports or shopping areas), users, when authenticated, are charged as a function of connection time or traffic volume, or more recently with flat rate (responsible for traffic growth). In some cases, the user account is shared with other wireless networks.

## 2.2.2 Radio Interface

The IEEE WLAN family (also referred to as Wireless Fidelity (Wi-Fi)) is standardised under the 802.11'x' specifications. There are currently five main specifications in the family: 802.11 [IEEE99a], 802.11a [IEEE99b], 802.11b [IEEE99c], 802.11g [IEEE03a], and 802.11n [IEEE09b]. They all use the Ethernet protocol and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) for media sharing.

The modulation used in 802.11 has historically been Phase-Shift Keying (PSK). The modulation method selected for 802.11b is known as Complementary Code Keying (CCK), which allows higher data speeds, and is less susceptible to multipath-propagation interference. 802.11a uses OFDM, enabling data speeds up to 54 Mbps, but most commonly, communications take place at 6 Mbps, 12 Mbps, or 24 Mbps. In Table 2.4, the main parameters are presented.

Table 2.4 - IEEE 802.11 WLAN family basic comparison.

Standard	802.11b	802.11a	802.11g	802.11n
Access technique	CSMA/CA			
Coding and Modulation Schemes	CCK/DSSS QPSK	OFDM with [16, 64]QAM, QPSK and BPSK	CCK for DSSS with QPSK OFDM with [16, 64]QAM, QPSK e BPSK	OFDM, with BPSK, QPSK [16, 64]QAM MIMO
Throughput [Mbps]	1, 2, 5.5 and 11	6, 9, 12, 18, 24, 36, 48 and 54	1, 2, 5.5, 6, 9, 11, 12, 18, 24, 36, 48 and 54	6.5 up to 300
Frequency Bands [GHz]	[2.4, 2.4835]	[5.150, 5.250] [5.250, 5.350] [5.725, 5.825]	[2.4, 2.4835]	[2.4, 2.5] [5.150, 5.950]
Channel Bands [MHz]	3×25	8×20	3×25	20-40
Power levels[W] [mW/MHz]	1, 0.1 10	1, 0.05 25	1, 0.1 10	0.1 10

The 802.11b standard is limited to the PHY and MAC network layers. IEEE also defines other additional/amendment standards, described in Table 2.5.

Table 2.5 - 802.11 Standard and amendments basic description.

802.11 Extensions	Specific amendment
b	An extension to 802.11 that applies to WLANs providing 11 Mbps (with a fallback to 5.5, 2 and 1 Mbps) in the 2.4 GHz band. 802.11b uses only DSSS, allowing wireless functionality comparable to Ethernet.
d	It deals with information exchange between systems; local and metropolitan area networks, where specific requirements are defined at MAC and PHY layer specifications [IEEE01]. International roaming extensions.
e	New MAC layer, to enable QoS Support.
a	802.11a keeps the same data link layer protocol and frame format, but an OFDM based air interface. It operates in the 5 GHz band with a maximum net data rate of 54 Mbps, [IEEE03c].
h	It is an amendment to spectrum and transmit power management extensions in the 5GHz band, defining mechanisms for dynamic frequency selection and transmit power control that may be used to satisfy regulatory requirements for operation in Europe [IEEE03b].
g	802.11g was introduced by extending the 802.11a version to the 2.4 GHz band, the physical layer bitrate being 54 Mbps, [IEEE03d].
n	Specifies enhancements to IEEE 802.11 PHY and MAC sub-layers to provide modes of operation with useful data rates substantially higher than those previously available. This is accomplished by using wider channel bands and MIMO systems.

### 2.2.3 Other Aspects

Due to the current WLAN success, the future sounds very promising, since new incoming systems are already being prepared by standardisation bodies. The IEEE 802.20 Mobile Broadband Wireless Access (MBWA) which is also known as Mobile-FI, aims to enable high-throughput data rate Non Line of Sight (NLoS) links for vehicles and trains travelling up to 250 km/h in a metropolitan area network environment.

Additionally, the IEEE 802.21 standard defines services in the 802 family that enable and enhance handover between heterogeneous systems, through service interfaces within the MAC and PHY layers and the Heterogeneous Media Convergence (HMC) layer above the Logical Link Control (LLC). This crosses heterogeneous interface types, enabling policy enforcement, network selection, QoS parameter mapping, and handover signalling between heterogeneous interfaces in multi interfaced systems.

IEEE [IEEE09a] has launched a call for standards proposals in the areas of dynamic spectrum access, cognitive radio, interference management, coordination of wireless systems, advanced spectrum management, and policy languages for next generation radio systems. IEEE is

interested in ideas to be implemented in commercial products in the near to medium terms.

In Japan, the National Institute of Information and Communications Technology (NICT) and their wireless access group [NICT05] has researched and developed a wireless access system for new-generation mobile communications systems. The system is applicable to several network types i.e., cellular, WLANs, broadcasting, home, and intelligent transport, and is suitable for covering large areas, high-speed movement, and broadband communications. The wireless access group has also developed a multi-mode multi-service terminal for systems using software-defined radio. Also interesting is the mobile networking group [NICT09] within the e-Japan plan. This group develops technology that will assure complete convenience to the user through the utilisation of all available networks, without the user being aware of transferrals between mobile networks. More recently, NICT, [NICT09], is promoting a new research ambition, whose basis is the testbed network with advanced functionalities having a transmission speed in Terabit magnitude, which is the NICT vision towards the ubiquitous era.

## **2.3 Cellular Networks**

### **2.3.1 Network Architecture**

The general cellular network architecture, Figure 2.2, is characterised mainly by the radio stations, which are the MT and the BS and their corresponding Base station Controller (BC), the Switching Centre (SC) being the most important component where all communications are processed, supported by data base systems. The operator can manage the network via the Operation and Maintenance (O&M) centre. This general architecture can be divided in two main ones, the hierarchical type, where BSs are connected and controlled by an external element (BC), and the one, where BSs are directly connected to the SC, since they integrate many mobility and control functions.

Currently, the well known GSM is the most used cellular system in the world, which supports both CS and PS based services. Figure 2.3 presents an overview of GSM, UMTS and LTE connections, being possible to observe different interfaces between network elements (data base systems, controllers and switching systems). In Figure 2.3, each supporting node has functionalities that are described in what follows. The Mobile Switching Centre (MSC) is

responsible for the main functions of CS based services, being connected to all major data bases on the network. If a MSC is connected to other networks (mobile and/or fixed) it is called the Gateway Mobile Switching Centre (GMSC).

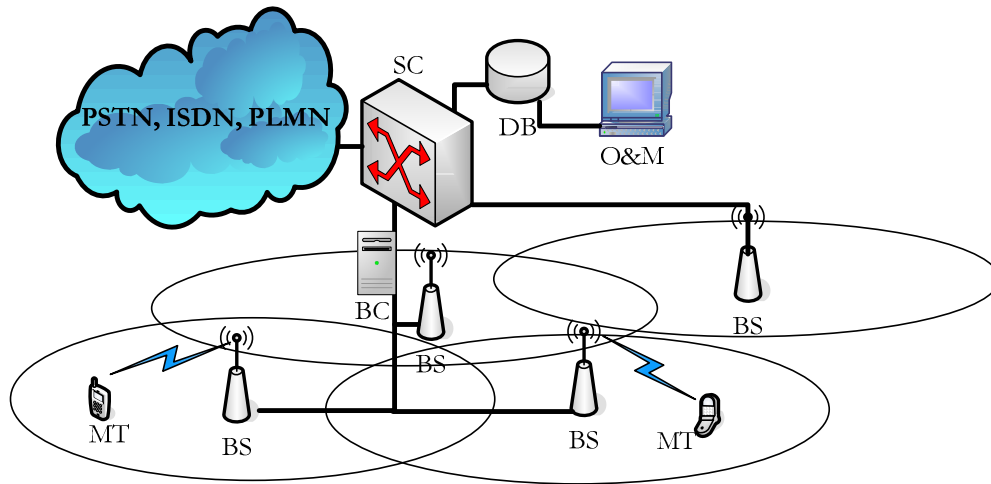


Figure 2.2 – Cellular networks basic architecture.

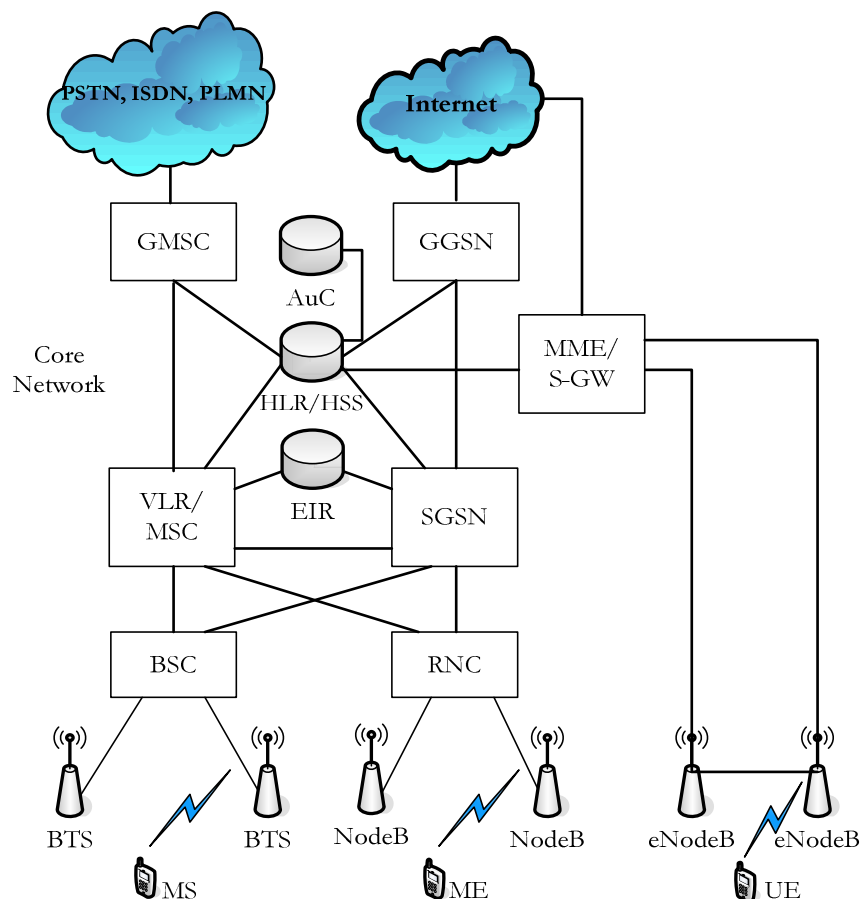


Figure 2.3 - Architecture of a GSM/UMTS/LTE Network supporting CS and PS services and interfaces (adapted from [3GPP00a] and [3GPP10]).

The main service in these networks is still voice, supported on CS, however, the PS world has

converged to cellular networks, and currently networks have a multitude of multimedia services, ranging from a simple Machine to Machine (M2M) message to video telephony or virtual reality communication. The PS elements in the 2G/3G core network are mainly the Serving GPRS Support Node (SGSN) and Gateway GPRS Support Node (GGSN). The SGSN is responsible for data packets delivery from and to MTs within its geographical service area, and also performs packet routing, mobility management (attach/detach and location management), logical link management, and authentication and charging functions. The GGSN is responsible for the interworking between the GPRS network and external PS ones. For LTE, a simple network architecture is adopted, by connecting the eNodeB, with more network control responsibilities, directly to the Serving Gateway (S-GW), which, among other functions, executes packet routing and mobility anchoring. The Mobility Management Entity (MME) executes a wide set of functions, such the ones related to users' mobility, roaming, security and tracking [3GPP10].

Cellular networks are conceptually related to high coverage and mobility, meaning that these networks are designed in a way that a user can experience high mobility without QoS degradation. These networks have a huge importance, from the coverage view point, typically characterised by a high percentage of geographical or population coverage.

From the capacity view point, operators easily adapt their networks to the required capacity, being typically supported on a hierarchical cellular and layered structure, which can be adaptable to hot spot areas, urban, suburban, and rural areas, by using pico-, micro- and macro-cells. When capacity demand increases heavily, operators are forced to increase the density of the radio resources offered to users; usually, this is done by inserting new cells into the network, leading to a cell radius reduction. However, these networks have a major drawback; since they are dedicated to a huge number of users, the user throughput is relatively low; currently each new generation aims to increase this parameter. Cellular networks cannot compete with WLANs on user throughput, therefore, the latter are complementary to the former.

Cellular networks QoS may vary, depending on the geographical region and its traffic density, and of course on the network planning quality itself.

### **2.3.2 Radio Interface**

In cellular networks, the radio interface is a key aspect that has been enhanced throughout the years, leading to a technological generation increment when relevant improvements are



established is announced.

GSM has been upgraded to GPRS and EDGE, by introducing PS in the former and increasing data throughput in the latter. EDGE may reach speeds up to 384 kbps, by using a new enhanced modulation, moving from Gaussian Minimum Shift Keying (GMSK) to 8-Phase Shift Keying (8PSK), requiring new transceivers and software updates.

Another 2G system, based on Code Division Multiple Access (CDMA), is cdmaOne, defined by the Telecommunications Industry Association / Electronic Industries Association Interim Standard – 95 (TIA/EIA IS-95) family [OjPr98], which works at 800 and 1900 MHz bands, each carrier having 1.25 MHz bandwidth. In addition to voice services, many operators provide CS data connections at 14.4 kbps, the chip rate being 1.2288 Mcps. In cdmaOne, like in GSM, coverage is limited by only one service, speech.

The cdmaOne 2.5G is the IS-95B system, which offers 64 kbps PS data, in addition to voice services. The cdmaOne 3G version is the cdma2000, which specifications were developed by the 3<sup>rd</sup> Generation Partnership Project 2 (3GPP2) [3GPP05], cdma2000 providing full backward compatibility with IS-95B. cdma2000 is not constrained to only the International Mobile Telecommunications 2000 (IMT-2000) bands, but operators can also overlay cdma2000 1x system, which supports data rates up to 307 kbps, on top of their existing cdmaOne network.

For the CDMA radio interface, one of the most important characteristics is the fact that power is the common shared resource among users. RRM is done by allocating power to each user, ensuring that the maximum interference is not exceeded, among other functionalities. Fast power control in DL increases network performance, especially in indoor and low-speed outdoor environments, which will increase cell capacity. RRM functions should track channel dynamics, therefore, RRM functions can be classified according to the time scales. Looking at the radio interface time units, one can identify and map RRM functions onto WCDMA, Table 2.6 [RSAD05].

Table 2.6 –RRM functions and Time Scale.

WCDMA time scale	RRM Functions
1 time slot	Fast power control.
1 frame	Packet scheduling, transmission rate.
10-1000 frames	CAC, handover, code management, congestion control, slow power control (open/close loop).

Capacity evolution is a key issue in cellular networks, being important to estimate the number of users per cell and per MHz. Capacity in UMTS depends mainly on: DL total power, available orthogonal channel codes that depend on users behaviour (used services, bitrate,  $E_b/N_0$  targets),

quality network targets (blocking and delay), urban environment (multipath spread), signalling, and Soft HandOver (SHO) channels. Capacity depends more on the load in DL than in UL, since in DL the maximum transmission power is the same, regardless of the number of users, being shared among them, while in UL each additional user has its own power amplifier. Therefore, even with low load in DL, coverage decreases as a function of the number of users. So, coverage is limited by UL, while capacity is DL limited.

In this thesis, 2G/3G and 3.5G networks are classified as Low Bitrate Networks (LBN) and Medium Bitrate Networks (MBN) respectively. It is assumed that usually the LBNs group offers bitrates up to 100 kbps on average, being the maximum up to 360 kbps. The MBNs have corresponding bitrates of 1 Mbps on average, and the maximum up to 10 Mbps.

3GPP has also upgraded UMTS to HSDPA, to have higher data transfer speeds and capacity. HSDPA deployments support DL speeds of 1.8, 3.6, 7.2 and 14.0 Mbps, Table 2.7. Further speed increases are available with HSPA+, which provides speeds of up to 22 Mbps UL and 42 Mbps DL. These capabilities are achieved by introducing advanced RRM techniques, adaptive modulation schemes, channel coding techniques, and MIMO systems.

Table 2.7 – 3GPP family basic comparison.

Standard	GSM EDGE	WCDMA (R99)	HSDPA (R5)	HSUPA (R6)	HSPA+ (R7)	LTE (R8)
Access technique	FDMA /TDMA	CDMA				OFDM
Coding and Modulation Schemes	GMSK, 8PSK	QPSK	16 QAM, QPSK	QPSK, BPSK	QPSK (UL), 16 QAM (DL/UL), 64 QAM (DL/UL)	
Maximum Throughput [Mbps]	0.4736	2	14.4	5.7	42	326.4
Frequency Bands [MHz]	850,900, 1800,1900	2100				900, 1800, 2100, 2600
Channel Bandwidths [MHz]	0.2	5				1.4, 3, 5, 10, 15, 20 (Scalable)

The Evolved- Universal Terrestrial Radio Access (E-UTRA), defined in Release 8 [3GPP09a], [3GPP09b] is the air interface of the so called Long Term Evolution initiative, being the latest 3GPP step towards 4<sup>th</sup> Generation. LTE uses OFDM as the air interface, and its throughput depends on the channel bandwidth, among other things.

Table 2.7 summarises some fundamental differences among 3GPP releases in the last decade or

so. One observes that, besides the inclusion of MIMO techniques in the latest releases, modulation schemes and channels bandwidth are the fundamental reason for the expected increase on bitrate.

Moreover, the LTE future is already being defined by the LTE-Advanced, described in the Release 10 standard. This new release includes faster protocols stacks, bandwidth aggregation up to 100 MHz, advanced MIMO, antennas and BSs cooperation techniques, among other new features. Combining these previous techniques it will increase BSs capacity, offered bitrate and reduce delay.

### 2.3.3 Other Aspects

More recently, the European Commission has launched a programme for Future Internet research projects to promote new networks architectures, routing and addressing mechanisms, and novel concepts and related technologies. The fundamental idea is to promote new networks technologies capable of offering a high level of flexibility and data access speed. The research ICT-4WARD project [4WAR10] is an example, having developed several concepts and technologies towards this goal, such as the network virtualisation concept [BaGo09], which can be applied from RF carriers up to transport networks. Cellular radio resources are multiplexed by different entities, enabling the implementation of new ideas, such as: operators extension, dynamic and adaptable networks topology, fast new operators installation, virtual joint radio resource management, and sharing of resources among operators, like radio channel blocks [CSCC10]. Currently, the ICT-SAIL project [SAIL11] aims at further developing these new techniques, and account for the transition from today's networks to such future concepts, by reducing costs for setting up, running, and combining networks, applications and services, increasing the efficiency of deployed resources (e.g., personnel, equipment and energy).

Other different ideas are those related to multi-cell and multi-RAT energy efficiency concern. This is a key concern for vendors and operators, the ICT-EARTH [EART11] research project being fully devoted to identify and develop key techniques and technologies to minimise networks energy consumption. Some of them have impact on network capacity, deployment, and dynamics, e.g., the number of active BSs as a function of traffic level, or even the bandwidth assigned to a given BS. Furthermore JRRM and RRM entities can move MTs to the most energy efficiency BSs/RATs, by triggering handovers [Godo11].

## 2.4 General Comparison between Systems

This section presents a general comparison between the presented wireless systems based on their main characteristics, a summary being presented in Table 2.8.

Observing the trends of previous systems, it becomes clear that a CN (based on IP) common to all these systems by a convergence/integration, is expected. Thus, in order to implement this convergence/integration, a JRRM strategy becomes indispensable, this being possible since wireless systems in most cases are superimposed.

The main JRRM goal is to establish the best way to serve a user and the operator interests, which in some cases may be conflicting, meaning that, in a given time, a user service may be served by two or more different wireless systems, but from the user and operator perspectives the best system is not necessarily coincident. This situation may happen in systems load management, e.g., from a user view point a given system could be the best one, and on the contrary from the operator side this can be overloaded.

Table 2.8 – Comparison among different groups of wireless systems.

Main Characteristic	WLAN	Cellular
System Architecture	Simple	Complex
Services Characteristics	Data	Circuit-Data
QoS	High	Medium
Mobility	Low	High
Throughput	High	Low-Medium
Working Environments	Indoor	Outdoor/Indoor
Spectrum Licence	Free	Regulated
Capacity	High	
Coverage	Low	High
Power Levels		Medium
Deployment Cost		High
Operational Cost		
Billing Policies	Free - Volume	Time and Volume
Frequency bands [GHz]	2.4, 5.2 and 5.8	[0.4, 2.6]

Another issue to explore is the best system available concept, which means that each user can access services with a defined mobility profile. An operator that offers access to different types of RATs, identifies the user service and mobility profile, and then, based on this information, will connect the user to the RAT that best matches the user profile, this process being transparent to the end user. For example: a high mobility user accessing the Internet will probably be in handover to a 3G cellular network, but if the user is stopped, having WLAN coverage, he/she will probably go to a WLAN, increasing the service throughput and decreasing the 3G load.

Users can setup a user profile at a given MT subscriber module, and based on this information operators may decide which is the best system that at a given moment will serve the user. For instance: a young user can have preferences on streaming services and instead of streaming audio or video on a cellular system, he/she perhaps will stream via a WLAN. This possibility should manage to attach MTs to the best RAT at a given point in time and space. Observing Table 2.8, this idea is present, where the higher performance levels dealing with: mobility, throughput, cost, coverage or service type are found in different kind of systems.



# Chapter 3

## A Review on Resource Management

This chapter aims at presenting the state of the art related with algorithms and strategies to RRM and JRRM proposals, when LBNs, MBNs and HBNs are integrated in a heterogeneous environment. Relevant aspects related with RRM are given in Section 3.1. Section 3.2 presents the MIMO impact in cellular networks. Section 3.3 presents cellular heterogeneous networks architectures and functional models. Section 3.4 discusses different aspects related with JRRM, such as framework, architecture and implementation. Section 3.5 highlights some cost function available in literature. Finally, Section 3.6 presents a discussion on handovers criteria.

### **3.1 RRM Aspects of Wireless Systems**

Different wireless systems have different ways of managing their radio resources. This diversity is closely related to the implemented radio interface technology, thus, RRM in a wireless system must comply with the system's characteristics and capacity needs, enabling the most suitable radio resource allocation to MTs. Considering the restrictions imposed by the radio interface, RRM algorithms and functions are responsible for decisions that have a large impact on the radio interface behaviour, QoS and performance. When wireless networks are close to the maximum capacity, RRM takes a key role on the overall QoS. The following sub-sections describe the main RRM functions associated to the different wireless systems "families" LBN, MBN and HBN, previously defined. Special attention is dedicated to MBN RRM, due to its typical complexity and flexibility. Different JRRM architectures, features and algorithms, as well implementation aspects, are also covered. Note that RRM in LBNs and MBNs groups, some functions are overlapped because they are related with cellular networks radio typical issues, and therefore the RRM mechanism has to deal with similar functions. In the case of HBNs, RRM is more closely related with WLANs addressing other radio issues.

#### **3.1.1 Low Bitrate Networks**

For the LBN group, the example provided here is based on the current UMTS R99 RRM features, which are common to most of the LBN types. For UMTS R99 [3GPP00b], RRM main concerns are related to call admission control, congestion control, streaming services and packet scheduling.

For UMTS R99, the considered QoS attributes are: traffic class, delivery order, maximum service data unit, delivery error information, transfer delay, maximum bitrate, traffic priority, and retention priority. All these parameters should be kept under or above a given limit of quality by the RRM entity, where QoS management functions enhance initial best-effort data services, being able to guarantee the user application specific QoS requirements. These QoS functions are based on the aggregation of data flows belonging to the same service class, and the prioritised admission control and scheduling of these aggregate flows in the radio network.

RRM procedures include the functions related to the management of the common transmission



resources, e.g., physical and signalling channels. In general, the purpose of these RRM procedures is to establish, maintain and release radio resource connections that allow a point-to-point dialogue between the network and an MT with a given QoS.

One important and inherent RRM feature in LBNs is power control; it has different dependencies on the time scale. Fast power control adjusts the transmitted power on each slot/frame in order to address the SINR required target level. The slow power control in close loop monitors the service Bit Error Ratio (BER) levels, and based on that, changes the SINR targets to a more suitable value, thus, adapting the SINR targets to the dynamics of the environment. Power control in open loop is used to estimate the first transmission power level, when the MT is requesting a service to a BS, which is performed based on the cell DL pilot power. By doing this, the MT avoids causing interference to other already attached connections.

The focus of the resource allocation problem is placed in the admission control issue, which has to calculate the network resources that are required to provide the requested QoS, to determine if those resources are available, and if this is possible, then to reserve those resources. Thus, admission control is performed in association with RRM functions, in order to estimate the radio resource requirements within each cell. The admission control protocol aims at maximising the number of admitted or in-session traffic sources supported over the wireless medium, while guaranteeing their QoS requirements and ensuring that the new connection does not affect the QoS of the connections currently being performed. The system tries to assign the available resources, if any, to the incoming user.

When MTs have been admitted in a WCDMA based network, a new RRM concern rises: the code management function. This task is dedicated to manage the Orthogonal Variable Spreading Factor (OVSF) code tree, which is used to allocate orthogonal channel codes to MTs radio links. The use of branches in this tree disables the possibility of using codes of the same branch (due to correlation and orthogonally dependence among branches). Thus, a main concern is to avoid the code-blocking situation, which may be caused by bad channel allocations of the OVSF code tree, leading to virtually no channel codes being available at the BS, even if in reality there are.

The system measures the DL average packet delay as a function of the number of users per BS. This delay considers the time spent from packet generation at the BSs to the reception of the ACKnowledgment (ACK) also at the BSs.

Hot spots dynamics may cause overload situations where user QoS requirements can not be guaranteed. These overload situations can be prevented by RRM mechanisms (e.g., admission control or congestion control algorithms), which determine how the radio interface is used and

shared among users. Another technique, commonly used, is to adjust the transmission pilot power of the hotspot and adjacent cells. The objective is to reduce the differences in the load of the different cells, by redirecting traffic from overloaded cells to low loaded ones. By doing this, a more uniform traffic distribution is obtained, then, these overload situations will be reduced. This technique can be optimised by using more than one RF carrier in a hot spot area [Sall04a] (redirecting services to RF carriers in a suitable way).

Another important RRM procedure is handover. In UMTS R99, this function is very flexible, because the MT can be attached simultaneously to more than one cell, the handover process being mainly triggered and performed by the network RRM entity. The handover process is critical, increasing connections dropping probability, which, from a QoS view point, has more impact, compared to connection blocking. Therefore, RRM strategies define a certain reservation region in order to reduce the dropping probability rate, at the expense of increasing the blocking probability (based on the user location knowledge). Similarly, [Nagh03] proposes reservation algorithms in order to assure a given service to users in handover.

In [3GPP01], 3GPP defines the cell-selection and cell-reselection procedures taking the presence of a Hierarchical Cell Structure (HCS) layout into account. In general, the selection depends on propagation conditions, user speed, and network parameters, the last one being the focus of UMTS R99 RRM algorithms. HCS comprise macro- and micro-layers, the identification of thresholds controlling the algorithms applied by the MT for the identification of the high/low mobility conditions, based on the cell reselections performed in a fixed period of time.

As already mentioned, LBNs supports a wide range of multimedia services, thus, in order to optimise the radio resources for a given service, a set of RRM functions decides the suitable parameters for a given connection request, the main task being packet scheduling optimisation. These functions usually run in real time (frame time level), taking advantage of the unload cell situation, meaning that, if the current cell load is below a given threshold, data users can increase the bitrate, or other users can initiate services like data messages or e-mail for example. This enables to increase the overall network performance, by using cell unload periods to increase the QoS to connected users. Another important feature is the type of connection that should be applied to a given MT (dedicated or common channels), which depends on the volume and type of data that needs to be transmitted. Therefore, this real time mechanism applies the best suitable channel resources to a given request.

In [Sall05], a new useful parameter is introduced, which synthetically defines the satisfaction degree of a user on a range from 0 to 1, being linked to the percentage of lost bytes and blocks.

The main idea is that losses during a session are perceived as a major sign of a poor system quality, whereas the percentage of lost bytes, even if important, has a lower weight, because it does not prevent from enjoying the service (e.g., video). Another important parameter that was identified is the Real Time Protocol (RTP) packet size, which is the amount of segmentation introduced by this protocol. The application throughput is nearly constant and equal to its maximum value when the RTP packet is greater than 400 byte; if this is reduced down to 100 byte, the throughput decreases from its maximum value, affecting the segmentation in packets. On the other hand, the selection of an adequate RTP packet size involves also the analysis of delay variation (jitter), because as the RTP packet size decreases the jitter decreases as well. In that sense, the selection of very small sizes is an advantage; however, this leads to a significant reduction of the offered throughput, which is not desirable. Simulations shown that, by configuring a dimension of RTP packet size equal to 500 byte, a high offered throughput is provided, while maintaining a low jitter level.

Another feature that should be optimised is the compression of protocol headers, which saves bandwidth and exploits the radio resources efficiently. Additionally, the limitation of the receiver initial buffering time is important, since the determination of service acceptability or unacceptability significantly depends on the jitter; the size of this buffer will be critical to decide whether a given jitter is acceptable or not. Furthermore, from the network viewpoint, the functionalities provided by this mechanism along with Radio Link Control (RLC) retransmissions reduce the requirements on radio resources allocation for streaming sessions, in terms of delays and jitter by satisfying the requested QoS levels. Simulations reported in [Sall05] show that jitter effects are easily compensated by a minimum buffering time of 1s for low bitrates and 3s for high ones, assuming that 95% of users are satisfied.

Besides jitter, mobility and user speed affect the optimal setting of the pre-jitter buffer length during an active video streaming session, buffered data fluctuations changes, being due to the different values of spatial shadowing affecting the transfer delays of data packets.

### **3.1.2 Medium Bitrate Networks**

For the MBN group, the example provided here is based on current 3.5G networks, UMTS R5 [3GPP02], which is common to most of the MBN types. 3.5G cellular networks, like UMTS R5 HSDPA, have an inherently flexibility to handle the provision of mobile multimedia services. 3GPP has defined a high degree of flexibility to carry out RRM functions. These networks offer

the possibility of optimise the capacity in the air interface by means of efficient RRM algorithms.

For MBNs, RRM processes are mainly related to the radio interface, since this is the main network bottleneck. However, in the CN, RRM also takes a very important role (e.g., mobility related issues). The main purpose of RRM is to keep radio interface parameters under control, like Call Admission Control (CAC), transmission algorithms parameters, code allocation management, power control, packet scheduling, congestion, and QoS, among others with less impact in the overall network performance.

In MBNs, RRM algorithms are particularly important, since typically their radio interface is based on complex and flexible parameters, therefore, MBNs coverage and capacity are strongly limited by the applied RRM strategies, these being more important when the network reaches the “limit”. The MBNs group is intrinsically dynamic. Some parameters are continuously changing, like users, services and corresponding transmission rates, users’ mobility pattern, traffic source behaviour, transmission power level, propagation conditions, and interference from different intra- and inter-cellular sources.

The CAC algorithm decides if a request performed by an MT is accepted or not. This request should be admitted if, and only if, a minimum QoS is guaranteed, not only for the new MT, but also for the ones already connected. The main network parameters that define the criteria are the BS load (traffic and interference dependent) and channel coding availability; additionally, it is possible to include different priorities to services (e.g., data and voice).

The congestion control function is related to the BS load control. Load in MBNs radio interfaces, as mentioned before, is highly dynamic; in order to avoid congestion problems, this RRM function should work in real time, in order to announce, e.g., that new connections should be refused or that existing ones may perform handover to other neighbouring cells. If these basic mechanisms do not control the load rise, then, data services (usually tolerant to delay) bitrates may be reduced, or even delayed/stopped. But if all these measures are not enough, then, some real time connections (e.g., voice) must be dropped (just as a last resource).

The UMTS R5 (HSDPA) scheduling process is very flexible, allowing spreading codes sharing, which means that one or several spreading codes may be allocated to one user, and that several users may receive data under one Transmission Time Interval (TTI). It is also possible to schedule all channels to one user under one TTI, this being considered as the primarily means of sharing. The scheduling method used to decide which user is allocated to the channels is of great importance. In [Sall04a], three HSDPA schedulers simulated the Round Robin (RR) [MaMS01], Max Channel Quality Indicator (CQI) and Proportional Fair (PF) [KaWi02] approaches. In a low

load and good radio coverage scenario, the PF scheduler provides a good trade-off between high average bitrate and fairness, while for an increasing packet loss probability the schedulers' performance becomes more and more similar.

An additional optimisation concerning RRM is the RAT sharing among competing operator networks, to cooperate without exchanging operational information and share carriers simultaneously, being investigated in [PLDH04], [PLDH05]. Sharing the resources among operators may provide a reduction of investment costs, especially in limited coverage areas, as well as a higher efficiency with respect to fixed spectrum allocation, especially when traffic demand varies significantly throughout the day.

When only RT services at Constant Bit Rate (CBR) are considered, the RRM flexibility is reduced. An overload situation can not be solved by reducing the bitrate of certain users, because users are CBR. A set of algorithms have different ways to increase the system efficiency by blocking connection requests or, if necessary, by dropping a certain number of established connections. These algorithms are listed as follows:

- Half power, when a user from an operator A makes an admission request, it is accepted if the total power devoted to this operator is lower than half of the maximum power.
- Total power with dropping, when a user from an operator A makes an admission request, a BS power availability check is carried out in this BS, it is accepted if exists power available, or if an operator B uses more than half power, then an user from B, must be dropped to allow the acceptance this new user (from operator A).
- Multi-cell algorithm, similar to the "Total power with dropping", but exploring the possibility to move calls to neighbouring cells.

### **3.1.3 High Bitrate Networks**

For the HBN group, the example provided here is based on the current WLAN family 802.11's RRM features, which are expected to be common to most of the HBN types. The WLAN IEEE 802.11 family specifies only the Physical and MAC layers. Extensions to this family brought new QoS and security mechanisms. In the basic 802.11 standards [IEEE99a], only best-effort service is provided, not considering throughput, delay, etc., due to this lack of QoS assurance, services frequently not having the minimum QoS when competing with other MTs. The 802.11e version [IEEE05] includes new QoS functions in MAC sub layers, offering different QoSs, depending on

the class of service (voice, data and video). A priority scheme is made using 802.11d [IEEE01], in order to provide access categories dependent on a given application.

The rapid deployment of IEEE 802.11 based networks, popularity and effectiveness of this technology, together with the fast growth of multimedia application, made WLAN users interested in supporting more sophisticated applications, like audio or video streams; however, IEEE 802.11 is unable to guarantee RT traffic requirements, like low delay, jitter or error rate. In order to answer this need for QoS enhancements, IEEE additionally defined a new MAC layer, by adding to it service differentiation mechanisms. Every new user tries to access the shared medium for transmitting and receiving data; consequently, the QoS of all users in the network degrades, in terms of throughput, delays, jitter and transmission errors. This is particularly true for the Distributed Coordination Function (DCF) access, therefore, it is clear that blocking new users, when specific load conditions occur, must be applied as follows:

- Admission control for IEEE 802.11a/b/g - Admission control policies can be applied, in order to enable the support of RT data services (i.e., conversational and streaming classes), requesting a minimum amount of bandwidth. This policy consists of three main steps:
  - the throughput offered by the network to each RT user is evaluated by means of an analytical model, which considers the RT services, bitrates, and packet lengths, as well as the requested bandwidth for the services;
  - results coming from the previous step are exploited, in order to identify the maximum number of users for each class (i.e., services mix) that the considered WLAN network can support, providing a so-called Capacity Region (CR), this being compliant with a minimum level of offered throughput (UL and DL) per user;
  - the algorithm in charge of the admission control policy can be based on the CR related to the network and keep the number of active users for each class of service within the range of the QoS constrains.
- Admission Control Algorithms (ACA) for IEEE 802.11e - The incorporation of QoS issues in communication networks involves treating some traffic preferentially to others, which implies the capability to accept or reject traffic. The standard defines the Enhanced Distributed Channel Access (EDCA), being classified into two main groups, measurement-based and model, each one being further split into centralised and distributed sets. Measurement-based algorithms take the decision about acceptance/rejection based on the continuous measurements of system parameters, such as retry count or delay. In contrast, in model-based schemes the admission control decision is taken according to the system status, evaluated by means of some established metrics derived in an analytical way. The Enhanced

Distributed Admission Control Algorithm (EDACA), is composed of two parts: one running in AP, and the other in each MT. The MT component of the algorithm is reduced to a minimum, and its responsibilities include: compute the Total Occupation Time (TOT) per beacon interval; for a given AC, decide the acceptance or not, of the new call depending on the TOT value and a Transmission Time Budget (TTB); Service Priority; and QoS enhancements.

Despite the important role of WLANs for best effort traffic, based in particular on 802.11b and 802.11g physical layers, limitations of the standard are apparent for mixed traffic scenarios, because of the lack of QoS support. Nevertheless, the 802.11e proposals modify parameters that define how an MT accesses the AP, i.e., they modify parameters of either the fundamental access method of the IEEE 802.11 MAC, the DCF, or the optional access method, the Point Coordination Function (PCF). In fact, some of these methods are being included in Hybrid Coordination Function (HCF) in 802.11e [IEEE02], which consists of two new access methods, the EDCA and the HCF Controlled Channel Access (HCCA). EDCA corresponds to the legacy DCF, while HCCA corresponds to the legacy PCF. The EDCA, supports prioritised QoS. A problem with legacy DCF is that the MAC uses a single first-in-first-out transmission queue, hence, there is no way to differentiate traffic and provide priority to particular traffic types. EDCA defines four different access categories: voice, video, Best Effort (BE) and BackGround (BK). Every category implements a unique queue, and for each one, there is a specific EDCA parameter set, which defines the unique properties of the access category. Every access category can be seen as a virtual station, which competes individually for channel access. Traffic can be divided further into User Priorities (UPs), which are simply a priority scheme within an access category; there are eight different UPs, derived from 802.11d.

When frames arrive from the higher layer, the MAC layer examines the Type of Service (ToS) field in the IP header; the ToS value corresponds to the UP, and the incoming frame is mapped onto an access category, and queued in the appropriate queue. An additional timing interval is introduced, in order to differentiate the four access categories, being referred to as Arbitration Inter Frame Space (AIFS).

## **3.2 MIMO Impact**

Modern RATs incorporate MIMO systems, because they offer significant gains in channels

throughput and link range without additional bandwidth. MIMO offers a higher spectral efficiency and link reliability or diversity. Therefore, MIMO is an important part of modern wireless communication standards, thus, evaluating MIMO gains is relevant to understand the MIMO impact on systems performance.

The inclusion of MIMO systems must have a simplified approach, in order to keep the focus on JRRM issues, thus, one option is to include MIMO as a relatively gain over Single Input Single Output (SISO) systems as presented in [KuCo06] and [SeKC08a]. The model for the throughput gains that can be achieved by using MIMO systems is a statistical one, aimed at being used in system-level simulators, providing CDFs for the relative MIMO gain.

In the geometrical based single bounce channel model [KuCo06] and [MaCo04], the propagation environment is composed of scatterers, which are grouped into clusters. Clusters are distributed inside the environment by means of a uniform distribution, while the scatterers inside the clusters follow a 2D Gaussian distribution. Among others, the number of clusters and the average number of scatterers within a cluster can be set with a parameter. The reflection coefficient of each scatter can be described by its complex value, where the magnitude of the reflection coefficient is the attenuation due to reflection losses, uniformly distributed in  $[0, 1]$ ; the phase of the reflection coefficient is an extra phase change, which is uniformly distributed in  $[0, 2\pi]$ . Pico- and micro-cell environments consider a LoS signal, while the macro-cell does not. The micro-cell environment is modelled by an ellipse, whereas the pico- and macro-cell ones are modelled by circles. For both pico- and micro-cells, the MT is located inside the area, whereas for the macro-cell, only MTs are located inside the circle, the BS being outside, Figure 3.1.

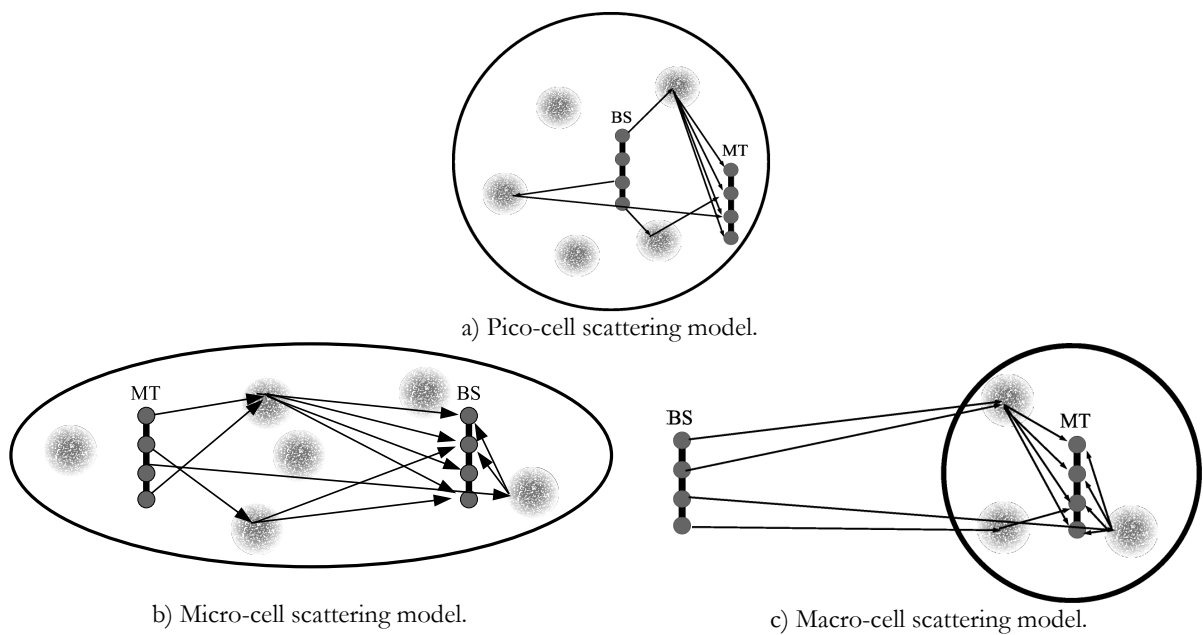


Figure 3.1 - MIMO scattering models scenarios (extracted from [Serr06b]).



The gain that can be achieved by using MIMO over SISO can be defined by:

$$G_{M/S} = \frac{C_{MIMO_{[bps]}}}{C_{SISO_{[bps]}}} \quad (3.1)$$

where,

- $C_{MIMO}$  is the MIMO capacity;
- $C_{SISO}$  is the SISO capacity.

The Relative MIMO Gain (RMG),  $G_{M/S}$ , has been described in detail in [Serr06b]. Based on the simulation results presented in [MaCo04], the distribution of the RMG has been modelled. Simulation results of these distributions of the RMG are presented in [Sall07] and [Sall06], for pico-, micro-, and macro-cells: a pico-cell is used for distances up to 100 m, whereas a micro-cell is used between 100 and 600 m, and the macro-cell for larger distances. It should be noted that the exact border between pico-, micro- and macro-cells depends on the environment.

The distributions of RMG can be given by a sigmoid function, which is completely modelled by its mean and variance. The general sigmoid function is given by [Bala92]:

$$F(x, \mu, s) = \frac{1}{1 + e^{-\frac{x - \mu}{s}}} \quad (3.2)$$

where,

- $\mu$  is the mean value of the distribution;
- $s$  determines the slope, which is related to the variance,  $\sigma^2$ , by

$$\sigma^2 = \frac{\pi^2}{3} s^2 \quad (3.3)$$

The variance of the distribution depends on the number of Tx (transmit)  $n_{tx}$  and Rx (receive)  $n_{rx}$  antennas, being moderately related to distance. For a certain number of Tx and Rx antennas, the variance is very low within all cells, i.e., the slope of the sigmoid function does not change much within the same cell range, therefore, the slope has been assumed to be constant within a cell type.

In order to obtain a model for RMG, the inverse of the distribution in (3.2) is required,

$$g(u, \mu_{RMG}, \sigma_{RMG}) = \mu_{RMG}(d, n_{tx}, n_{rx}) - \frac{\sqrt{3\sigma_{RMG}^2(d, n_{tx}, n_{rx})}}{\pi} \ln\left(\frac{1-u}{u}\right) \quad (3.4)$$

where,

- $u$  is a random value with a Uniform distribution, i.e.,  $u \in U[0, 1]$ ;
- $\sigma_{RMG}^2(d, n_{tx}, n_{rx})$  is the variance, depending on the cell via distance  $d$ , Table 3.1;

- $\mu_{\text{RMG}}^2(d, n_{\text{tx}}, n_{\text{rx}})$  is the average, which has been approximated by 0<sup>th</sup> and 1<sup>st</sup> order functions, Table 3.2.

Table 3.1 - Variance for different number of Tx and Rx antennas.

$\sigma_{\text{RMG}}^2 (10^{-3})$		$n_{\text{rx}}$					
		pico-cell		micro-cell		macro-cell	
$n_{\text{tx}}$	#antennas	2	4	2	4	2	4
	2	18.5	10.4	24.0	15.9	1.9	1.8
	4	11.8	45.4	15.9	71.4	0.8	1.1

Table 3.2 - Model for RMG, for different number of Tx and Rx antennas and distances.

$n_{\text{tx}} \times n_{\text{rx}}$	Cell	Pico		Micro	Macro
4×2	Range [m]	[10, 2400]			
	RMG	1.70			
4×4	Range [m]	[10, 31]	[31, 57]	[57, 686]	[686, 2400]
	RMG	$50.32d_{[\text{km}]} + 1.77$	3.36	$-2.00d_{[\text{km}]} + 3.47$	2.10

### 3.3 Heterogeneous Cellular Architectures

Mobile industry standardisation bodies and research groups are currently developing new cellular architectures related to heterogeneous cellular environments. These efforts lead and confine the definition of JRRM strategies that are sustained in a heterogeneous architecture platform, which is basically the integration and common management of LBNs, MBNs and HBNs. JRRM functions are intended to achieve an efficient use of the radio resources in heterogeneous scenarios, by means of a coordination of the available resources in the existing RATs. Therefore, JRRM is a general concept, applicable to any combination of RATs, although the specific implementation and the degree of coordination depend highly on the degree of coupling that exists between the specific RATs. The following sub-sections present different JRRM architectures and algorithms proposals on how and where the JRRM entity should be located.

#### 3.3.1 JRRM Functional Model

The functional model assumed in 3GPP [3GPP02] for JRRM is defined as Common Radio Resource Management (CRRM), which in fact has the same meaning of JRRM used by this thesis. CRRM/JRRM operation considers two types of units for managing the radio resource pools of heterogeneous cellular networks, Figure 3.2. The RRM unit carries out the management

of the radio resources in a pool of a given RAT. This functional unit aggregates different physical entities in the BSs and radio controllers sub systems, being assumed to be resident on the radio controller part.

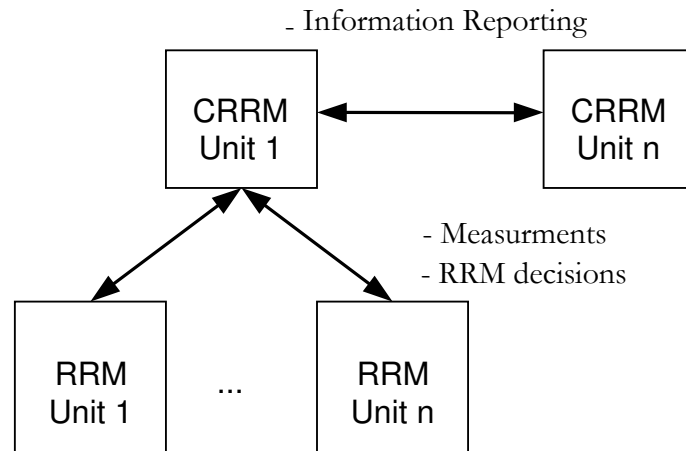


Figure 3.2 –CRRM/JRRM and RRM functional model, proposed by the 3GPP (adapted from [3GPP02]).

The CRRM/JRRM unit executes the coordination management of the resource pools controlled by different RRM units, ensuring that the decisions of these RRM entities also take the resource availability in other RRM units into account. Each JRRM unit controls several RRM ones, and may communicate with other JRRM is as well, thus, collecting information about other RRM is that are not under its direct control. Information exchanged between JRRM and RRM units is mainly of two types:

- Measurement information, which allows the RRM unit to inform the controlling JRRM one of the current status of their cells, like load, capacity, and available resources, among others measurements (QoS related). Besides RRM to JRRM reports, it is also possible to exchange information among JRRM units, being possible to have access to measurements reported by RRM units controlled by other JRRM unit.
- RRM decisions, depending on how the JRRM unit is implemented, e.g., a JRRM unit can be the master of a decision (e.g., RRM unit binds the JRRM decision, or only advise the JRRM unit).

The JRRM unit can be implemented in the network by using two different topologies: the JRRM server and the integrated or distributed JRRM. As a server, the JRRM works as a stand alone block, as shown in Figure 3.2, while in the integrated/distributed topology JRRM unit functions are integrated in the same machines that execute RRM instances in the different RAT's. This later topology is very useful for handover procedures.

These two topologies have a huge impact on JRRM capabilities, e.g.: time based functions of radio resources, like power control, must be decided very close to the radio interface, being inadequate to perform them on a centralised JRRM server. The location of the management decisions depends on the typical periodicity or signalling load, therefore, very frequent decisions are typically assumed by the RRM unit, the high level decisions, or less frequent ones, being carried out by the JRRM unit.

In [KKGD05] and [Kyr02], another framework is proposed that considers a heterogeneous cellular environment, with a different hierarchical RRM architecture, Figure 3.3. This architecture is divided into four main components or units:

- The Global Management Unit (GMU), which fulfils the requirement for efficient global RRM, the main tasks concerning congestion being the split of traffic among all RATs, keeping the QoS to all sessions, and solving black spot areas.
- The Resource Management Unit (RMU), which assumes the requirements for efficient local RRM, defining the traffic load, selecting the best RRM strategy to cope with the congestion, and applying the solution to a given RAT.
- The Interface Traffic Monitoring Unit (ITMU), which is linked by means of dedicated wired lines or an IP based backbone network being, responsible for monitoring the corresponding network, collecting reports and surveying these reports, to recognise a congestion situation, and reporting back to the corresponding RMU.
- A Location Server (LS) to track users' mobility and location, where such information can be exploited by GMU for a global optimisation.

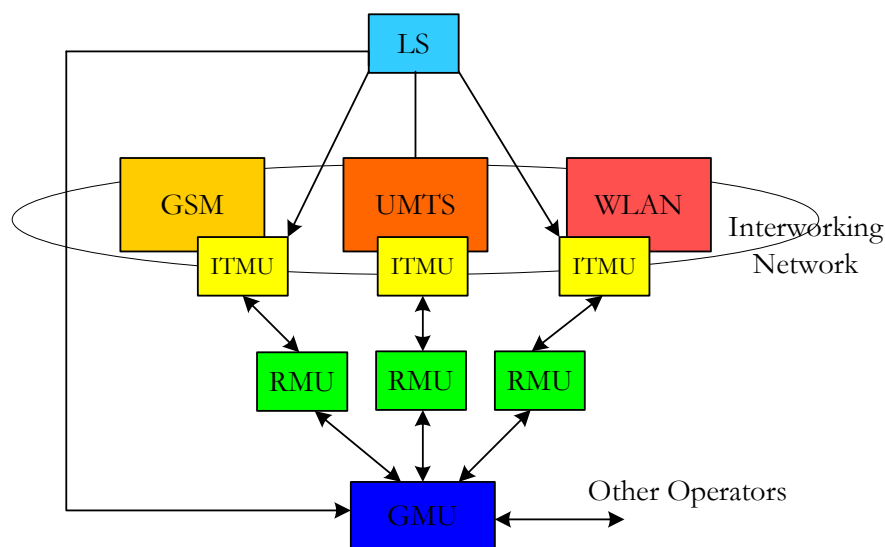


Figure 3.3 – Reference architecture (adapted from [Kyri02]).

This proposal covers most of the identified problems in JRRM. However, due to an extra unit

(ITMU), this proposed framework increases the model complexity, being harder to be implemented, compared with the one proposed by 3GPP. The ITMU and the RMU units and their functionalities can be merged into the RRM unit, proposed by 3GPP.

### 3.3.2 JRRM Framework

The adaptive and flexible framework resulting from the conjunction of JRRM and local RRM techniques applied at the individual RAT level may indicate a review over static network planning. Certainly, reconfigurable technologies will change the operational mechanisms. Dynamic Network Planning and flexible network Management (DNPM) refers to the radio network planning, self-tuning network parameters and flexible and suitable management processes interworking with JRRM processes [RSAD05]. It can be envisaged that an operator can expect that in its operational area some of the coverage will be offered using the classical method, whereas in some special areas, DNPM will be applied. Additional techniques can be applied, such as Advanced Spectrum Management (ASM), which enables the dynamic management of spectrum blocks within a single or among different RATs.

The ultimate realisation of ASM, DNPM, JRRM and RRM in a consistent and coherent way allows for the achievement of high spectrum efficiencies and efficiency in radio resource usages, on top of the potential capabilities provided by the physical layer design of the involved RATs. The high level relationships among the different elements are presented in Figure 3.4.

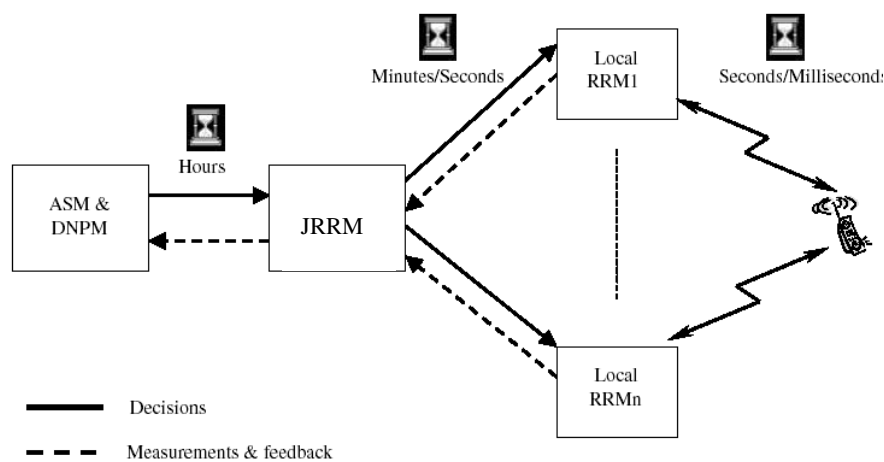


Figure 3.4 - Framework for JRRM operation (adapted from [RSAD05]).

As highlighted before, the main distinguishing factor is the time scale at which interactions between elements occur and/or actions from a given element are taken, e.g., it can be foreseen

that:

- network deployment can be seen as static for the study of JRRM purposes, since it can change in the order of months/weeks depending on the network maturity;
- DNPM and ASM act at a rather long-term scale (e.g., typically once or twice a day), in response to very significant demand profiles changes; an example of a situation triggering DNPM would be a temporal event, such as, a congress, a football match, and users mass mobility in rush hours;
- for a given configuration in the scenario, and for the period of time that all RATs and amount of radio resources assigned to the cells in the scenario remain fixed, it will be the responsibility of JRRM to achieve a good efficiency in the overall usage of the radio resource pool; given that JRRM has the perspective of several RATs, it is expected that interactions occur in the order of minutes/seconds, thus, responding to some higher-level objectives, such as load balancing among RATs (e.g., Vertical HandOver (VHO) procedures);
- the local RRM element will cope with the most dynamic events elements, such as traffic variability (e.g., fast variations on load), user mobility, and propagation/interference conditions within a given RAT; actions of the corresponding functionalities may occur in a very short time scale, in the order of seconds (e.g., handover) or milliseconds (e.g., packet scheduling).

For the variety of entities that may potentially be involved (i.e., ASM, DNPM, JRRM and several local RRM, such as networks categories, like LBN, MBN and HBN), it is important to assure consistency among the decisions taken at the different hierarchical levels, in order to achieve an overall coherent behaviour.

The parameters deemed feasible to be exchanged depend on the heterogeneous network architecture and the coupling scheme. Within this general framework, the focus of this section is on JRRM aspects, including the relationships between JRRM and RRM, as well as issues related to implementation aspects. The overall challenge is to focus on new RRM algorithms operating from a common perspective that take the overall amount of resources offered by the available RATs into account, designated as JRRM algorithms. Furthermore, for a proper support of such algorithms, suitable network architectures and procedures must ensure the desired interworking capabilities between the different RATs.

### 3.4 JRRM Approaches

The envisaged beyond 3G scenarios include the integration of heterogeneous networks, with a multiplicity of access technologies as well as the diversity of MTs with reconfiguration capabilities. This vision introduces a new dimension into the general RRM problem, in addition to the need for a proper interworking of RATs through adequate architectures. Therefore, instead of performing the management of the radio resources independently for each RAT, some form of overall and global management of the pool of radio resources can be envisaged. JRRM algorithms are the envisaged processes to manage dynamically the allocation and de-allocation of radio resources within a single or between different RATs. In the following sub-sections, an overview of JRRM is provided and a list of some algorithms is presented and discussed.

#### 3.4.1 JRRM Algorithms

JRRM algorithms are basically designed to coordinate and manage resource pools over the heterogeneous air interface in an efficient way, which depends on how to construct their features or functionalities. There are a range of possibilities for the set of features that JRRM may undertake, which basically depends on two factors:

1. definition of the master to take RRM decisions, it being either RRM or JRRM;
2. the interactions level among RRM and JRRM units.

In [PSAK05], these possibilities were further explored by considering how to incorporate JRRM functionalities into RRM ones in order to support the different procedures. The RRM functionalities arising in the context of a single RAT are the admission and congestion control, VHO and Horizontal Handover (HHO), packet scheduling, and power control, among others. When these functionalities are coordinated among different RATs in a heterogeneous scenario, they are executed by the JRRM unit, having, e.g., common admission and congestion control. When a heterogeneous scenario is considered, at least two specific additional functionalities arise, namely the initial RAT selection and the VHO. The different possibilities that are envisaged when considering the operation between RRM and JRRM entities are the following:

- No JRRM functionalities: in this case, it is considered that, although different RATs operate in a heterogeneous scenario, no coordination among them is performed. The initial RAT selection and VHO algorithms are associated to RRM entities, so that the decisions are taken without any knowledge from the radio network conditions in other RATs.

- Initial RAT selection and VHO: in this situation, the RAT selection procedures are associated to the JRRM unit. The local RRM entities provide RRM measurements, including the list of candidate cells for the different RATs and cell load, so that the JRRM can consider the availability of each RAT for a corresponding MT.
- Common Admission and Congestion Control: this approach consists of moving these local functionalities that operate on a longer-term basis to the JRRM unit, while keeping in the local RRM ones the functions that operate at the radio frame level or below, like packet scheduling and power control.
- Common Packet Scheduling: this approach provides the highest degree of interaction between JRRM and local RRM, by executing joint scheduling algorithms in the JRRM unit. The local RRM functionality remains to a minimum, limited to the transfer of the adequate messages to JRRM and some specific technology dependent procedures that occur in very short periods of time. This solution requires for JRRM decisions to be taken at a very short time scale (in the order of milliseconds).

Within the set of RRM functions, the initial RAT selection and VHO are devoted to decide the appropriate RAT for a given service at session initiation and during its lifetime, respectively. Therefore, they necessarily involve different RATs and it is appropriate to devise them from a JRRM perspective. In that sense, the algorithm operation responds to specific policies, taking both technical and economical aspects into account, e.g., operator or user perspectives.

In [ToHH02], the benefits of JRRM in terms of inter-system handover and inter-system network controlled cell reselection are analysed in a heterogeneous UMTS Terrestrial Radio Access Network (UTRAN)/ GSM/EDGE Radio Access Network (GERAN) scenario. With respect to the combination of cellular and WLAN technologies, in [ASPG04] a methodology based on fuzzy logic and reinforcement learning mechanisms is presented, combining technical and economical issues to provide the specific RAT and bandwidth allocations. Access selection in heterogeneous networks has been also covered in [FoFL04] and [PeSA05].

These days, there are already several RATs available to users, offering different costs, performance levels, security levels, and application capabilities, therefore, offering new challenges to operators. The advantages that each technology intrinsically offers must be considered, the clearest one being, thus, network capabilities enhancements. The load can be divided among all RATs, achieving a more flexible management, and providing a uniform distribution. Also, higher performances can be reached by using technologies more adapted to a given application.

Initial RAT selection policies can be a complex feature to be solved, since an operator can define



several rules/policies that will select the suitable RAT at each moment. These rules/policies can be contradictory among them, and probably are not aligned with the user's perspective.

Operators can define a kind of priority list of the RAT operator preferences [Agui04] of the available RATs, each of the preferences being completely independent of the others. In here, there are four issues that will influence RAT selection: RAT availability, core availability, type of the service, and a set of operator conditions. Operator preferences are related to their commercial strategies and how these affect the selection of the proper RAT. For instance, the operator may wish to select the RAT having the lowest cost of installation, which is typically the HBN one, hence, whenever it is possible, the service should be given through the HBN RAT.

At a first glance, it may seem very easy to deal with these issues. If there were only one operator rule, then, the selection would be in fact straightforward. But the real problem arises when there are several operator rules that may be contradictory among each other, creating ambiguous situations, a method to solve ambiguity being required. By providing different weights to the different rules factors, operators may weight their RAT preferences. The result will be a list of the RAT relative importance for a specific service. The final selected RAT should be best suitable based on a cost function. This approach enables the JRRM/operators to select the RAT that best fits to their strategies, solving the problem of the contradictory preferences. An algorithm described in [Sall04a], that allows operators to define the important issues when a VHO is performed is an example. It can be improved with economical aspects in order to influence the selection of a RAT.

Besides RAT selection, the VHO procedure from one RAT to another may be useful to support a variety of objectives, such as: avoiding disconnections due to lack of coverage in the current RAT; blocking due to overload in the current RAT; envisaged QoS improvement by changing the RAT; support of user's and operator's preferences in terms of RATs usage; load balancing among RATs. Thus, the VHO procedure introduces another dimension into the JRRM problem, and provides an additional degree of freedom for traffic optimisation, which is exploited by means of the specific VHO algorithm. However, a trade-off arises between the flexibility in JRRM and signalling overhead.

Several authors have already identified the importance of the VHO mechanism in future mobile scenarios [ToHH02], [LiSa04], [SiSL03]. Especially in [ToHH02], the benefits of JRRM by carrying out load-based VHOs in order to balance the load of the different cells and RATs are analysed. Similarly, in [LiSa04], the advantages of distributing the load among different networks, to increase flexibility and reduce network equipment costs, are addressed, and in [Linc04]

different policies to overflow sessions that arrive to saturate RATs are discussed. Finally, in [SiSL03], different procedures for making measurements of different RATs are discussed as a means to provide support for VHO decisions.

The main policy related to HHO and VHO interaction is the following: the HHO compared to the VHO option has priority, VHO being used only for special situations, like the ones already mentioned. This handover flexibility has a positive impact on the user's throughput, and on services dropping probability.

Another feature that can/should be optimised by using coordinated RRM and JRRM strategies is load balancing. This feature is a possible guiding principle for resource allocation, in which the RAT selection policy will distribute the load among all resources as evenly as possible. However, in some situations, a load balancing policy may not be desirable, at least not the only to be applied. Indeed, at one stage, an operator may be more interested in allocating users according to a service policy (e.g., because it increases the revenue), rather than performing a load balancing assignment. Load balancing algorithms have been considered to improve performance among single-RATs [ChRa97]. In this particular case, the algorithm operates when the coverage areas of different BSs overlap, thus, whenever an MT is attached to more than one BS, the new connection can be assigned to the BS with the largest number of available channels, which is probably the least loaded BS.

For multi-RATs, the allocation problem is extended in a way that resources may be assigned in different RATs. In [ToHa02], the effect of tuning the load-based handover thresholds depending on the load of inter-system/inter-layer/inter-frequency cells is studied. In order to avoid unnecessary handovers, and their corresponding signalling overhead, a minimum load threshold ensures that no load balancing activities are carried out below that value. However, to reduce handover attempts and handover failure rates, adjustable thresholds using neighbour load information are suggested and evaluated.

In [PDJM04], a force-based load balancing approach is proposed for initial RAT selection and VHO decision making. This approach considers the decision cost, among others, this decision being based on the load in the target and source cells, the QoS difference between radio links, the time elapsed from the last HO, and the HO overhead. However, these proposals either compare results obtained in combined HBN/LBN systems and observe the so-called trunking gain, or just consider a single load balancing approach with changes on the algorithm parameters [ToHa02].

A more complete approach to the problem is provided in [Sall05], where the problem of the initial RAT selection for new incoming users requesting a service in either of the available RATs

is addressed. Also, the effects of HHO and VHO are considered jointly with the initial RAT selection policies. The JRRM unit can use different load sharing strategies, e.g., in order to obtain a capacity as high as possible. Different load sharing strategies can be used:

- No control over the load sharing, when users may be served by several RATs, the decision being taken in a random way, so, no previous load sharing is decided by the JRRM.
- Voice services can only be carried out by one RAT and data services by a different RAT, so that this other RAT is able to spend all of its available resources among data users.
- Data services can only be carried out by one RAT and voice services may be carried out in two RATs, but in a different percentage set a priori by the operator; the JRRM admission control shares the voice load in a way defined by the operator, e.g., by giving different priorities.

The selection of the best strategy is dynamic, meaning that the best strategy depends on the overall network current status.

Other strategies can be taken by JRRM, like RATs preferences for the requested service, set by the operator according to the QoS offered by each RAT, or balance among the radio resource occupation of the different RATs, which is achieved by a suitable traffic load balance among them. Since some JRRM decisions are based on imprecise information, some fuzzy subset methodologies have been tested, providing good results. Attached to these strategies one can include the so-called reinforcement learning, which is suitable to tune network parameters.

Another relevant algorithm is the so-called Fittingness Factor (FF) [Pere07], which is a generic model that attempts to capture all the effects influencing on RAT selection decisions. Specifically, in order to cope with the multi-dimensional heterogeneity, two main levels are identified in the RATs selection problem:

1. Capabilities: a user-to-RAT association may not be possible due to limitations by the user terminal capabilities (e.g., single-mode MTs able to be connected to a single RAT) or the type of services supported by the RAT (e.g., videophone not supported in 2G networks).
2. Suitability: a user-to-RAT association may be suitable, depending on the matching between the user requirements in terms of QoS and the capabilities offered by a given RAT (e.g., a business user may require bitrate capabilities feasible on MBNs but not on LBNs, or these capabilities can be obtained in one or another RAT depending on its occupancy). In that respect, there are a number of considerations, that the FF definition splits into two different levels:
  - Macroscopic - radio considerations at cell level, such as load level or equivalently, the

amount of radio resources available.

- Microscopic - radio considerations at user level, such as path loss, inter-cell interference level, etc. This component is relevant for the user-to-RAT association when the amount of radio resources required for providing the user with the required QoS significantly depends on the local conditions where the user is located (e.g., power level required in WCDMA DL, and measured interference).

IEEE defines also mechanisms to manage mobile heterogeneous networks, which handle inherent cross-layer interaction and interworking problems between largely different RATs. JRRM components need to know about the currently available access technologies and have to issue commands to lower layers. This is not trivial, given that current systems do not always provide this information, and it is usually not propagated through the protocol stack. In addition, lower layer interfaces are access system-specific, which leads to complex implementations due to the intrinsic heterogeneity of the problem. Over the last years, several research projects have addressed the question how a generic cross-layer interface shall look like, which services it has to provide, and how it can best be implemented. Standardisation bodies have adopted these ideas and now standards are emerging that have the potential to largely facilitate the realisation of the JRRM ideas, e.g. the IEEE 802.21 Media Independent Handover standard [IEEE07].

Several authors describe how 802.21 can generally be used for JRRM, but little attention is given to an integration of an 802.21-enabled solution with existing 3GPP and non-3GPP networks. In [MuES09], it has been found that, although 802.21 defines a media independent interface, it is still necessary to distinguish whether an MT is being served by a 3GPP or non- 3GPP access network. This is due to the different degree of IEEE 802.21 support by the respective RATs, especially the absence of signalling transport channels for 802.21 messages in 3GPP access networks. This will lead to a modified structure of the JRRM components.

### **3.4.2 JRRM Implementation Aspects**

The implementation of JRRM mechanisms naturally depends on the features associated to it since these features will set the requirements in terms of interactions among JRRM and RRM units. Furthermore, such interactions will only be possible provided that the proper interworking capabilities among the different RATs are enabled. In all approaches, it is important to note that the trade-off between the highest possible gains and the additional delay and signalling load must be considered [Sall04b].

The JRRM unit may be physically deployed either into existing nodes (e.g., Radio Network Controller (RNC), Base Station Controller (BSC) and Access Point Controller (APC)) or in a separate node [3GPP02]. In the former case, the JRRM/RRM interactions do not need to be defined, being left to vendor's implementation, while the latter needs to define an open interface among the JRRM node and the nodes where RRM entities reside. Clearly, an open interface facilitates interoperability among equipments from different vendors. On the other hand, in terms of algorithms upgrades, implementing JRRM as a separate node will reduce upgrading tasks, as long as functionalities are centralised. In this respect, introducing policy-based management concepts may also facilitate the operator's interface to the JRRM mechanisms.

The interaction level among RRM and JRRM entities may have different degrees, ranging from low to very high interaction levels. Between these two extremes, network RRM features and policies have a huge impact on signalling complexity, the importance/complexity of RRM and JRRM will decrease and increase respectively. For example, in the very high interaction case, only power control is performed by the RRM at each RAT, Figure 3.5.

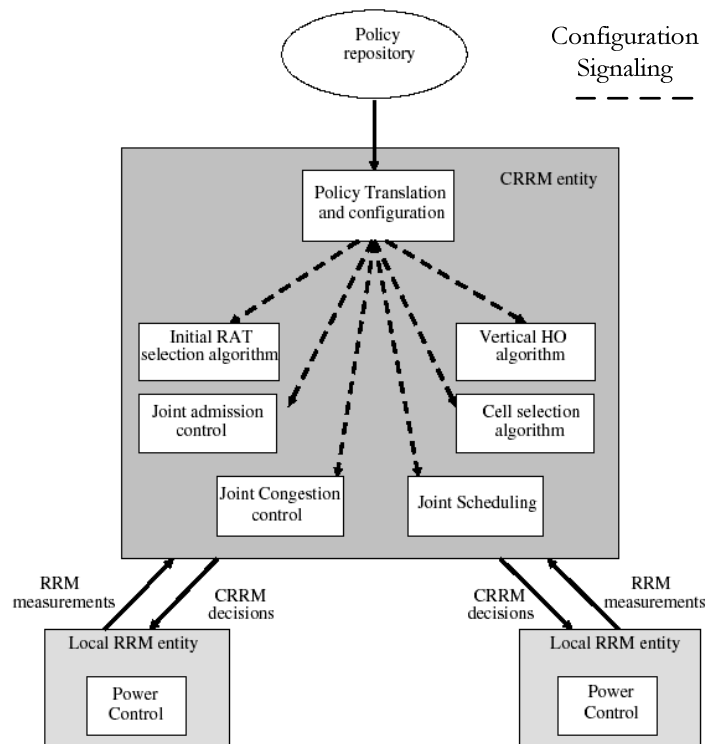


Figure 3.5 – Very high interaction level among JRRM and RRM (extracted from [RSAD05]).

Some examples on RRM and JRRM algorithms implementation are defined in [RSAD05] and [Sall04a] based on the physical location of the JRRM entity, and from the functional viewpoint, based on the different degrees of interaction that may exist. The interaction level depends on the master entity, i.e., if the JRRM is the master of all decisions, or if it is a simple RRM advisor (the

local RRM being the master). This depends on the coupling level between the JRRM and the local RRM. The coupling degree of the JRRM and RRM can have different scenarios where, on the one hand, the JRRM can delegate almost all functions to local RAT RRM, and on the other, JRRM may assume all functionalities and the local RRM is reduced to report measurements, close power control and execute decisions taken by the JRRM entity.

### **3.5 JRRM Cost Functions**

While scanning literature concerning JRRM strategies, Cost Function (CF) based algorithms applied to cellular networks are frequent, being computed on a given network KPIs set. In this context, CFs are typically used to solve network optimisation problems, like the cases presented in [LKHo02] where BSs' cost and KPIs are mapped onto colours (KPIs and RGB association), providing a human perception of the network conditions. In [FlNo02], the soft handover in UMTS is optimised based on a normalised CF that uses weighted KPIs to classify BSs conditions.

As previously mentioned, heterogeneous cellular networks may be defined by several, KPIs that determine their performance. In order to guarantee a desired QoS, a proper balance of KPIs is required. An approach to integrate a set of KPIs into a single one by using a CF that takes them into account, providing their corresponding cost as output, which in reality reflects both network conditions and each of the individually players in the network, BSs and MTs, is needed.

In some cases, the CF is used to perform JRRM decisions, e.g., VHO decisions, like the cases proposed in [CSCR04], [Sall05], [Sall06] and [NaHH06], where, based on a CF result, the best network interface and the best moment to perform handover is presented. Based on these, one may conclude that the CF is also a good way to build a common and comparable parameter to all RATs in a heterogeneous cellular network environment.

The JRRM and RRM entities, and corresponding functionalities and algorithms, must perform important decisions based on a huge amount of spatiotemporal data. This data consists of counters and KPIs generated mainly by BSs. Since the number of these parameters is increasing, and JRRM requires a high level view of the network performance, a common and integrated parameter that can evaluate radio resources availability or network conditions, is required. In order to implement this important task, a CF model must be defined.

In [FWJG09], the focus is about admission control in heterogeneous networks, where services

priority is defined according to their type. A new admission algorithm is proposed, considering a service cost function, used to maximise networks capacity and balance the load of heterogeneous networks.

### **3.6 VHO and HHO Criteria**

As already mentioned, an important mechanism in JRRM is the handover; in a heterogeneous networks environment, the handover process can be done in two different ways: the HHO and VHO.

In literature, different authors address this issue, using different parameters to trigger VHO: in [FGSP05] the service type, network conditions, operator policies, user preferences, and signal level are taken into account for a VHO decision; the authors in [CCJY06] use the service financial cost, signal level, QoS, user velocity, and link capacity; similarly, in [DuSr03], the service financial cost, signal level, and throughput are taken into account. A fuzzy control approach is also considered in [LiTD06], which is based on signal level, service financial cost, and bandwidth. In [ZdSc04] and [BiHJ03], the signal level, signal to interference ratio, and BER are used, therefore, being much focused on signal quality, neglecting other network conditions. In [CCOJ05], a combination of signal level, service delay sensitivity, service financial cost, and mobile conditions is used. A novel and interesting approach is taken in [Sall05], where signal level, QoS, user's and operator's preferences, and load balancing are used. Finally, a set of references propose VHOs triggers using less parameters: the authors in [SCSK04] take only user velocity, only signal level and distance are considered in [BiHJ03], and in [YPVM99] HO uses only delay and users velocity. Many of these references have, as VHO triggering parameters, signal level and service financial cost in common, but in most recent publications, the trend is to include others, like operator's policies and network conditions. Therefore, a more complex decision process is expected in the future, caused not only by the increasing number of parameters considered in the decision method, but also by the increasing number of wireless systems available to a multi-system MT.

In [SEMF07], JRRM strategies that achieve lowest blocking are presented. Numerical results compare the different JRRM strategies and point out the advantages and drawbacks for each of them. The best performance is obtained when VHOs are performed.

As previously presented, the FF model [Sall06], defines a generic model which tries to capture all the effects influencing the RAT selection decisions. Specifically, in order to cope with the multi-

dimensional heterogeneity.

In [FaCh06], a Joint Call Admission Control (JCAC) algorithm for heterogeneous networks is presented, which considers the user's preference in making admission decision. A specific case where the user prefers to be served by the RAT that has the least service cost is modelled and evaluated using Markov Decision Process. The results obtained show that overall service cost in heterogeneous network can be significantly reduced by using the proposed JCAC algorithm.

When scanning literature concerning VHOs analytical models, it is not frequent to find simple models capable to extract the main characteristics of a VHO process. For example, in [LLGD06], a framework to evaluate VHO algorithms is proposed, and in [ZaLi05] a model is proposed to evaluate the impact of VHO algorithm design on system resource utilisation and user perceived QoS. A fuzzy-logic based decision-making algorithm for VHO is presented in [HoBr06], and authors in [LLGD08] propose VHO algorithms performance metrics, and users' mobility impact on VHOs analysed. These, relatively complex, models are used to optimise and trigger VHOs, based on radio signal levels among others.

In [ZaLS08], Markov based techniques are also used to investigate the mobility impact on heterogeneous networks performance, being focused on users' session time network performance metrics, such as handover blocking probability, call holding duration, mobility pattern, network utilisation time, and handover rates. In [HaFa08], authors also propose a Markov chain based model to analyse the JRRM for End-to-End QoS in multi-service heterogeneous wireless networks; nevertheless, besides being a complex model, it also depends on probabilistic inputs for all network states.

In [NiHo09], authors applied the evolutionary game theory into the heterogeneous networks RAT selection procedures problem, but the model does not consider other problems beyond the networks selection phase, which are relevant to JRRM.

Energy can be also used to trigger RRM and JRRM functionalities/algorithms, one of them is definitely networks infrastructures energy consumption, and the corresponding impact on networks operators cost, such the Operational Expenditure (OPEX), simultaneously addressing the carbon dioxide emissions problem. Nowadays, the whole Information and Communication Technologies (ICT) industry [EART11], [ERIC07] is responsible for about 2% of CO<sub>2</sub> emissions worldwide, energy cost ranging from 20 to 35% of operators OPEX. Thus, it is very important to decrease power consumptions in all areas.

In recent literature and research projects, VHOs are used to save energy in MTs especially the new 4G ones. In [DeAD09], authors use VHOs between IEEE 802.11 and 802.16e systems to



reduce terminals power consumption; detailed power and performance models for both standards are defined to evaluate the VHO opportunity. More recently, European projects are dedicated to Energy Efficiency (EE) in mobile networks: EARTH [EART11] is devoted to reduce networks infrastructure power consumption, using a wide set of saving techniques; C2POWER [RRGS11], addresses EE optimisation in MTs, assuming multi-RAT capabilities, attaching MTs to the most efficient radio link. Authors in [KYII10] also address VHOs as a fundamental technique, by proposing a RAT selection algorithm that selects a RAT with lower energy consumption to increase MT battery life, while respecting QoS. In [SeSo09], authors propose EE VHOs by reducing MTs frame overhead. Nevertheless, relevant network infrastructure EE using VHOs is not addressed.

In this thesis, VHOs are used to provide additional EE gains in the network infrastructure. The idea is as follows: in a multi-RAT environment, legacy RATs are usually less energy efficient by comparing power and information relation, thus, moving active MTs (and corresponding services) to modern RATs provides additional EE, assuring a reasonable QoS balance among RATs. Aiming at this goal implies taking three steps: the EE metric is identified and used in a CF; a VHO trigger algorithm is implemented and proposed; a system level power model is computed to obtain the overall energy gain in a given BS, knowing the radio power gain.

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# Chapter 4

## Models and Algorithms

This chapter presents the proposed models used to manage and evaluate the JRRM algorithms applied to LBN, MBN and HBN. In Section 4.1, JRRM Cost Functions are presented. In Section 4.2, a new theoretical model both for RRM and JRRM is proposed. In Section 4.3, a priority strategy to map users' services onto RATs is presented. In Section 4.4, a BS power model is described for energy efficiency studies. Finally, Section 4.5, defines how output variables are computed.

## 4.1 JRRM Cost Functions

In the following sub-sections two algorithms are presented, the fittingness factor and the cost function, the first is a proactive algorithm that execute handovers, using metrics to decide the handover execution, the second computes a wide range of KPIs to be used by proactive algorithms such the fittingness factor one.

### 4.1.1 Fittingness Factor

The FF proposed in [Pere07],  $\psi_{i,p,s,r}$ , reflects the degree of adequacy of a given RAT to a given user. It is defined with respect to each cell of the  $r$  RAT for each  $i$  user, who belongs to the  $p$  customer profile, requesting a given  $s$  service.

The RAT selection algorithm is considered differently depending on whether the selection is done at session set-up (Figure 4.1) or during an on-going connection (Figure 4.2).

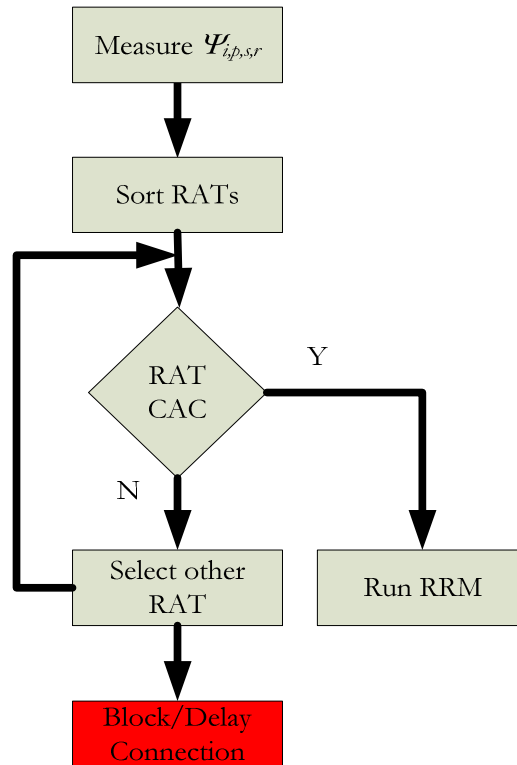


Figure 4.1 – FF RAT selection algorithm (new connections).

The algorithm presented in Figure 4.1, for new connections, starts by selecting a given RAT for a

user requesting a given service  $s$ , as the following procedure:

- Measure the  $\psi_{i,p,s,r}$  for each candidate cell  $k_r$  of the  $r$  detected RAT.
- Select the RAT  $r$  having the cell with the highest  $\psi_{i,p,s,r}$  among all candidate ones:

$$r = \arg \max_r \left( \max_{k_r} \psi_{i,p,s,r}(k_r) \right) \quad (4.1)$$

In case two or more RATs have the same  $\psi_{i,p,s,r}$  value, then, the less loaded RAT is selected.

- Run the CAC procedure in RAT  $r$ .
- If admission is not possible, try the next RAT in decreasing order of  $\psi_{i,p,s,r}$ , provided that  $\psi_{i,p,s,r} > 0$ . If no other RATs with  $\psi_{i,p,s,r} > 0$  exist, block or delay the connection.

For on-going connections, Figure 4.2, the proposed criterion to execute a VHO algorithm based on the FF is as follows, assuming that the MT is connected to the RAT denoted as “servingRAT” and cell denoted as “servingCell”.

- For each candidate cell and RAT, monitor the corresponding  $\psi_{i,p,s,r}(k_r)$ . Measures should be averaged during a period  $T_{VHO}$ .
- If the condition

$$\psi_{i,p,s,r}(k_r) > \psi_{i,p,s,\text{servingRAT}}(\text{servingCell}) + \Delta_{VHO} \quad (4.2)$$

holds during a period  $T_{VHO}$ , then a VHO to RAT  $r$  and cell  $k_r$  should be triggered, provided that there are available resources for the user in this RAT and cell. Note that  $\Delta_{VHO}$  should be configured to distinguish the serving and potential new cell, therefore, used as a triggering threshold. This can be used for fine tune the FF model, like  $T_{VHO}$ .

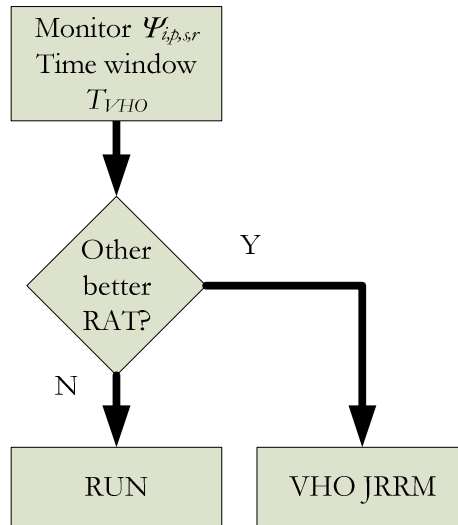


Figure 4.2 – The FF VHO triggering process (ongoing connections).

The FF algorithm also proposes a utility function that considers the influence levels on the RAT selection strategy defined previously. It is computed as the product of three different terms, which are detailed in what follows, and account for the capabilities and the suitability from the user and network perspective:

$$\psi_{i,p,s,r} = C_{i,p,s,r} \times Q_{i,p,s,r} \times \delta(\eta_{NF}) \quad (4.3)$$

where,

- $C_{i,p,s,r}$  represents of hard constraints posed by the capabilities of either the MT or the technology. It takes the value 1 if the both the  $i$  user's MT supports the  $r$  RAT and the  $r$  RAT supports the  $s$  service in a given  $p$  customer profile, and the value 0 otherwise.
- $Q_{i,p,s,r}$  is the suitability factor of the  $r$  RAT to support the  $s$  service requested by the  $i$  user with the  $p$  customer profile. It accounts for a user-specific suitability according to the bitrate that can be allocated to the user, depending on the existing load and the path loss experienced by the user, being defined empirically or analytically. In [PeSA07], analytical expressions for its computation for voice, video call and interactive services were presented.
- $\delta(\eta_{NF})$  is the RAT suitability factor, intending to capture the suitability from the RAT perspective, providing further flexibility to the FF definition. The non-flexible load  $\eta_{NF}$  in one RAT is the total load coming from non-flexible traffic, which is the traffic that can only be served through one specific RAT, and therefore it does not provide flexibility to JRRM.

#### 4.1.2 Proposed Cost Function Model

Since this thesis deals with multiple RATs, which have intrinsically differences on QoS indicators, it is required to identify a particular CF definition for each RAT, using slightly different KPIs, defined in [SeCo07b], and fully updated in [SeCo10a]. Thus, each BS-RAT type has its own normalised CF, supported on different and appropriate KPIs. The CF result can be used by the FF replacing the utility function,  $\psi_{i,p,s,r}$ , this integration is taken by this thesis.

Other important issue that is considered when the CF model is computed is the different perspectives that different network players have over the network, which in this model are the operator's and user's perspectives. When they "look" at the cellular network, they are sensitive to different parameters. For a user, the operator/network is seen as a service provider/infrastructure, therefore, in his/her perspective, parameters like service cost and quality

are important; for a network operator, the same parameter can have an opposite perspective, e.g. the service cost, from an user view point, should be the cheapest as possible, while, for an operator, the same service must provide good revenue and simultaneously be competitive with other operators. Therefore, in order to provide a more realistic balance in the overall network solution, the overall CF must combine both operator's and user's perspectives.

Based on the previous concepts, the network total CF model is divided into two sub-CFs, one being the operator's cost and the other the users' one. Furthermore, the operator CF is also subdivided, since different CFs are computed for each different RAT type. Each one of these "sub CFs" are weighted with different values, enabling the implementation and evaluation of different policies on the JRRM and RRM algorithms over each type of RAT.

Based on the previous discussion, the network total cost,  $C_{NT}$ , is computed according to:

$$C_{NT} = \frac{1}{w_o + w_u} \left( w_o \cdot \frac{1}{\sum_{r=1}^{N_{RAT}} w_{o_r}} \sum_{r=1}^{N_{RAT}} w_{o_r} \cdot C_{o_r} + w_u \cdot \frac{1}{N_U} \sum_{n=1}^{N_U} C_{MT,n} \right) \quad (4.4)$$

where,

- $w_o$  and  $w_u$  are the operator's and user's weights;
- $N_{RAT}$  is the number of existing RATs;
- $N_U$  is the total number of users;
- $w_{o_r}$  is the operator's weight for each RAT  $r$ ;
- $C_{o_r}$  is the operator's total cost for RAT  $r$ ;
- $C_{MT,n}$  is the  $n^{\text{th}}$  MT cost.

The value of  $C_{o_r}$  for a given RAT  $r$  (e.g.,  $r \in \{\text{LBN}, \text{MBN}, \text{HBN}\}$ ) is calculated as follows:

$$C_{o_r} = \frac{1}{N_{BS_r}} \sum_{b=1}^{N_{BS_r}} C_{o_r,b} \quad (4.5)$$

where,

- $N_{BS_r}$  is the total number of BSs for a given RAT  $r$ ;
- $C_{o_r,b}$  is the operator's cost for each BS  $b$ , RAT  $r$ .

$C_{o_r,b}$  is computed by:

$$Co_{r,b} = \frac{1}{\sum_{i=1}^{N_{KPI_r}} w_{r,i}} \sum_{i=1}^{N_{KPI_r}} w_{r,i} \cdot k_{b,i} \quad (4.6)$$

where,

- $N_{KPI_r}$  is the total number of KPIs of a given RAT  $r$ ;
- $w_{r,i}$  is the weight of each  $i$  KPI;
- $k_{b,i}$  represents the normalised value of each KPI ( $0 \leq k_{b,i} \leq 1$ ).

The minimum value for  $k_{b,i}$ , 0, means that this KPI has the optimum value, and the maximum one, 1, means the saturation of that KPI, or that it has reached the worst value possible. In some particular cases, it can be above 1, which means that the current KPI is above the recommended/maximum value.

The cost for each user  $n$ ,  $C_{MT,n}$ , is given by:

$$C_{MT,n} = \frac{1}{\sum_{i=1}^{N_{KPI_u}} w_i} \sum_{i=1}^{N_{KPI_u}} w_i \cdot k_{u,i} \quad (4.7)$$

where,

- $N_{KPI_u}$  is the total of KPIs for users;
- $k_{u,i}$  corresponds to each user  $i$  KPI;
- $w_i$  is the weight of the KPI.

Both  $Co_{r,b}$  and  $C_{MT,n}$  are normalised parameters, thus, in normal situations, they should be between 0 and 1, all the others CF parameters intervals being defined in Table 4.1 . One should note that some  $k_{u,i}$  must be conveniently adapted, in order to have the same meaning of other KPIs, e.g., throughput must be normalised to the maximum value and converted to this criterion.

Table 4.1 – CF parameters range.

CF Parameters	Symbol	Range
Network total cost	$C_{NT}$	[0, 1]
Operator's weight	$w_o$	[0, 1]
User's weight	$w_u$	[0, 1]
Operator's weight for each RAT $r$	$w_{o,r}$	[0, 100]
Operator's total cost for RAT $r$	$Co_r$	[0, 1]
$n^{\text{th}}$ MT cost	$C_{MT,n}$	[0, 1]
Operator's cost for each BS $b$ , RAT $r$ .	$Co_{r,b}$	[0, 1]
Weight of each $i$ KPI	$w_{r,i}$	[0, 100]
KPI	$k_{b,i}$	[0, 1]



This CF model includes not only the KPIs of a given RAT, but also a set of RATs types (i.e., LBN, MBN and HBN), this being aligned with the scenarios section. Furthermore, this CF model includes different perspectives from two important players in the network, Operators and Users. Thus, the total cost of the set of RATs may be computed with high information level, coming from the network player's sensitivities and perspectives. The proposed CF has relevant parameters as inputs, such the number of channels available, load, delay, services and BSs cost, blocking, maximum bitrate, energy efficiency, among others. As output, the model provides the cost from 0 up to 1, for different levels, BSs, Users, and overall RAT, that can be associated to a cellular cluster.

One important objective/role of this model is the offered capability to RRM and JRRM entities to perform decisions (e.g., select a given BS, based on their cost and QoS criteria).

### 4.1.3 Performance Parameters

Table 4.2 presents a list of the identified KPIs, for both operator's and user's perspectives [FeSC06] and [SeCo07a]. This table is defined taking into consideration the following question: "What are the most important parameters that really matters from a user and operator view points?". Note that not all KPIs have a correspondence to both perspectives, e.g., power efficiency; it is clear that for an operator this is a very important parameter, but for a typical user does not carry any meaning.

Table 4.2 presents relevant KPIs for the CF, the following paragraphs present their formulation.

Table 4.2 – User and Operator Cost Function Parameters.

Parameters/KPIs	Perspective	
	User	Operator
Delay	User's Service, $D_u$	BS Average, $D_b$
Blocking	User's Service, $B_u$	BS Average, $B_b$
Cost	Service Cost, $C_s$ (Free, Flat, Volume or time dependent)	BS Cost, $C_b$
Throughput	Service Throughput, $R_s$	BS Average Throughput, $R_b$
Load	-	BS Load (power), $L_b$
Channels	-	BS Occupied Channels, $O_{cb}$
Energy Cost	-	BS and RAT energy cost, $C_u$
Data Efficiency	-	BS and RAT data efficiency, $\eta_{DT}$
Power Efficiency	-	BS and RAT power efficiency, $\eta_{PT}$

For users' delay  $D_u$ , is defined according to:

$$D_u[s] = \sum U(D_{\min}[s], D_{\max}[s]) \times t_f[s] \quad (4.8)$$

where,

- $U(D_{\min}, D_{\max})$  is a uniform random generation function that generates back off delay values between  $D_{\min}$  and  $D_{\max}$ ;
- $t_f$  is the system frame duration.

Thus,  $D_u$  is the produced system multi frame duration delay when no radio resources are available for a given instant. The BS average delay,  $D_b$ , is computed as follows:

$$D_b[s] = \frac{1}{N_c} \sum_{u=1}^{N_c} D_u[s] \quad (4.9)$$

where,

- $N_c$  is the total users' connections in the BS.

Users' blocking probability,  $B_u$  is defined according to:

$$B_u = \frac{T_{s,u}}{T_{c,u}} \quad (4.10)$$

where,

- $T_{s,u}$  is the total number of unsuccessful RT services performed by the user  $u$ ;
- $T_{c,u}$  is the total number of RT connections performed by the user  $u$ .

The BS' average blocking,  $B_b$  is defined according to:

$$B_b = \frac{T_{s,b}}{T_{c,b}} \quad (4.11)$$

where,

- $T_{s,b}$  is the total number of unsuccessful RT services performed at the BS  $b$ ;
- $T_{c,b}$  the total number of RT connections performed at the BS  $b$ .

For the Cost, two parameters are defined,  $C_s$  and  $C_b$  for users and operators, respectively. They represent the service cost viewed from the users side, and the BSs infrastructure cost from the operators viewpoint.

The BS average throughput,  $R_b$ , is defined according to:

$$R_b[\text{bps}] = \sum_{s=1}^{N_{s,b}} R_s[\text{bps}] \quad (4.12)$$

where,

- $N_{s,b}$  is the number of connections attached to a BS  $b$ ;
- $R_s$  is the bitrate of each one.

The Load,  $L_b$ , is only seen by operators and is in fact the BSs power load (if applicable), being defined by,

$$L_b = \frac{P_{b,pilot}[w] + \sum_{i=1}^{N_{i,b}} P_{tx,i}[w]}{P_{b,total}[w]} \quad (4.13)$$

where,

- $P_{b,pilot}$  is the power transmitted by a given BS  $b$  pilot channel;
- $P_{tx,i}$  is the power transmitted in DL by a given BS  $b$  to a MT  $i$ ;
- $P_{b,total}$  is the maximum power transmitted in DL by a given BS  $b$ .

The number of occupied channels  $O_{c,b}$ , is only seen by operators, representing the number of channels occupied by users in a given BS  $b$ .

Energy and data and power efficiency parameters are defined in detail further in this section.

Note that in literature, e.g., [LKHo02], [FlNo02], authors typically use two or three main network KPIs to compute the CF, like Blocking, Load or Link capacity, because these KPIs in some cases are sufficient to represent the overall network QoS, these proposals being used to optimise these few parameters. However, in the current work, this is not the case, since JRRM decisions depend on many other KPIs from different RATs. Furthermore, to evaluate the JRRM behaviour/sensitivity to KPIs, others KPIs are included into the CF computation.

As already mentioned, for each type of RAT, the CF has a set of different KPIs, Table 4.3 presenting the adopted KPIs for each RAT. Note that, the Blocking concept is applied to MBN and HBN (PS based RATs), because it is assumed that applications that are almost RT exist over PS networks, e.g., VoIP. This is valid when PS networks support minimum QoS to users, which is the case assumed in the current work.

Table 4.3 – CF parameters adopted for each RAT type.

RAT type	Blocking	Delay	Load (Power)	Throughput	Occupied Channels	Interference	BS Cost	User Type	Handover	Drop Rate	Data	Efficiency	Power	Efficiency
LBN						√								
MBN	“√”					√								
HBN	“√”	√	NA	√	NA				√					

Parameters like Delay, Throughput, Interference, BS Cost, Handover Drop Rate (VHO and HHO) and User Type are used by the CF in all RAT types. Since these parameters reflect the network status, they influence the RRM and JRRM decisions, therefore, they are included in the CF of each network element. Load and Occupied Channels KPIs are excluded in HBN RATs, since it is assumed that communication between MTs and BSs, is performed one at a time.

The User Type parameter can be defined as Mass Market or Premium. This means that for an operator two different users can have different levels of importance. For example a Premium user can have more privileges when competing with other users for the same radio resources. Therefore, a Premium user is classified as a priority user, having a weight equivalent to several Mass Market users.

The BS Cost parameter, is focused on the BS cost, but addresses the cellular infra structure cost (installation cost and revenue issues). In these case BSs can be classified in three classes: Low, Medium and High cost.

In normal situations, the cost should provide a normalised value as result, thus, each KPI must be normalised to the maximum possible or in some special cases to the recommended value, it being usually the admissible QoS one (e.g., 2% for blocking). For each KPI, a correspondent maximum or the recommend value is used to guarantee the normalisation of the KPI and consequently the CF. However, in some cases (e.g., delay and blocking) the cost value can be higher than 1, e.g., if the blocking is higher than 2%, then the corresponding cost is higher than 1. In this case, an alarm should be activated to highlight this event (processed by the JRRM), to further analysis and to solve and identify the causes.

The CF result applied to all BSs in a heterogeneous cellular network, offers to RRM and JRRM entities a good way to implement the Always Best Connected (ABC) concept [BCFG03], since each BS has a number associated, their cost value, computed by the CF. Based on these values, the JRRM entity can sort a list of BSs reported/visible by each MT via the RRM level. In the top of this list, it is expected to have the best BS (the lowest cost) that potentially offers the best connection to a given MT, this being the ABC concept implementation.

Similar to BSs, each MT has a cost value attached. This MT's cost is computed into the serving BS cost. This information is vital to take into account the user's interests, in the overall network management, which is assured by the JRRM algorithms and strategies.

Recently, networks power consumption became a major concern for several reasons, economical growing costs from the operator side and also from the environmental impact that equipments

have on the overall electricity consumption and CO2 emissions. For these reasons, data and power energy efficiency are also included in the cost function KPIs set.

In the recent ICT-EARTH project, energy efficiency metrics were defined, such as energy or power and overall information ratio, or even devices power consumption efficiency. However, the separation between users' data and systems' overall data is omitted. In general, transmission of user data is accompanied by additional network signalling. In some cases, even in an "empty" network, radio beacons transporting network information must be continuously transmitting useful data (e.g., BS identification) to standby MTs. Moreover, user data includes other information, such as, radio channel formatting and coding overhead, high network layers protocol additional information, and retransmission of information when radio channels are of poor quality. Therefore, in the end, the relation between real user data and overhead is relevant when discussing energy efficiency and the relation between transmitted bit and power. This difference is important to classify systems or radio resource usage, thus, this thesis proposes to differentiate system overhead information from the user data and associated power efficiency and include this strategy into the CF as a KPI that can be used to guide JRRM decisions.

According to Figure 4.3, one can divide the previous concepts into the following parameters:

- The information volume related to overhead and signalling (includes network and users signalling data) issues,  $V_o$ ;
- The information volume only related to real user data generated by the application,  $V_D$ ;
- The total information volume  $V_T$ , required to transmit a user data is defined by:

$$V_{T[\text{bit}]} = V_{O[\text{bit}]} + V_{D[\text{bit}]} \quad (4.14)$$

- The power required to transmit the overhead information (includes network and users signalling data),  $P_o$ ;
- The power required to transmit the user information,  $P_D$ ;
- The total power  $P_T$ , defined by:

$$P_{T[\text{w}]} = P_{O[\text{w}]} + P_{D[\text{w}]} \quad (4.15)$$

The system or network data efficiency,  $\eta_{DT}$ , is defined by:

$$\eta_{DT} = \frac{V_{D[\text{bit}]}}{V_{T[\text{bit}]}} \quad (4.16)$$

which establishes a relation between useful user data volume, and the overall required info to support the user data.  $V_T$  includes all required signalling overhead and possible data retransmissions.

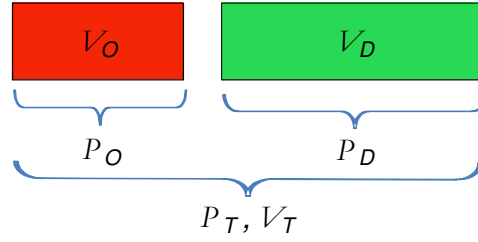


Figure 4.3 – Network, users' power and information parameters map.

The system or network power efficiency,  $\eta_{PT}$ , is defined by:

$$\eta_{PT} = \frac{P_{D[w]}}{P_{T[w]}} \quad (4.17)$$

which establishes a relation between the power required to transmit useful user data volume, ( $P_D$ ;  $V_D$ ), and the overall power required to transmit ( $P_T$ ;  $V_T$ ) signalling and user data.

Additionally, further relations can be established, being assumed as an energy cost to the network. The total power cost required to transmit  $V_D$ ,  $C_U$  is as follows:

$$C_{U[w/bit]} = \frac{P_{T[w]}}{V_{D[bit]}} \quad (4.18)$$

This power cost  $C_U$  is a key metric to measure the EE of a given BS, however, appropriate RRM decisions should be taken based in opportunistic time scale, being crucial to evaluate BSs efficiency, and therefore,  $C_U$  can also be measured in W/bps.

The first step to obtain EE gains is by computing the BS RF power level, compared to the case of EE and RRM algorithms being OFF and ON. Therefore, the BS RF gain,  $G_{RF}$  is as follows:

$$G_{RF[\%]} = \left( 1 - \frac{P_{RFON[W]}}{P_{RFOFF[W]}} \right) \times 100 \quad (4.19)$$

where,

- $P_{RFOFF}$  is the BS RF reference power (FF OFF);
- $P_{RFON}$ , is the BS RF power when the FF algorithm is ON;

For RRM QoS performance parameters are defined in order to analyse the QoS behaviour. Thus, in Table 4.4 these parameters are presented for each type of RAT and for each connection mode (RT and Not Real Time (NRT)).

Table 4.4 - RRM QoS performance parameters adopted for each RAT type.

Parameters/Networks	LBN		MBN		HBN	
	RT	NRT	RT	NRT	RT	NRT
Average Number of Connections	√					
Average Throughput	√					
Average Delay		√		√		√
Average Services Session Drop Rate	√		√		√	
Average Packet Drop Rate		√	√		√	
Blocking	√		√		√	
Average load for each network	√					
Average Number of Active Users	√					
System data efficiency	√					
System power efficiency	√					

Each RAT can be evaluated using different parameters besides the ones used to extract the RAT QoS. These system parameters can be seen as system's main characteristics. Table 4.5 presents a list of these parameters, where each RAT is characterised.

Table 4.5 – RRM output system parameters adopted for each RAT type.

RAT Type	BS/km <sup>2</sup>	#HHO	#New Sessions	#End Sessions	Average Load	Average number of active users	System data efficiency	System power efficiency
LBN	√							
MBN	√							
HBN	√				NA	√		

## 4.2 JRRM Priority List

Besides the CF guidelines, each service is initially mapped onto a given RAT (this concept was developed previously by [Agui04]), based on a priority table that considers the most suitable RAT for a given service.

The priority list must distribute services in a proper and balanced manner, otherwise services will overload a given RAT, causing difficulties to the JRRM entity, decreasing the overall QoS. The priority list and the CF work separated from each other, since at the beginning of a session the priority list is used to search for a RAT for a given service, after this initial RAT attachment and during a given service session, MTs management is based on the CF computational/policy result. This list is a map between services priorities onto RATs, inspired by the service priority described

in Section 2.1 and according to Table 2.3, adapting services to adequate RATs.

Figure 4.4 represents the algorithm behind the priority list concept, where new connections of a given service  $s$  will be initially mapped onto the most priority RAT  $r$  available with radio resources to support this new connection. Running the CAC algorithm to the selected BS/RAT, the service is admitted or not: if yes, then the appropriated procedures starts, running that BS/RAT RRM; if not, other RAT is selected based on the priority list,  $n$  is incremented up to the maximum RATs available. If all RATs do not have radio resources, then, the service is blocked or delayed, depending on its nature.

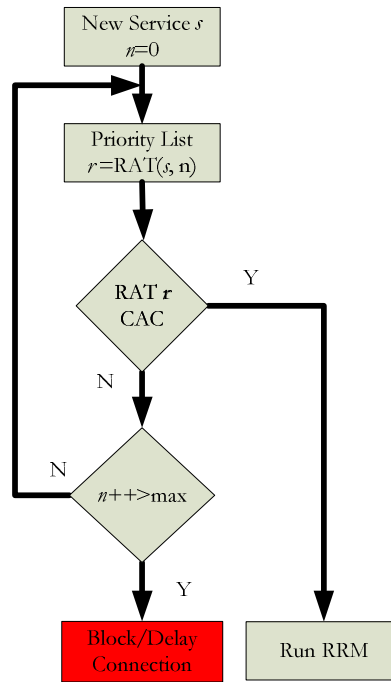


Figure 4.4 – Priority list algorithm.

For ongoing connections, all MTs active services are under the JRRM entity responsibility, which handles all types of handovers based on the CF.

### 4.3 Theoretical JRRM and RRM Model

In wireless mobile heterogeneous network environments, RRM and JRRM entities, and their corresponding functionalities/algorithms, are very complex to be full modelled by using an analytical approach, being frequently explored by many researchers by using complex simulations tools [Serr07] to extract some results and conclusions on their work. In this environment, the VHO is a key procedure to enable advanced network management by handover MTs to most



appropriated RAT, if required.

Naturally, that HHOs, will co-exist and support most of the intra RAT users' mobility needs. In literature, it is not easy to find simple models capable to extract the main characteristics of a VHO process assuming the presence of multiple RATs. However, it is very useful to setup a simple approach/model to extract theoretical VHO related parameters. One proposal is to assume that a given RAT type cluster, Figure 4.5, can be modelled as a single cell. This assumption, enables the use of the previous model mechanism (established for dealing with HHOs) to extract some VHOs assumptions and theoretical results. This means that users previous cell transitions are now translated to transitions between RATs (clusters based).

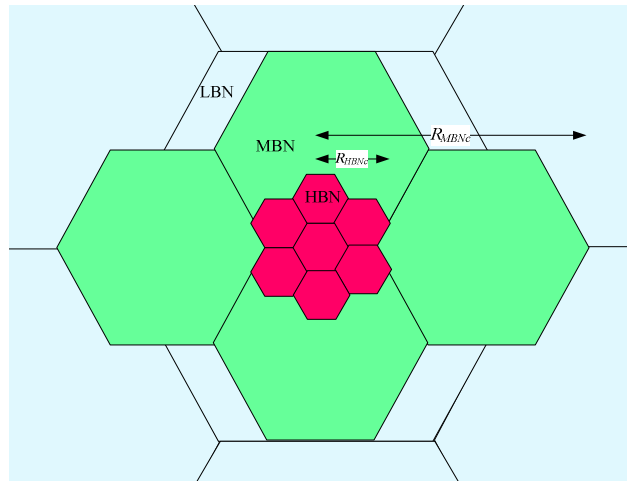


Figure 4.5 – Different RAT clusters (example).

Based on the previous assumptions, one can define several parameters for VHO studies. For example, the  $r$  RAT crossing rate or VHO crossing rate  $\eta_{VHO,r}$ , assumes RAT clusters distributions similar to the case presented in Figure 4.5. Different RATs have different levels of coverage and cluster radius, thus, in some RATs service continuity can be only provided by other RATs. To compute  $\eta_{VHO,r}$ , the previous assumptions are also assumed, like network users' arrival and departure process being balanced, network equilibrium, users uniformly distributed directions of movement in  $2\pi$ , where  $\eta_{VHO,r}$  is defined by [LiCF01],

$$\eta_{VHO,r,[/s]} = \frac{4\bar{v}_r[m/s]}{\sqrt{3}\pi R_r[m]} \quad (4.20)$$

where,

- $\bar{v}_r$ , the average speed;
- $R_r$  is the RAT cluster approximated radius.

The proposed theoretical model is defined by the following mechanism.

To estimate users' multi service generated traffic and the multi RAT's capacity, first the model defines the number of active users  $N_{AU}$ , being the sum of voice and video (i.e., real-time conversational type services) users  $N_{AU-V}$ , and data (i.e., non-real time other services) users  $N_{AU-D}$ :

$$N_{AU} = N_{AU-V} + N_{AU-D} \quad (4.21)$$

where  $N_{AU-V}$  is defined by,

$$N_{AU-V} = \sum_{s=1}^2 \lambda_s [\text{session/s}] \times \tau_s [\text{s/session}] \times N_{CorU} \times P_{Sps} \times (1 - P_{Be}) \quad (4.22)$$

and,

- $\lambda_s$  is the service/session  $s$ , arrival rate;
- $\tau_s$  is the service/session duration for the service  $s$ ;
- $N_{CorU}$  is the number of coverage users;
- $P_{Sps}$  is the service  $s$ , penetration probability;
- $P_{Be}$  is the expected JRRM blocking probability.

and  $N_{AU-D}$  is defined by,

$$N_{AU-D} = \sum_{s=1}^{N_d} \left( \lambda_s [\text{session/s}] \cdot \left( \frac{D_s [\text{bytes/session}] \cdot 8}{\overline{R_{b,s}} [\text{bps}]} + \tau_{Ce} [\text{s}] \right) \cdot N_{CorU} \cdot P_{Sps} \right) \quad (4.23)$$

where,

- $D_s$  is the data volume for a given service  $s$ ;
- $\tau_{Ce}$  is expected JRRM overall delay;
- $\overline{R_{b,s}}$  is the average bitrate per service  $s$ .

Assuming one service per user, then, the user bitrate equals the service one, i.e.,  $\overline{R_{b,i}} = \overline{R_{b,s}}$ .

The total JRRM average bitrate,  $\overline{R_{bt}}$ , is defined according to (4.12),

$$\overline{R_{bt}} [\text{bps}] = \frac{1}{N_{AU}} \sum_{i=1}^{N_{AU}} \overline{R_{b,i}} [\text{bps}] \quad (4.24)$$

Taking the service area,  $S_a$ , then, the active users' capacity density  $\rho_{AU}$  is:

$$\rho_{AU} [\text{km}^{-2}] = \frac{N_{AU}}{S_a [\text{km}^2]} \quad (4.25)$$

From the number of active users and the JRRM average bitrate per user, and a given time

interval,  $\Delta t=1h$ , it is possible to compute the total generated traffic  $T_{AN}$ , for that interval,

$$T_{AN}[\text{Bytes/hour}] = N_{AU} \cdot \frac{R_{bt}[\text{bps}]}{8} \cdot \Delta t[\text{s}] \quad (4.26)$$

Finally the total traffic density  $T_{\rho_N}$ , also for a given period,  $\Delta t=1h$ , is given by:

$$T_{\rho_N}[\text{Bytes/hour/km}^2] = \rho_{AU}[\text{km}^{-2}] \cdot \frac{R_{bt}[\text{bps}]}{8} \cdot \Delta t[\text{s}] \quad (4.27)$$

The amount of traffic allocated to each RAT type  $T_{\rho_N, r}$  is a percentage of total traffic density that will be initial transported/attributed to each RAT, this percentage being defined by  $P_{Init, r}$

$$T_{\rho_N, r}[\text{Bytes/hour}] = P_{Init, r}[\%] \cdot T_{\rho_N}[\text{Bytes/hour/km}^2] \cdot S_r[\text{km}^2] + A_v[\text{Bytes/hour}] \quad (4.28)$$

where,

- $S_r$  represents the area occupied by a given RAT type  $r$ ;
- $A_v$  represents the traffic that comes/goes from/to other RATs by the VHO mechanism.

$A_v$  is based on the percentage applied to a given RAT  $P_{VHO}$ , taking JRRM inter RATs VHO policies:

$$A_v[\text{Bytes/hour}] = P_{VHO} \cdot T_{\rho_N, r}[\text{Bytes/hour}] \quad (4.29)$$

Naturally, when  $P_{VHO}$  is different from 0, then the destination RAT should add traffic in the same amount than other traffic source RAT should decrease.  $P_{VHO}$  can be negative or positive depending on the VHO traffic flux management policy. Note that  $P_{Init, r}$  is conservative, being constrained by the following condition ( $N_{RAT}$  is the number of different RATs):

$$\sum_{r=1}^{N_{RAT}} P_{Init, r} = 100\% \quad (4.30)$$

$T_{\rho_N}$  is very useful, since heterogeneous network capacity can be computed also based on network resources per area. Then, the overall network capacity density,  $T_{CN}$ , is computed according to:

$$T_{CN}[\text{Bytes/hour/km}^2] = \sum_{r=1}^{N_{RAT}} T_{CN, r} \quad (4.31)$$

where,

- $T_{CN, r}$  is the network capacity of each RAT type  $r$  defined as follows:

$$T_{CN, r}[\text{Bytes/hour/km}^2] = \sum_{bs=1}^{N_{BS, r}} \frac{C_{bs, r}[\text{Bytes/hour}]}{A_{cov, r}[\text{km}^2]} \quad (4.32)$$

where,

- $C_{bs,r}$  is the RAT  $r$  BS capacity;
- $A_{cov,r}$  is the BS coverage area.

After capturing the traffic generated by users and the network capacity, it is important to establish a relationship to JRRM QoS parameters. However, an analytical model to capture the overall heterogeneous network performance at the JRRM level is not straightforward, since the intermediate steps are complex and usually obtainable only by simulation approaches. Nevertheless, a simple approach to this problem needs to capture the relation between traffic generation and overall network capacity, similar to an Erlang-B model relation [Mess72]. Using this model, it is possible to roughly predict the network blocking probability. To compute this relation, a shape correction parameter  $B_\alpha$  was defined to obtain the JRRM blocking probability (matching Erlang's traffic tables using a simple curve fitting process in a local curve approach),  $P_B$ , and  $B_\alpha$  is also required to introduce the traffic channels efficiency effect. Thus,  $P_B$  takes as input the users' multi-service traffic generation density  $T_{\rho_N}$ , over the heterogeneous traffic capacity density,  $T_{CN}$ .

$$P_B[\%] = \left( \frac{T_{\rho_N}}{T_{CN}} \right)^2 B_\alpha \quad (4.33)$$

For computing  $P_B$ , based on  $T_{\rho_N}/T_{CN}$ , a non linear correction parameter  $B_\alpha$  was required, to introduce the traffic channels efficiency effect.

For computing the JRRM delay  $\tau_{Jd}$  based on  $T_{\rho_N}/T_{CN}$ , a similar approach was taken, thus, a non linear correction parameter  $D_\alpha$  was also defined.

$$\tau_{Jd}[s] = \left( \frac{T_{\rho_N}}{T_{CN}} \right)^2 D_\alpha \quad (4.34)$$

In Table 4.6, both  $B_\alpha$  and  $D_\alpha$  values are defined.

Table 4.6 – Shape values for  $B_\alpha$  and  $D_\alpha$ .

$T_{\rho_N}/T_{CN}$	$\leq 0.3$	$0.3 < \leq 0.55$	$0.55 < \leq 0.85$	$0.85 <$
$B_\alpha$	0.1	0.2	0.25	0.3
$T_{\rho_N}/T_{CN}$	$\leq 0.4$	$0.4 < \leq 0.7$	$0.7 <$	NA
$D_\alpha$	0.3	1	1.3	

Generally, for each individual RAT  $r$ , it is also possible to compute blocking and delay, which are based on each RAT traffic. The multi-service generated traffic density  $T_{\rho_{N,r}}$  and RAT capacity density  $T_{CN,r}$  are used to compute RAT  $P_{B,r}$  and  $\tau_{d,r}$  according to the following:

$$P_{B,r}[\%] = \left( \frac{T_{\rho_{N,r}}}{T_{CN,r}} \right)^2 B_{\alpha} \quad (4.35)$$

$$\tau_{d,r}[\text{s}] = \left( \frac{T_{\rho_{N,r}}}{T_{CN,r}} \right)^2 D_{\alpha} \quad (4.36)$$

Based on the previous assumptions and parameters, it is possible to produce several others output parameters, by computing and/or combining with other interesting parameters/models available in literature, e.g., the horizontal cell crossing rate  $\eta_{HHO,r}$  presented in [LiCF01]. Assuming hexagonal cells, and uniformly distributed directions of movement in  $2\pi$ , the  $\eta_{HHO,r}$  applicable for intra RATs, or cell crossing events estimation, is

$$\eta_{HHO,r}[\text{/s}] = \frac{4\overline{v}_r[\text{m/s}]}{\sqrt{3}\pi R_r[\text{m}]} \quad (4.37)$$

$R_r$  being the cell radius of a given RAT type  $r$ .

From the cell crossing rate, it is possible to compute the number of HHOs,  $N_{HHO,r}$  in a given RAT  $r$  and time interval  $\Delta t$ ,

$$N_{HHO,r} = \eta_{HHO,r}[\text{/s}] \cdot N_{AU,r} \cdot \Delta t[\text{s}] \cdot P_{CH,r} \quad (4.38)$$

where,

- $P_{CH,r}$  is the JRRM initial traffic percentage for RAT  $r$ ;
- $N_{AU,r}$  is the number of active users attached to a given RAT  $r$ .

The drop probability  $P_D$  (handover calls, only for voice and video), is computed based on network equilibrium (cell handover incoming rate equal to outgoing one).

$$P_D = \frac{P_H P_{HF}}{1 - P_H (1 - P_{HF})} \quad (4.39)$$

where,

- $P_{HF}$  is the handover failure probability (HHO calls) assuming that new calls and handover ones are processed in a same way, then  $P_{HF} = P_B$  is also assumed;
- $P_H$  is the HHO probability computed as follows:

$$P_H = \frac{\eta_{HHO_r}[\text{/s}]}{\frac{1}{\tau_s[\text{s}]} + \eta_{HHO_r}[\text{/s}]} \quad (4.40)$$

Another interesting parameter is the HHO calls average arrival rate,  $\lambda_b$ , computed as follows:

$$\lambda_b = \frac{P_H(1-P_B)}{1-P_H(1-P_{HF})} \lambda_s \quad (4.41)$$

where,

- $\lambda_s$  is the call arriving rate from neighbouring cells.

The number of VHOs in a given JRRM scenario,  $N_{VHO_r}$ , and time interval  $\Delta t$ , is given by,

$$N_{VHO_r} = \eta_{VHO_r}[\text{/s}] \cdot N_{AU_r} \cdot \Delta t[\text{s}] \cdot P_{CV_r} \quad (4.42)$$

where,

- $P_{CV_r}$  is the JRRM influence in the number of VHOs.

Similar to HHOs, the VHO drop probability  $P_{VD}$  (VHO calls) is computed, where network equilibrium is again assumed. For the VHO failure probability  $P_{VHF}$ ,  $P_B$  was again assumed.

$$P_{VD} = \frac{P_{VH}P_{VHF}}{1-P_{VH}(1-P_{VHF})} \quad (4.43)$$

The VHO probability  $P_{VH}$ , can be now estimated as follows,

$$P_{VH} = \frac{\eta_{VHO_r}[\text{/s}]}{\frac{1}{\tau_s[\text{s}]} + \eta_{VHO_r}[\text{/s}]} \quad (4.44)$$

For the VHO calls average arrival rate,  $\lambda_{nb}$  is computed as follows:

$$\lambda_{nb} = \frac{P_{VH}(1-P_B)}{1-P_{VH}(1-P_{VHF})} \lambda_{sp} \quad (4.45)$$

where,

- $\lambda_{sp}$  is the call arriving rate from other RATs.

In simulation, when a VHO event is required, a BS-RAT decision is performed at JRRM, based on the CF result, thus, knowing VHOs estimation events it provides knowledge about the frequency of this events at JRRM entity.

## 4.4 BS Power Model

This section defines a BS micro-cell power consumption estimation, required to estimate the BS system level EE gain. This model assumes maximum load conditions for 2010. Although, this work assesses RF power gains achieved by VHOs, the EARTH system level model [ImKa11] is also used, enabling the computation of system level gains.

The power consumption of BSs is dominated by the radio equipment. This is especially critical, as it provides a physical interface between MTs and the BS; therefore, it must guarantee, at any time, a continuous flow of information, while providing an acceptable QoS. This sub-section shows a high-level model of such a radio system. In general macro-, micro-, pico- and femto-cells BS equipment blocks include multiple transceivers (TRXs) with multiple antennas. Each of these TRXs comprises a Antenna Interface (AI), a Power Amplifier (PA), an RF transceiver and a Baseband (BB) interface including both a receiver (UL) and a transmitter (DL), a DC-DC (DC) power supply regulation, an active COoling (CO) system, and finally a main AC-DC Power Supply (PS) for connection to the electrical power grid. Note that active cooling is only relevant for a macro-cell BS, being negligible for smaller ones.

In Figure 4.6, the BS overall power consumption dependency on RF output power is highlight. One may observe that this relation is roughly linear, hence, for studies not dealing specifically with component improvements, a linear approximation of the power model is reasonable.

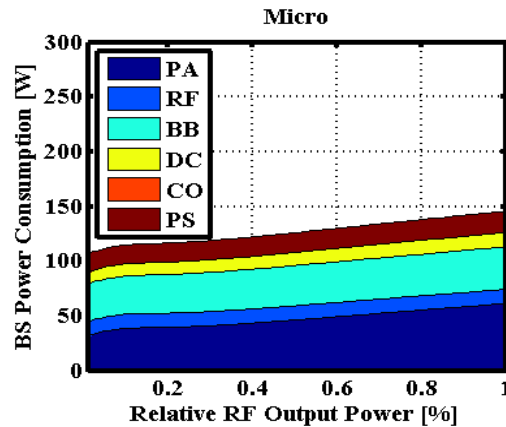


Figure 4.6 - Micro-cell RF and BS power relation (extracted from [ImKa11]).

The EARTH project proposes a simple relation between RF and BS power as follows:

$$P_{BS} = P_0 + \Delta_P \cdot P_{RF}, \quad 0 \leq P_{RF} \leq P_{\max} \quad (4.46)$$

where,

- $P_{BS}$  is the required BS power;

- $P_{RF}$  is the output RF power;
- $P_o$  is the power consumption calculated at the minimum possible RF power;
- $\Delta_p$  is the linear  $P_{BS}$  relation with  $P_{RF}$ , for each BS type;
- $P_{max}$  is the maximum RF power.

Using (4.46), the EE gain at BS system level,  $G_{SL}$ , is computed according to:

$$G_{SL}[\%] = \left( 1 - \frac{P_{BSON}[W]}{P_{BSOFF}[W]} \right) \times 100 \quad (4.47)$$

where,

- $P_{BSOFF}$  is the BS reference total power (FF OFF);
- $P_{BSON}$  is the BS total power when the FF algorithm is ON.

## 4.5 JRRM Output Parameters

At JRRM level, relevant output parameters are computed, many of them being average values, JRRM QoS counters reported by RATs (RRM level). This is performed once per second as default. Some parameters, described in Section 4.1.3 used at RRM level and taken by the CF model, are used to compute these JRRM parameters. The set of key parameters is as follows:

- JRRM blocking,

$$P_{bJRRM} = \frac{N_{Bco} + N_{Bpo}}{N_C} \quad (4.48)$$

where,

- $N_{Bco}$  is the number of blocked calls at CAC due to lack of channels;
  - $N_{Bpo}$  is the number of blocked calls due to load threshold limit at CAC;
  - $N_C$  is the total number of calls.
- JRRM delay,

$$\overline{\tau_{JRRM}}[s] = \frac{\sum P_{rt}[s]}{N_p} \quad (4.49)$$

where,

- $P_{rt}$  is the packet retransmission time randomly generated and uniform distributed when radio resources are unavailable;
  - $N_p$  is the total number of packets.



- JRRM Instantaneous delay (in one second period),

$$J_{id}[s] = \frac{\sum_{t=1}^t p_{rt}[s]}{N_{p(t)} - N_{p(t-1)}} \quad (4.50)$$

- Number of active users (active users in all RATs),

$$N_{AU} = \sum_{r=1}^{N_{RAT}} \sum_{b=1}^{N_{BS_r}} N_{AUr,b} \quad (4.51)$$

where  $N_{AUr,b}$  is the number of active users in a given BS/AP  $b$  and RAT  $r$ ,

- JRRM average number of BS/APs reachable by all active MTs,  $\overline{N_{BSMT}}$ ,

$$\overline{N_{BSMT}} = \frac{1}{N_{AU}} \sum_{i=1}^{N_{AU}} N_{BSMT,i} \quad (4.52)$$

where  $N_{BSMT,i}$  is the number of BS/APs reachable by each active MT  $i$ ;

- JRRM average bitrate,

$$\overline{R_{bJRRM}}[s] = \sum_{r=1}^{N_{RAT}} \sum_{b=1}^{N_{BS_r}} \sum_{s=1}^{N_s} Sbr_{r,b,s}[s] \quad (4.53)$$

where,

- $N_s$  is the number of active services in a BS/APs  $b$  of a given RAT  $r$ ,
- $Sbr_{r,b,s}$  is the  $s$  service bitrate for a given BS/AP  $b$  and RAT  $r$ .
- Network Total Cost,  $C_{NT}$ , already presented in the CF Section 4.1.2;
- Load Balancing Factor (LBF), defined in [Sall05] can be used to compare the loads in LBN and MBN RATs, acting as a fairness quantifier. In particular, the  $L_{BF}$  for a set of  $N_{RAT}$  different RATs is given by,

$$L_{BF} = \frac{1}{N_{RAT}} \frac{\left( \sum_{r=1}^{N_{RAT}} \overline{L_r} \right)^2}{\sum_{r=1}^{N_{RAT}} \overline{L_r}^2} \quad (4.54)$$

with  $\overline{L_r}$  the average load in RAT  $r$ , and  $1 \leq r \leq N_{RAT}$ . The  $L_{BF}$  is bounded between 0 and 1.

A perfect load distribution (i.e., equal loads in each RAT) yields a  $L_{BF}$  equal to 1. On the other hand, a total unbalanced situation yields a  $L_{BF}$  equal to  $1/N_{RAT}$ ;

- Number of HHOs,  $N_{HHO}$ , is a simple incremental counter of HHO events,

$$N_{HHO} = N_{HHO} + 1 \quad (4.55)$$

- HHO Failure rate,

$$F_{HHO} = \frac{N_{Hf}}{N_{HHO}} \quad (4.56)$$

where  $N_{Hf}$  is the number unsuccessful HHOs;

- Number of VHOs,  $N_{VHOsim}$ , a simple incremental counter of VHO events,

$$N_{VHOsim} = N_{VHOsim} + 1 \quad (4.57)$$

- Number of VHOs triggered by the FF algorithm,  $N_{FFVH}$ ,

$$N_{FFVH} = N_{FFVH} + 1 \quad (4.58)$$

The difference between  $N_{VHOsim}$  and the  $N_{FFVH}$  is the number of VHOs that are executed due to other causes besides the FF, such out of coverage.

- VHO Failure rate,

$$F_{VHO} = \frac{N_{Vf}}{N_{VHOsim}} \quad (4.59)$$

where  $N_{Vf}$  is the number unsuccessful VHOs;

- Number of active users per service  $s$ ,  $N_{MTact,s}$ ;

$$N_{MTact,s} = N_{MTact,s} + 1 \quad (4.60)$$

The previous JRRM output parameters are useful to evaluate different aspects of different JRRM policies. From the individual RAT up to JRRM QoS performance level, it is possible to compute key parameters that access the impact of network inputs loads/variation combined with JRRM policies into the overall QoS. Nevertheless, one selected the most representative ones to be evaluated and compared, as follows: average delay, bitrate, blocking, number of active users, and RATs load balancing.

# Chapter 5

## Algorithms and Implementation

This chapter aims at presenting the most relevant functional blocks proposed and implemented into the JRRM simulator. Section 5.1 presents the relevant algorithms. Section 5.2 presents a short overview about the developed simulator. In Section 5.3, a key list of input and output parameters is presented. In Section 5.4, a brief simulation assessment strategy is explained.

## 5.1 Algorithms

### 5.1.1 Functionalities

RRM functionalities are divided over MTs and BSs. The MT entity is responsible by initiating events, like calls, packet sessions, link power control, etc. By using a state machine, the MT interacts with the BS monitoring the radio link quality, and keeping the link respecting to the QoS required. If something changes on the radio link, then the BS/RRM makes the appropriated changes, like changing the power level, or changing the bitrate of a service, depending on the network type and capabilities. The BS/RRM is responsible for the allocation and release of resources among BSs and MTs, which is done by testing the power and channel/bandwidth resources in a given BS. If the minimum QoS requirements are guaranteed, then UL/DL power and channels resources are allocated to the MT.

When an MT attempts to initiate an RT service, and if the BS can not accept this request, the BS/RRM will block this service, updating the blocking statistical parameters. On the other hand, if the service is NRT, then the BS/RRM will delay this MT/service by shifting the MT/service traffic structure, using a random and uniform period of time, updating the delay QoS parameter, similar to the blocking case.

The cell breathing process is a standard method in LBN, in some case offered by manufactures in MBN has an advance method (not standard). This RRM procedure, has a preventive purpose, in which the BS load is monitored and if the load level achieves, very high or very low levels, then the power of the BS pilot channel will decrease or increase, respectively. The decrease/increase level is defined by the algorithm configuration variables as a percentage step over the current pilot power. At the end the maximum and minimum level allowed for this channel is verified, and then truncated if needed. After this process, the new coverage for the BS is computed updating the BS pilot power matrix.

### 5.1.2 General Algorithm

Figure 5.1, besides representing the zoom over the general algorithm functionalities, also presents the scope of different entities, like RRM and JRRM. The RRM entity, here represented in pink, besides the intrinsic RAT basic functions, covers the basic RAT algorithms, like call admission control, power control, and link control. The JRRM entity covers the yellow region; note that besides the proper JRRM functionalities, the JRRM entity may also cover or manage the RRM ones, since JRRM has the capability of changing the guide parameters of the RRM algorithms and functionalities. These excludes fast (time dependent) RRM functions, like fast power control. In any case, the JRRM entity covers other algorithms, like congestion control, HHO and VHO, load balancing, and the CF.

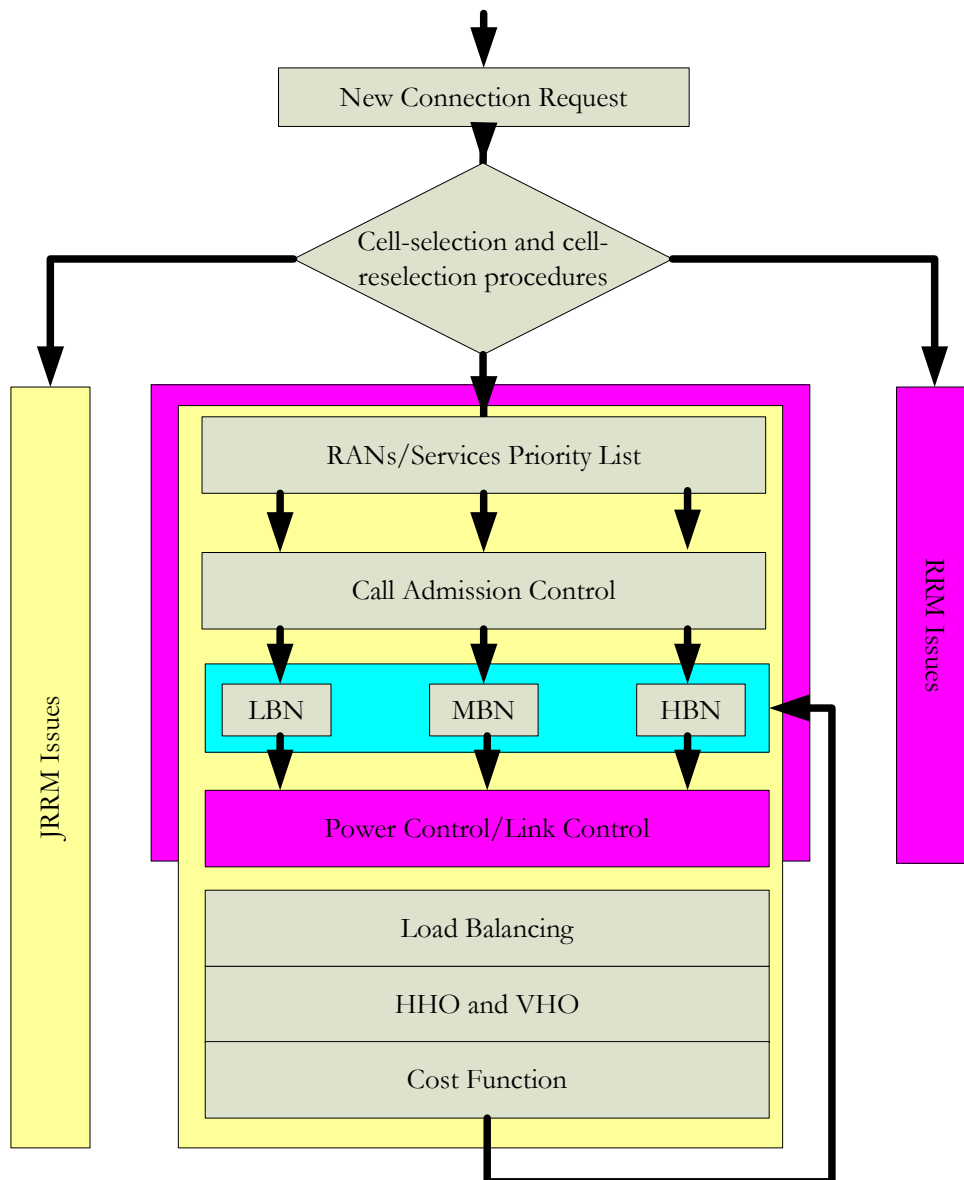


Figure 5.1 – JRRM general functionalities.

The JRRM/RRM CAC process, Section 3.1.2, is a very important mechanism to allocate the initial BS to a given MT/service, Figure 5.2. The CAC is triggered when a given MT has a potential starting call/session. When this event is detected, the MT launches a request to the JRRM, this request is processed by the JRRM CAC algorithm, which executes the following steps: first, the predefined priority list (JRRM service/RAT's priority policy), is used to obtain the most priority RAT to a given service, it can be also based on the FF or CF computation. If the HBN is the RAT selected then the MT verifies the communication viability (UL and DL propagation), after this process the BS or AP bandwidth availability is verified, if so, the MT will be attached, otherwise, will be rejected by blocking or delay depending on the service switching type (CS or PS). If the RAT selected is an LBN or MBN, a similar process is executed, which is: the BS load limit and the orthogonal codes availability are verified, if both are enabled then the attachment process is executed. If any of the previous radio resource are unavailable (BS power or channels), then the same treatment is performed as in the HBN case (blocking and delay).

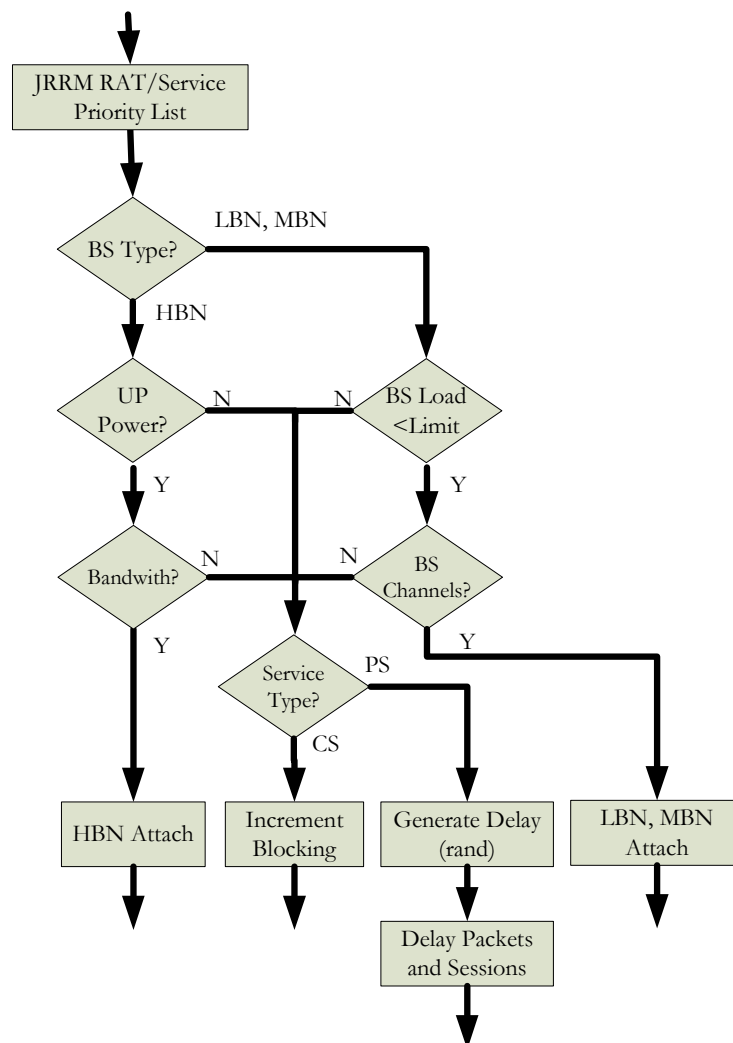


Figure 5.2 – JRRM/RRM CAC algorithm.

The Load Balancing (LB) algorithm is a process that may be triggered if the  $L_{BF}$  is below a given threshold. If this condition is verified, then the LB algorithm starts. This process pushes MTs (forcing handovers) away from highly loaded BSs until they present a predefined load level. According to Figure 5.3 and Section 3.4.1, when the LB ends, the  $L_{BF}$  is computed according to (4.54) and updated. The LB algorithm may cause a ping pong effect on MTs, since they can be moved endless from one BS to another; therefore, a counter is implemented to limit and avoid this effect.

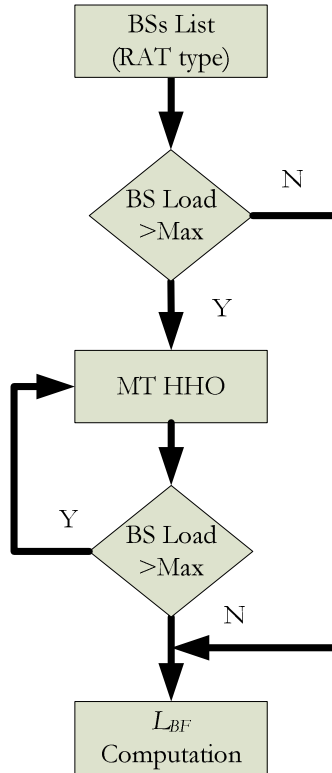


Figure 5.3 – Load Balancing algorithm.

The cell breathing process, tries to keep (in individual bases) BSs load between a given recommended maximum and minimum values. The definition of these values should avoid the use of this procedure often, since this procedure may have a huge impact on results, due to the fact that it can decrease or increase the BS radius and consequently the number of MTs covered, causing instability, not only in the BS itself, but also in neighbouring cells. To avoid these effects, at the end, the pilot power level is limited to a given maximum and minimum.

The HHO and VHO process (Section 3.3.2), are managed by the same algorithm, Figure 5.4, since they are decided based on the cost that each BS computes based on the JRRM/CF policy. This algorithm is as follows: first, a candidate list is generated, based on the MT/service and on the communication capabilities between BSs and the current MT, after this, the list of BSs is sorted based on cost. If the lowest BS cost in the list is from other RAT type, than a VHO is

performed, but if the RAT type is the same, then a HHO is triggered. After this decision, the old BS is release radio resources regarding the MT/service, and the selected/new BS being requested; if in this process the BS (for any reason) rejects the request, then, the next BS from the sorted list is selected, repeating the allocation process, until the list is empty or after a successful handover, otherwise, the algorithm returns a drop indication, and the MT/service drops the current service.

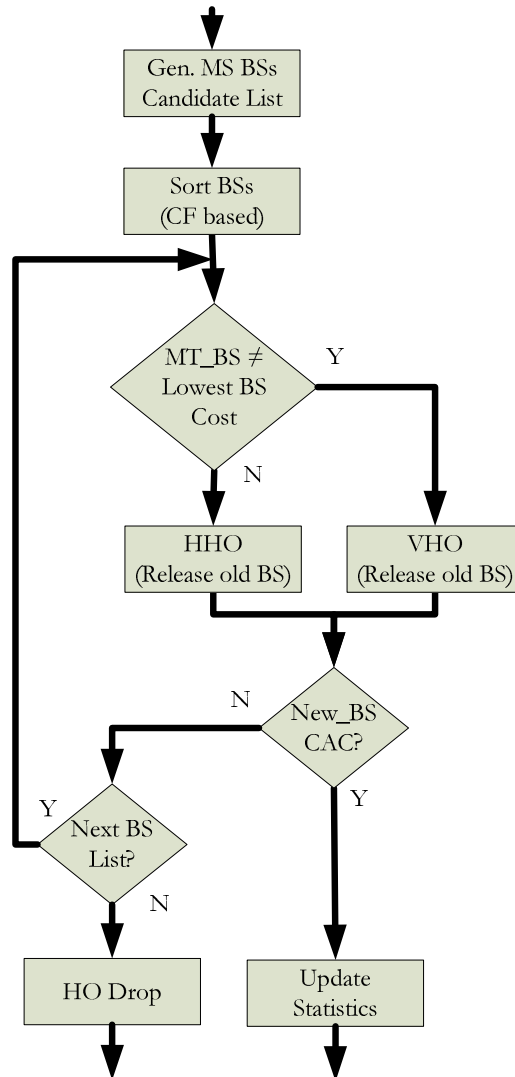


Figure 5.4 – HHO and VHO processes.

In this thesis, the HHO and VHO processes are treated as one, i.e. the triggering method is common to both processes. The BS re-selection procedure is based on a BS candidate list, this list being sorted according to the CF results (stored in each BS). This means that the JRRM entity is able to process HHOs and VHOs.



### 5.1.3 MIMO Implementation

The introduction of MIMO systems in this thesis is based on the strategy described in Section 3.2 where the described RMG function was implemented and validated. The MIMO simulation tool was used with the set of theoretical scenarios defined in [Ljun06], which is the same used in this thesis.

MIMO is used in only for PS services, since it is assumed that only this type of services will really take advantage from the MIMO gain. Therefore, packets duration will be decreased compared to the initial case (SISO).

Figure 5.5 shows how the RMG model can be implemented. The MIMO flag is tested to check if MIMO systems are present. If so, then, the MT mobility profile is tested: if MT's mobility profile is slow (associated to pedestrians' average speed), then the RMG 4×2 case is computed, if not (else) then a static or fast profile is assumed and the RMG 4×4 case is computed. After this stage, the RMG value is stored and used to compute the current packet duration; this can change the packet radio resources occupation period. In some packets, this does not have a relevant impact, since the initial packet duration (volume based) is already less than a frame duration. Therefore, only in large packets sizes the RMG has a reasonable impact, since it reduces the number of required radio frames.

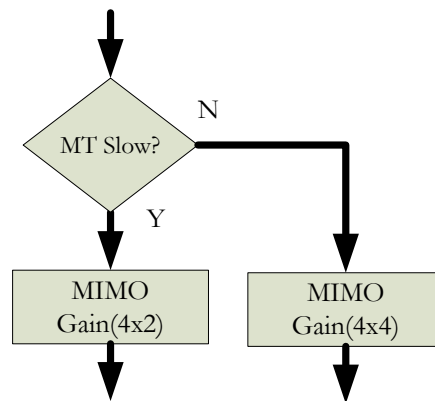


Figure 5.5 - MIMO gain mechanism.

In order to include the type of terminals (size and environment dependency) into scenarios, the following strategy was assumed: for static and fast users, a 4×4 MIMO communication is possible (since the use of a size equivalent laptop terminal or a vehicle type are assumed); for pedestrian users, a 4×2 MIMO scheme is adopted, being used for handheld size terminals. Therefore the MIMO Tx×Rx number of antennas, depends on the user's mobility profile. The distance between BSs and MTs has only influence on the cell type decision in this algorithm.

The RRM/JRRM partially includes some of the features of the MIMO gain algorithm, namely the

pico- and micro-cells scenarios applied to 4x2 and 4x4 antennas cases.

### **5.1.4 Additional Models**

To introduce users' mobility, the Random Walk Mobility Model, was adopted and implemented to reproduce MTs heretic behaviour [CaBD02]. This model gives a memory-less mobility patters, as each step is calculated without any information of the previous one. At regular time intervals, both the direction (uniform distributed from  $0^\circ$ , to  $360^\circ$ ) and the speed of the MTs are updated. MTs' speed is combined with this mobility model, using a triangular distribution density model [ChLu95], being capable of generating different speeds for each MT, which is important for link load variation and handover generation due to propagation changes. The detailed description and some discussion concerning mobility models can be found in the Annex-A.

For the estimation of the received average power, the simulator uses the well known COST 231 Walfisch-Ikegami propagation model for micro-cell environments [DaCo99]. This model is used to estimate the signal level on LBNs and MBNs. If it is a HBN (e.g., 802.11x family), then the algorithm switches to the double breakpoint model [PrPr01], this model being dedicated to estimate the signal level of WLAN of 2 and 5 GHz bands, defined in [Ljun06]. Both models detailed description can be found in Annex-B.

In order to generate the multi service traffic (heterogeneous traffic), different source models are used to define and generate services main characteristics. Detailed description of these models can be found in Annex-C.

## **5.2 Simulator Overview**

In this section, the developed simulation tool is described, highlighting the main features and capabilities implemented in the tool, the focus being the RRM/JRRM methods. This is a time based and system level simulator, developed over the Microsoft VC++2005 platform. Currently, this tool is capable to perform simulations over three types of RATs: LBN-UMTS R99, MBN-UMTS R5 and the HBN-802.11 family. Besides intrinsic and fundamental systems functionalities, like power control, link control, basic channel code management, radio bearer service, load control, access control, propagation estimation, interference estimation and generation, etc., the

simulator is also capable of generating service traffic mix (defined in 2.1), using service source models (details in Annex-C) for this propose. In order to insure the traffic and service heterogeneity (covering all service classes), the following service set is defined:

- Conversational (voice and video-telephony);
- Interactive (web browsing and File Transfer Protocol (FTP));
- Background (e-mail);
- Streaming (video streaming).

Based on these services, the MTs generated traffic can be divided in different levels (session, packet call, packet and circuit level) and applied to cellular RATs, bring up to live RRM and JRRM functionalities. RRM functions are assumed to be part of a given RAT type, the JRRM entity being the master of all media and high level decisions, namely, the initial access performed by a MT, which is based on a service/RAT priority table, previously described and implemented by the JRRM entity. Besides this, the JRRM is able to perform HHOs and VHOs based on the CF model proposed in this thesis.

For each RAT type, at RRM level, the following functionalities were implemented:

- LBN – Fast power control, basic channel orthogonal code management, radio bearer adaptation, load balancing (optional), HHO, access control (power and code), best effort packet scheduling, COST231 Walfish-Ikegami propagation model and noise and interference estimation [DaCo99].
- MBN - Link control (different modulation schemes), basic channel code management, radio bearer service, load control, access control (power and code), HHO, best effort packet scheduling, COST231 Walfish-Ikegami propagation model and noise and interference estimation [DaCo99].
- HBN - Radio bearer service adaptation (based on link level), access control (bandwidth based), double break point model propagation model [PrPr01], HHO, best effort packet scheduling, and interference estimation.

The simulator can be divided into three main functions, Figure 5.6, identified by the green, red and blue blocks. The green blocks are dedicated to the following inputs:

- Scenarios Inputs: represents the simulation area, services source models configuration data, services rates and duration, propagation models information, location of BS/APs, building and streets information, etc.
- Users Inputs: number of users, service penetration, etc.

- Multi-RRM Algorithms Inputs: parameters related with RRM issues, like service priority list, etc.
- JRRM Algorithms Policies Inputs: defines the parameters related with the CF weights (BS-QoS, user's preferences), maximum QoS parameters, for each type of RAT. Note that based on these parameters different policies can be simulated.
- RAT # 1 (BS 1) up to RAT # n (BS n): input parameters for different RAT, like pilot power level, MT maximum power, antennas pattern, total power, frequency, etc.

The red set of blocks is where most of the simulation computational effort is performed. These blocks have the following meaning:

- Traffic Generation: in this block all traffic information vectors of all MTs and services are built, usually within a time frame of one hour.
- RRM RAT #1 up to RAT #n: these blocks are very “intense”, since they perform the fundamental functionalities of a specific RAT, by running/managing and monitoring the radio links conditions and services attach (generated by the Traffic Generation block), thus requesting a high computational effort.
- JRRM Algorithms and Policies Engine: this is also an “intense” block, since it is here where major decisions are taken; being common to all RATs this block is requested many times, not just to perform all types of handover, but for initial BS selection, run the CF that is related to all BSs and MTs active in the scenario (more details will be provided on the next sections).

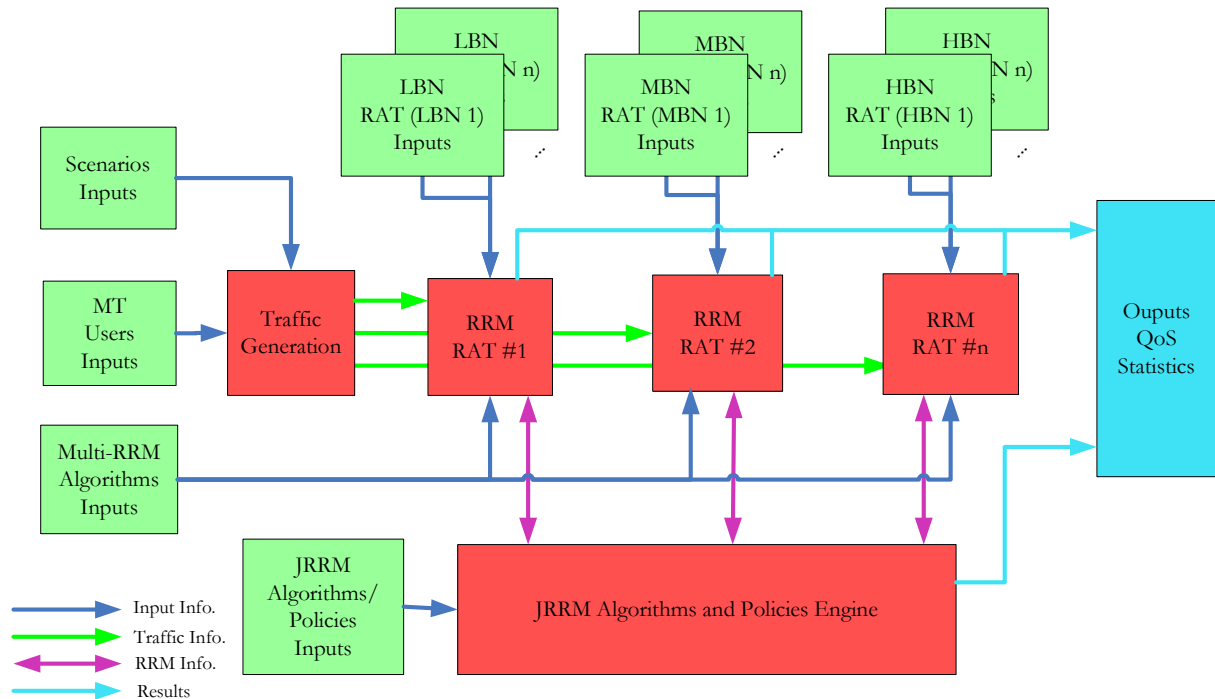


Figure 5.6 – JRRM simulator general block diagram.

Finally, the blue block is where the selected output parameters are displayed, most of them being QoS and system statistics at RRM and JRRM levels. These parameters can be used to extract others, by establishing logical relations among them.

## 5.3 Inputs and Outputs

### 5.3.1 Inputs

The JRRM simulator input component is loaded by the tool using a single scenario input file [SGFC06], where a list of a huge set of parameters values is defined, therefore being easy to repeat simulations or change minor details in the scenario. This input file is described Figure 5.6 green blocks, as follows:

- Scenarios and MT users;
- Multi-RRM Algorithms;
- JRRM Algorithms Policies.

The group called “scenarios and MT users” is where the main scenario parameters are defined, as well as MTs mobility and services characterisation:

- Simulator version,  $S_p$ ;
- Number of BS,  $N_{BS}$ ;
- Number of MTs,  $N_{MT}$ ;
- Percentage of fast MTs,  $P_{FMT}$ ;
- Percentage of slow MTs,  $P_{SMT}$ ;
- Minimum speed for fast MTs,  $V_{MTFmin}$ ;
- Maximum speed for fast MTs,  $V_{MTFmax}$ ;
- Minimum speed for slow MTs,  $V_{MTSmin}$ ;
- Maximum speed for slow MTs,  $V_{MTSmax}$ ;
- Service mix (voice, video-telephony, streaming, www, e-mail and FTP) and the corresponding individual source model parameters (here omitted due to their high number, described in Annex-C).

The Multi-RRM Algorithms section defines the parameters required to characterise BSs

propagation conditions, as well as some RRM initial parameters, like the service priority list:

- BS type,  $RAT_r$ ;
- BS location in x,  $X_{BS}$ ;
- BS location in y,  $Y_{BS}$ ;
- BS height,  $h_{BS}$ ;
- BS total power,  $P_{BS}$ ;
- Number of channels used for signalling,  $C_s$ ;
- BS total available channels,  $M_{CH}$ ;
- BS antenna gain (omni),  $G_{BS}$ ;
- BS orthogonal factor (CDMA environments),  $\alpha$ ;
- Receiver noise density,  $R_{N0}$ ;
- Thermal noise density,  $N_0$ ;
- Building loss (penetration additional factor),  $L_B$ ;
- BS receiver noise figure,  $F_{BS}$ ;
- User body loss,  $L_{UB}$ ;
- BS cable loss,  $L_C$ ;
- BS/AP frequency,  $f$ ;
- BS pilot Tx power,  $P_{BSp}$ ;
- MT maximum Tx power for a  $RAT_r$ ,  $P_{TX\ max}^{MT}$ ;
- Sector 1, 2, 3 orientation,  $S_O$ ;
- Antenna diagram for each sector (vertical and horizontal),  $G(\phi, \varphi)$ ;
- Building height,  $h_B$ ;
- MT height,  $h_{MT}$ ;
- Street width,  $w$ ;
- Urban type,  $U_r$ ;
- Street orientation,  $\Psi$ ;
- Building separation distance,  $d_B$ ;
- Services priority table (services priorities mapped into RATs),  $S_{Rp}$ .

For more details concerning propagation issues, consult Annex-B.

The JRRM Algorithms Policies parameters are closely related to the CF input parameters, where weights and the maximum values for each KPI are defined.

Table 4.2 presents the KPIs for the operator's and user's perspectives. In order to normalise the contribution of the different parameters to the CF output, each KPI has a weighting factor and a maximum value. For example, the delay KPI case for the LBN RAT is introduced by the CF using as input parameters the delay weight for LBN and the maximum delay for LBN. Therefore, the QoS delay (obtained by the simulator) is normalised by the maximum delay applied in the LBN case, both parameters must be defined as input for the JRRM CF. For all KPIs presented in Table 4.2, the previous example is applied, and the list can be adapted for each RAT according to Table 4.3.

### 5.3.2 JRRM Outputs

The JRRM simulator output block produces two files per each RAT type, and one file related to JRRM overall performance. The ones related to RRM have statistical information concerning QoS and general RAT system information. For the JRRM output, the simulator produces one single file. These QoS parameters (where all RATs are included) are very useful to represent and evaluate JRRM conditions and benefits. A set of these JRRM parameters is presented as follows (the equation with their definition is provided as well):

- JRRM blocking,  $P_{bJRRM}$  (4.48);
- JRRM average delay,  $\overline{\tau_{JRRM}}$  (4.49);
- Number of active users (active users in all RATs),  $N_{AU}$  (4.51);
- JRRM Average number of BS/APs reachable by MTs,  $\overline{N_{BSMT}}$  (4.52);
- JRRM Average bitrate,  $\overline{R_{bJRRM}}$  (4.53);
- Load Balancing Factor,  $L_{BF}$  (4.54);
- Number of VHOs,  $N_{VHOsim}$  (4.57);
- Number of VHOs triggered by the FF algorithm,  $N_{FFVH}$  (4.58);
- Number of active users per service  $s$ ,  $N_{MTact,s}$  (4.60);

## 5.4 Assessment

To assess a simulator that uses a huge number of functions (many of them stochastic), one can

follow different strategies. For example, simulation results might be assessed, by comparing with other already tested and validated tools. In the case this technique is not possible to use, then, simulator's isolated and combined functions should be validated/compared with known or expected results for each individual functions [Hugh03]. For this simulation platform, some functions of this JRRM simulator were already assessed in [Serr02], which implements the basic UMTS radio interface functions R99, which means that the traffic source generation and the LBN block/functions were previously assessed.

However, several new services and systems/functionalities were developed in this version of the simulator tool, such as MBNs, HBNs radio interfaces and their RRM functions (e.g., new propagation models for HBNs). Additionally, the JRRM entity and corresponding functions were also developed and assessed, e.g., the CF mechanism, JRRM CAC and handovers (horizontal and vertical). Thus, all these new procedures required a complementary validation work. To accomplish this goal, the simulator assessment process was again divided in different parts, corresponding to different simulation functions or abstraction levels, where each individual block was tested by observing the generate input and produced output that should correspond to the expected result for the all range of inputs.

Since this simulator is very dependent on random functions, the very first step was to assess the new random variables generation distributions functions (e.g., the triangular for mobility issues). All fundamental functions were assessed by comparing the simulator generated functions histograms with theoretical curves produced by the Matlab probabilistic library. Besides this fundamental simulation validation, new services traffic source models were also assessed individually, since they represent a key role in this thesis, all these models were validated and described in Annex D. RRM and JRRM mechanisms and fundamental algorithms were also validated by observing the output coherence with a given input, stability and parameters convergence. Furthermore, the proposed theoretical model in also a way for some cases to confirm simulation results, since they converge to output parameters of the same order of magnitude, and in some cases very similar.

Another process to assess some simulators features was by computing statistics over real time results. For example, by computing voice duration and arrive rate that is being process by networks, one may conclude that they converge to the average values used in traffic source models. Another example is when the number of active sessions both for CS and PS are kept coherent when computed by each service individually or globally. This means that all active MTs are processed. For the power control mechanism, also the up and down procedures can be



visualised in the statistical simulator window where vital parameters are also presented to insure the normal simulation behaviour. Other key parameters are also displayed in real time, like: HHOs, VHOs (normal or triggered by JRRM), RAT's load and channels availability, number of services active in real time, individual delay, power delay/blocking, channels delay/blocking statistics, etc.



# Chapter 6

## Scenarios and Theoretical Results

This chapter aims at presenting the most relevant reference used scenarios, and also results achieved by using the theoretical models developed throughout this thesis. In Section 6.1, a set of used reference scenarios is presented. In Section 6.2, one presents the theoretical simulation strategy by presenting scenarios variations. Section 6.3 discusses and analyses theoretical model limits. Section 6.4 presents a theoretical analysis about the CF. Finally, Section 6.5 presents theoretical results.

## 6.1 Reference Scenarios

A set of reference scenarios were defined to perform simulations and evaluate networks solutions performance. An urban hotspot scenario [Ljun06] was chosen to evaluate JRRM policies, mobility, MIMO, services/users and traffic variations, coverage, services penetration/priorities, and propagation effects. The impact of other wireless systems combined with the reference ones was assessed on a train station scenario to study a particular situation with close cooperation with University of Bologna [SCCC10], [Serr08]. The energy efficiency problem is also addressed, by taking a simple single cell scenario, where power consumption is isolated and studied [Godo11].

### 6.1.1 Urban Hotspot

In this thesis, the Hot Spot in Urban Area (HSUA) reference scenario, defined by the AROMA project [Ljun06] is used as a reference/starting point for the theoretical analysis, and also for simulations input parameters variations. This scenario can be classified by four different groups:

- Users and services characterisation;
- RATs deployment and propagation issues;
- Services priority table;
- JRRM/CF general configuration.

The number of users in the scenario is 450, located in a 0.02 km<sup>2</sup> area. Users and services characterisation, and traffic generation, are defined according to Table 6.1, where the typical service duration and their corresponding bitrate are defined, enabling the volume traffic computation for each service. Additionally, services distribution can be extracted. For the service mix generated traffic, the BHCA for all services is 1.

Table 6.1 – Services load per user type.

Service	Service Penetration [%]	Time [min/user]	Bitrate [kbps]	Volume[kB]	BHCA
Voice	56	1.00	12	-	1
Video telephony	4	0.35	64		1
Video streaming	10	0.85	128		1
WWW	12	-	384	2764.8	1
E-mail	10		384	2217.6	1
FTP	8		384	1843.2	1

Further details about services traffic source models and parameters, can be found in Annex C. For voice, video and streaming the volume per service is computed based on average time

multiplied by services nominal bitrate. For WWW, e-mail and FTP the average time per user is computed based on service volume divided by the service nominal bitrate, according to [Ljun06].

The network RATs deployment and propagation issues related with BS/APs characterisation are defined in Table 6.2.

Table 6.2 – Main parameters for the hotspot within HSUA scenario.

RAT type	LBN	MBN	HBN
Path loss model (Annex B)	COST231 – WI		Double Break Point
BS height [m]	25	15	3
#BS cells in the area	2	3	11
LOS ratio to building	50	50	Indoor only
Pilot Power [W]	0.5	2	0.1 (fixed)
Total Power [W]	20	20	NA

In AROMA scenarios [Ljun06], the user mobility distribution per user type is not defined. However, in [Rodr05] a proposed penetration ratio is presented for fast, slow and static users in urban environment, being 15, 25 and 60% respectively. The speed associated to fast and slow urban users ranges from 0 up to 50 km/h, and from 0 up to 6 km/h respectively. The mobility model is based on random walk, with speed modelled by a triangular distribution, where fast, slow and fixed users are defined.

As described previously, Table 6.3 presents the reference adopted scheme for the services priority table, having an expected impact on the RATs traffic/service distribution. On the one hand the priority table configuration aims to balance services/traffic among different RATs; on the other, this service priority relation has the highest priority level for the most appropriate RAT, keeping/introducing a service-RAT suitability perspective. Additionally, the service cost profile, which can be free, flat or Time/Volume depended (TVd) is also presented.

Table 6.3 – Services RATs priority and cost mapping.

Mode	Services	LBN	MBN	HBN	Cost Level	Cost Level [Free, Flat, TVd]
RT	Voice	1	2	3	High	TVd
	Video-Telephony	1	2	3		TVd
NRT	www	3	1	2	Low	Free
	e-mail	2	1	3		
	FTP	3	2	1	Medium	Flat
	Streaming	3	2	1		

For an operator, each RAT has intrinsic costs, which in most cases conflicts with users' interests. The BSs/APs costs assumed in this simulation were the following ones: LBNs and MBNs, 20 k€ and 10 k€, respectively, and for HBNs APs, 0.5 k€ is assumed (defined in Table 6.4). This is very

useful to compare the financial weight cost of each RAT type.

The CF normalisation process, applied to parameters defined in Table 4.2, is also relevant since the maximum value defined for each KPI impacts on the BS and/or user cost Table 6.4.

Table 6.4 – Maximum values for the CF KPIs normalisation procedure.

RAT Type/CF Parameters	LBN	MBN	HBN
Blocking [%], $B_b$	10	5	5
Delay [ms], $D_b$	500	500	500
Load (Power) [%], $L_b$	0.7	0.7	-
Bitrate [Mbps], $R_b$	2	10	54
#Occupied Channels, $O_{c,b}$	512	512	-
BS Cost [k€], $C_b$	20	10	0.5

The CF weights, used as reference in the HSUA scenario are as follows: Blocking, Delay and Bitrate. These weights were set with the same value (10). Also each RAT type, operator and users CF weights were set using the same value (e.g., 1). The mentioned CF model was implemented and tested using the developed JRRM Simulator, different JRRM/CF being evaluated using some KPIs, in order to isolate the impact of some KPIs on JRRM performance.

### 6.1.2 Train Station

The train station scenario is one more reference scenario that can be used to study JRRM mechanisms, being described in detail in ICT-NEWCOM++ project [Serr08] and also in [SCCC10]. This scenario is challenging, since it enables studies on a “hot spot” area, where users start by being static, and then are allowed to move crossing different cellular RAT layers/coverage areas, thus, this scenario is capable to trigger several JRRM mechanisms.

The train station scenario is characterised by the following parameters:

- Train Station size platform: 200×20 m;
- Users’ distribution: randomly uniform distributed in the train platform;
- Users mobility: static;
- The number of users waiting in the station platform depends on the sub-scenario variation for Low Traffic (LT), Medium Traffic (MeT) and High Traffic (HT) one has about 200, 300 and 400 users respectively;

In Table 6.5, the number and BSs types located in the train station is defined. LBN and MBN BSs are located at the station platform centre. However, HBN APs are distributed on a line along the station platform, Figure 6.1.

Table 6.5 – Number of BSs in the train station scenario.

RATs	#BSs	Radius [m]
LBN	1	400
MBN	1	300
HBN	5	50

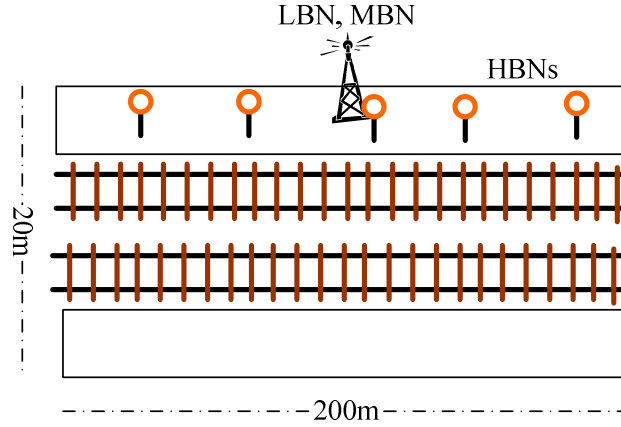


Figure 6.1 – Train Station APs' (HBNs) distribution with random users attached.

For the service set in the train station, Table 6.6, presents the main differences to the reference scenario. Services distribution percentage is according to the reference scenario.

Table 6.6 – Train Station set of services and basic characteristics.

Service	Time [s]	Volume [kB]
Speech	60	-
Video	60	
Streaming	90	
FTP	-	500
E-mail		300
WWW		180

### 6.1.3 Energy Efficiency Framework

In order to assess the impact on EE performance produced by the previous algorithms, micro-cell BS power and traffic models are used to design a reference scenario proposed in [ImKa11] and used in this thesis. The BS equipment power model consumptions correspond to a typical commercially available BS in 2010, used in this work as reference for simulations and for system level energy gains. Table 6.7 presents values for the BS, enabling an approximation to Figure 4.6,

being used to compute the system level power levels.

Table 6.7 – Model Parameters for Micro-Cells.

BS type	$P_{\max}$ [W]	$P_0$ [W]	$\Delta_p$
Micro	6.3	106	6.35

Different services are also under test, because different RATs present different radio bearers, since they handle services in a different manner (e.g., voice in CS or data in PS networks). The reference number assumed for the users' density is 1 000 user/km<sup>2</sup>, which corresponds to a Low (L) traffic case; in order to assess the traffic load impact on EE, users density is increased by 25 and 50%, corresponding to Medium (M) and High (H) traffic load cases, respectively. In the reference scenario, one assumes two BSs, LBN and MBN, with a 500 m radius, LBN being considered the legacy RAT in which EE may be enhanced. The considered service set is defined according to Table 6.8, where reference parameters are provided for each service, BHCA, session Time or volume are defined. These services correspond to two different classes, voice being of the Conversational type, while web browsing and file transfer of the Interactive one. The average number of active users is valid for the Low traffic situation and for both BSs.

Table 6.8 – Services and Traffic (reference).

Services	Average number of active users	BHCA	Time [s]	$V_D$ [MB]
Voice	15	0.31	90	-
WWW	6	0.5	-	0.1
FTP	6	0.1	-	10

## 6.2 Scenarios Variation Strategy

### 6.2.1 Users Density and Mobility

In order to better understand the impact of scenarios and algorithms on JRRM performance, two main different approaches may be taken. In one, strategic changes can be defined on interesting scenario characteristics, keeping all the other parameters constant, namely the JRRM algorithm/policy, and then evaluate the JRRM sensitivity to scenario changes. The other is to experience a coherent set of JRRM algorithms/policies over a “static” scenario. This enables the comparison of different JRRM strategies over a given scenario, and the evaluation and identification of the relation cause/effect, thus, between simulations a unique parameter



modification is done.

One of the relevant/interesting parameters that can be changed in a scenario is user's density, leading to a better understanding over the JRRM outcome when dealing with higher, medium and low user's densities. The proposed changes are expressed in Table 6.9, where HUD, MUD and LUD stand for High-, Medium-, Low- Users Density; the MUD case is defined in [Ljun06].

Table 6.9 – Hot spot user's density variation on the scenario.

Users Density level	Value [MT's/0.02 km <sup>2</sup> ]	Reference variation [%]
HUD	600	+33
MUD	450	0
LUD	300	-33

User's mobility profiles can have some impact on the JRRM performance taking the dynamic influence on the power control, load and handovers process into account. These profiles are defined in three different classes:

- Fast: Maximum of 120 km/h (this is the maximum value for suburban areas, in urban is 50 km/h);
- Slow: Maximum of 6 km/h, Mean of 3 km/h, and Minimum of 0 km/h;
- Static: for static users.

In order to test the mobility effect on JRRM performance, and based on the reference scenario, some new mobility patterns were defined and simulated. Table 6.10 presents the adopted variation in user's mobility profiles: High-, Medium- and Low- Mobility. These are based on the reference scenario, defined in [Rodr05].

Table 6.10 – Mobility profiles variation used for simulation.

Mobility level	Fast [%]	Slow [%]	Static [%]
HM	30	30	40
MM	15	25	60
LM	5	30	65

It is expected that user mobility patterns will have impact on the JRRM performance, since mobility suffers influence from power control, load and handovers management processes. Simultaneously, MIMO systems were compared when different mobility profiles are associated. In order to have a realistic approach, the number of antennas was ( $T_x \times R_x$ ) 4×4 and 4×2. A mapping criterion between mobility profiles and MIMO systems was defined as follows:

- Slow users: a pedestrian profile is assumed, carrying small MTs, therefore, having space only for 2 Rx antennas (4×2);

- Fast and Static users: vehicular and indoor users' profiles are assumed, capable of using MTs with enough space (e.g., laptops and in vehicles terminals), to install 4 Rx antennas (4×4).

Table 6.11, presents the assumed mobility profiles and the corresponding MIMO percentage.

Table 6.11 - Mobility profiles variation and MIMO equipments.

Mobility pattern	MIMO 4×4 [%]	MIMO 4×2 [%]
HM	70	30
MM	75	25
LM	70	30

## 6.2.2 Priorities Policies

The services priority table, previously defined, guides the JRRM entity for the initial BS/RAT allocation attempt of a given service. This JRRM prioritisation scheme enables the introduction of service/RAT mapping relation, very useful to the initial BS/AP allocation, which is enabled by the RAT coverage. This simple strategy allows the mapping of heterogeneous services onto heterogeneous RATs, which requires an adequate (JRRM policy based) prioritisation scheme. To evaluate the JRRM sensitivity to this mapping/schemes, different simulations using different priorities and RATs trends were defined.

Table 6.12 presents the reference case, where services and RATs are mapped onto the first, second and third priorities, when the initial connection is performed. For example, the Voice service will initially try to connect to a LBN. However, if this RAT is not available the MT will try to connect to a MBN, a third option being HBN.

Table 6.12 – Priority table for services and network type priority trends.

Services & RATs mapping	Reference			LBN Centric			MBN Centric			HBN Centric		
	LBN	MBN	HBN	LBN	MBN	HBN	LBN	MBN	HBN	LBN	MBN	HBN
Voice	1	2	3	1	2	3	1	2	3	1	2	3
Video-Telephony	1	2	3	1	2	3	2	1	3	1	3	2
WWW	3	1	2	2	1	3	3	1	2	3	2	1
e-mail	2	1	3	3	2	1	3	1	2	3	2	1
FTP	3	2	1	3	2	1	3	1	2	3	2	1
Streaming	3	2	1	1	2	3	2	1	3	3	2	1

Regarding services priorities schemes (mapping services priorities onto RATs), besides the reference case, three new strategies are defined, Table 6.12. These new services priorities strategies are defined to test the JRRM performance when services have more priority over a given RAT, centralising services into LBNs, MBNs or HBNs centric strategy.

### 6.2.3 Services Profiles

In order to better understand the impact that services penetration has on the network, one defines a few trends, where CS and PS centric service trends can be compared with the reference one. Session arrival rates for CS and PS services are defined according to Table 6.13. Note that the network session arrival rate is not fully in equilibrium due to individual service penetration rates, which naturally leads to one more or less users using a given service group. Thus, the effective session generated by each switching group is not balanced, leading to a non linear number of users for each service group. Nevertheless, Table 6.13 presents services trends (CS or PS centric) providing the capability to compare the impact on the different JRRM QoS parameters. These values are applied to all services of each switching group.

Table 6.13 – Service Switching group trends.

	Services group (arrival rate) BHCA	
	CS	PS
CS – Centric	1.5	0.5
Ref.	1.0	1.0
PS – Centric	0.5	1.5

Besides the previous switching type evaluation, also the service penetration combination was evaluated, three different services penetration scenarios being defined, Table 6.14.

Table 6.14 – Services penetration combinations used in simulations.

	Service/Penetration [%]	PS_30_CS_70	PS_50_CS_50	PS_70_CS_30
CS	Voice	60	45	25
	Video-Telephony	10	5	5
PS	WWW	10	15	20
	e-mail	10	12	20
	FTP	5	10	15
	Streaming	5	13	15

These new scenarios, combine CS and PS services, as two main blocks, ranging from 30 to 70%

penetration. Note that all these scenarios have as penetration combination of 100%, thus, it is assumed that users are using only one service at a given moment.

Environment has a natural influence on propagation conditions. In mobile networks, users can be located outdoor or indoors, this location having impact on radio link conditions, namely on the additional attenuation due to building penetration loss. Since the link budget model implemented in the JRRM simulator includes the average building loss, the impact of this parameter on JRRM performance can be evaluated by defining different buildings attenuation factors scenarios, additional scenarios being defined, Table 6.15. Note that in all these scenarios, the CF was used with the BD policy (blocking and delay KPIs).

Table 6.15 – Indoor penetration scenarios.

Scenario definition	Scenario name	Building loss [dB]
Low building penetration factor	BD_BL_L	5
Medium building penetration factor	BD_BL_M	15
High building penetration factor	BD_BL_H	20

## 6.2.4 RATs Coverage

Concerning the RAT cluster radius variation and their impact on VHOs, one can use a relative size as reference point, and then increase or decrease the overall cluster radius on each RAT. Besides the reference one, two other different coverages were defined: HCov, MCov and LCov scenarios, standing for High, Medium and Low coverage, respectively. The HCov corresponds to the cluster radius size duplication, and LCov for half size compared to the reference one.

In order to access the impact that a cellular structure trend has on the VHO probability, three scenarios were defined, the Macro-, Ref. and Micro-centric, Table 6.16, with a different number of BSs for each RAT/cluster in each scenario.

Table 6.16 – Scenario Set for Cellular Coverage Trend.

RAT	Number of BSs		
	Micro - Centric	Ref.	Macro – Centric
LBNs	1	2	4
MBNs	8	3	2
HBNS	14	7	4

The impact that services penetration has on the JRRM overall parameters was studied via three different profiles for CS and PS services, Table 6.17. Their combination was defined in order to produce a CS/PS ratio (1/2, 1 and 2), which can be used to understand their influence on the JRRM QoS parameters.

Table 6.17 – Service Penetration Ratio Scenarios Set.

		Penetration [%]		
CS/PS		1/2	1	2
Voice [%]	CS	0.30	0.45	0.58
Video-telephony [%]		0.03	0.05	0.09
Streaming [%]	PS	0.20	0.14	0.09
FTP [%]		0.15	0.10	0.06
E-mail [%]		0.17	0.13	0.09
WWW		0.15	0.13	0.09

### 6.2.5 JRRM Policies

In (4.29) and (4.30), the theoretical model includes two JRRM parameters,  $P_{VHO}$  and  $P_{LNB}$  which aim to simulate the traffic distribution, and JRRM and service priority policies influence on the BS selection procedure respectively. Taking the first one into account, it is possible to setup some distributions percentages over the generated traffic and delivered to the correspondent RAT, enabling the QoS evaluation in each RAT. Table 6.18 presents two scenarios variation over the reference one (LBN – Centric and HBN – Centric). These variations are useful to understand the impact of traffic distribution in each RAT QoS. The LBN (one single BS in cluster will be the RAT type that will have more difficulties to observe high levels of traffic compared with other RATs, because it provides low capacity and high coverage. Therefore, LBN related traffic percentage distributed by the JRRM entity should be low, to kept LBN QoS indicators under control.

Table 6.18 – JRRM traffic distribution variation scenarios.

	JRRM traffic distribution [%]		
RAT	LBN - Centric	Ref.	HBN – Centric
LBN	10	7	4
MBN	60	45	35
HBN	30	48	61

The second parameter  $P_{VHO,r}$  proposed by the model, is the one related with VHO transfer among RATs. Similar to previous cases, in Table 6.19 one presents some traffic transfer

variations among LBN, MBN and HBN. Again, these traffic scenario variations take the same name as in the previous case. Basically the idea is to transfer traffic from one RAT to another; these transfer percentages have a physical limit, which is related to geographical superposition among RATs clusters. The VHO transfer rule, if negative, means that traffic flow will be the opposite with respect to the one symbolised by the arrow.

Table 6.19 – JRRM VHOs strategies scenarios.

VHO Rule	JRRM VHOs [%]		
	LBN - Centric	Ref.	HBN – Centric
LBN→MBN	-10	0	10
MBN→HBN	-5	0	5

In order to evaluate the CF flexibility and its impact over JRRM performance, eight different policies were evaluated:

1. The CF is not used (NoCF policy), which means that all weights are set to 0; this should reflect a non JRRM/RRM supervised HHO and VHO.
2. Delay Only (DO policy) KPI is considered by operators and users; this policy should decrease the overall delay at JRRM level, providing some privilege to PS based services (www, streaming, e-mail and FTP).
3. Blocking Only (BO policy) KPI is considered by operators and users; this policy should decrease the overall blocking at JRRM level, providing some privilege to CS based services (voice and video-telephony).
4. Both Delay and Blocking (DB policy) KPIs are considered (delay and blocking) using the same weights at the CF; this policy should result in a more balanced network.
5. Bitrate Only (BrO policy) KPI is considered, marking BSs with higher bitrate with less cost.
6. Bitrate and Delay (BrD policy) KPIs are considered, using the same weights at the CF, resulting in a more balanced network, without being based on Blocking.
7. Bitrate and Services (BrS policy) KPIs are considered, using the same weights at the CF, it takes, besides the bitrate, also the type of service and BS cost, for users being free, flat and time/volume dependent, and for operators considering the BS infrastructure cost.
8. All (ALL policy) previous KPIs are considered (Blocking, Delay, Bitrate and Service cost) using the same weights at the CF, leading to a broader network sensitivity to different KPIs.

In Table 6.20, the different JRRM policies and their corresponding configurations (KPIs weights) are presented. All other KPIs are set to 0, thus, not having influence on the CF outcome.

Table 6.20 – Simulated JRRM/CF policies.

JRRM/CF Policies	CF Weights/Perspectives							
	Operators				Users			
	Blocking	Delay	Service	Bitrate	Blocking	Delay	Service	Bitrate
NoCF	0	0	0	0	0	0	0	0
BO	10	0	0	0	10	0	0	0
DO	0	10	0	0	0	10	0	0
DB	10	10	0	0	10	10	0	0
BrO	0	0	0	10	0	0	0	10
BrD	0	10	0	10	0	10	0	10
BrS	0	0	10	10	0	0	10	10
All	10	10	10	10	10	10	10	10

### 6.3 Theoretical Model Limits

In order to explore the theoretical limits of the proposed theoretical JRRM/RRM model (Section 4.3), some extreme inputs were computed. An example of this approach is assuming all users and correspondent services attached to one single RAT, another being limiting mobility profiles, like all users being fast or static, or even assuming all active users with the same service. Based on these assumptions, Table 6.21 shows the obtained results.

Table 6.21 – Theoretical Model Limits Results.

Limit Inputs/Outputs	$N_{AU}$	$\overline{R}_{bt}$ [Mbps]	$N_{VHO_r}$	$N_{HHO_r}$	$T\rho_{N,r}/T_{CN,r}$			$\tau_{jd}$ [ms]	$P_B$ [%]
					LBN	MBN	HBN		
RATs									
Only LBN	55.6	5.6	0	513	1.300	-	-	1720.0	38
Only MBN				339	-	0.060		1.0	0
Only HBN				743		-	0.005	< 0.1	
Mobility									
100% fast	55.6	5.6	5420	10619	0.065	0.027	0.003	<0.1	0
100% static			0	0					
Services									
All Voice	55.6	0.7	893	1750	0.008	0.003	0.000	-	< 0.01
All Video		26.7	893	1750	0.311	0.130	0.012	-	< 0.01
All Streaming		21.4	895	1754	0.250	0.104	0.010	1.2	-
All FTP		13.4	896	1755	0.156	0.065	0.006	0.5	-

By observing Table 6.21 and analysing the output parameters, one can conclude the following:

- $N_{AU}$  - the number of active users (4.21) in all cases is the same (forced) in order to have a fair

comparison among the different results.

- $\overline{R_{bt}}$  – the JRRM bitrate (4.24) is constant when all users are forced to be attached to a single RAT, and when mobility profile changes radically. This is because users services bitrate are defined by they nominal bitrate and not RAT achievable bitrate, and in the model mobility does not have any impact on users bitrate. Nevertheless, when all users are using different services naturally that JRRM bitrate will change according to services requirements, achieving minimum and maximum values for all voice and video users respectively.
- $N_{VHO_r}$  - the number of VHOs (4.42), depends on the existence of more than one RAT, mobility and users average session time, therefore, when users are attached to only one RAT and when they are all static VHOs simple does not happen. However, when mobility reaches the maximum, the number of VHOs reaches the maximum (few thousands), and for the service variation the number of VHOs suffers minor changes, since it depends on the average session time (RATs borders crossing rate), which does not change substantially.
- $N_{HHO_r}$  - the number of HHOs (4.38) depends on RATs cells size, mobility and services. Different from VHOs, HHOs happens always, except on the static case. HHOs are clearly more frequent for the fast mobility profile (more than ten thousand). When only HBN is present in the scenario, HHOs events reach the maximum compared with LBN and MBN, since the number of cells in the HBN cluster is higher and the cell radius is shorter. Similar to VHO, at service level, the number of HHOs does not varies significantly, however, they naturally happen in a higher number.
- $T_{\rho_{N,r}}/T_{CN,r}$  - (4.28) and (4.32) for each RAT  $r$  (LBN, MBN and HBN), the model predicts different load levels, based on the offered traffic and network capacity ratio. Load is only expected in the RAT to which traffic is allocated, and here in the remaining ones. Note that for LBN, the theoretical load level goes above 1, which means that the generated traffic is 30% above the total capacity, leading to the highest and unpractical delay and blocking values at JRRM. For the mobility cases, load levels do not change, since mobility (as explained previously) does not have impact on cell load levels, nevertheless, HBNs case far less load, since they have much more capacity compared with LBNs and MBNs. Concerning services variations, voice is the one that produces less load video being the one that causes the highest load levels, because voice and video have the lowest and the highest nominal bitrate, respectively.
- $\tau_{jd}$  - JRRM delay (4.34), presents good results for almost all cases (under 2 ms) except when only LBN is considered (almost 2 s). Note that this is quite scenario dependent (users/services generated traffic and network deployment capacity). Nevertheless, one may



conclude that delay decreases significantly when MBNs or HBNs are present in the scenario. Note that when voice or video are individually the only services present, the JRRM delay does not apply, although the model generates delay in both cases, since it is based on load level. Also due to this load dependence, JRRM delay in the model does not change when mobility profiles change from static to fast.

- $P_B$  - JRRM blocking (4.33), is based on the load level, thus one can observe this dependence. For the LBN only case, JRRM blocking reaches 38 %, which is the very worst case situation (also unpractical/unrealistic), for this scenario. Additionally, for streaming and FTP services, blocking does not apply (these services are delayed not blocked), although the model generates blocking for loads above 0. Note that in the remaining input cases, when MBN and HBNs are present blocking drops almost to 0. This confirms the JRRM delay results, thus, the network presents good QoS levels when services and RATs have a minimum balance.

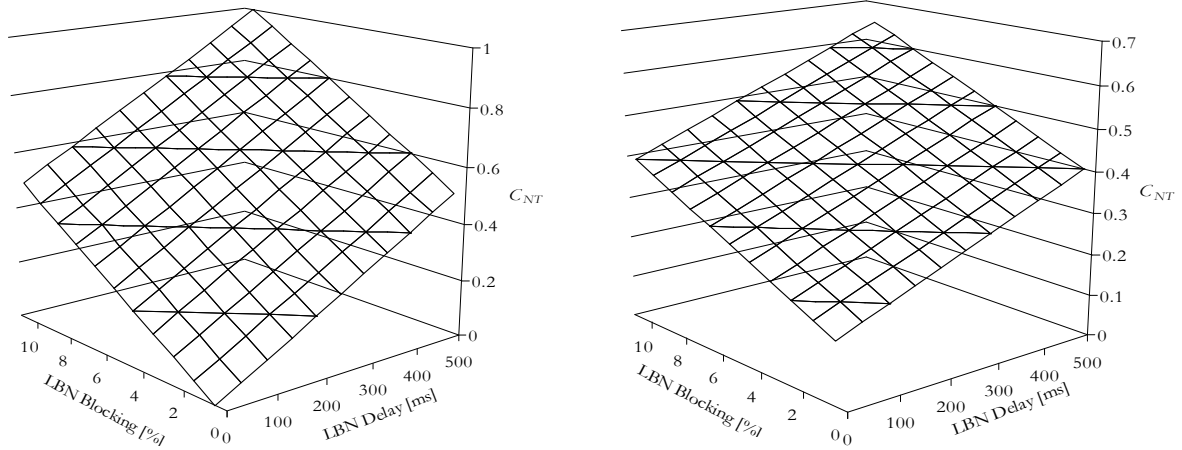
## 6.4 CF Theoretical Analysis

In order to present some possible results produced by the previous model, one has to decide which are the most relevant and interesting ones, as output and input parameters. Since the focus of this thesis is JRRM performance, then, the overall JRRM QoS and VHOs related parameters in the model should be the most explored ones. Therefore, as outputs one has: JRRM Bitrate  $J_{br}$  average user bit  $R_{b,p}$  blocking  $P_B$ , delay  $\tau_{cd}$ , users capacity density  $\rho_{AU}$  and RATs VHO related probabilities. For scenario inputs variation one considers the following parameters: users speed profile penetration, services centric (PS or CS), relatively RATs clusters coverage size, the number of BSs, service penetration ratio (CS/PS), initial JRRM traffic distribution and VHO traffic percentage flow among RATs. The IST-AROMA project reference scenario [Ljun06], is used as starting point for some parameters, namely services traffic generation.

In this section, the CF model is analysed from the theoretical view point. This analysis is useful to better understand the model behaviour and expected results, when given input network conditions are assumed. Since the CF model has a huge number of input parameters capable of generating a very large number of combinations, a simple and reasonable approach is required. Therefore, LBNs, MBNs and HBNs incremental impact on the total network cost,  $C_{NT}$ , (4.4), was computed using some inputs constant, as depicted in Figure 6.2.

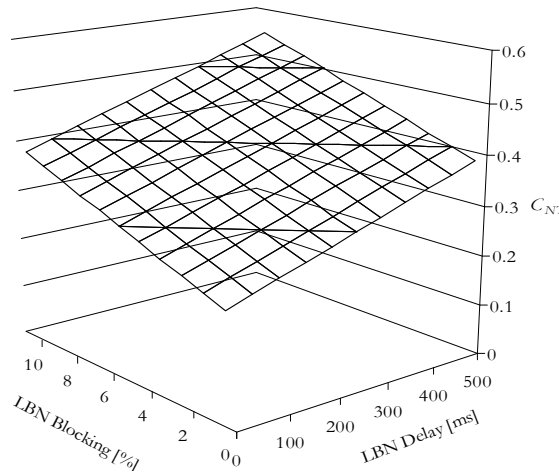
The theoretical results presented by Figure 6.2 (a) assume only the existence of LBNs, where a

3D surface represents  $C_{NT}$  as a function of LBN blocking and delay (LBNs KPIs, RRM parameters at RRM level).  $C_{NT}$  ranges from 0 up to 1, since LBN blocking and delay are normalised up to 10 % and 500 ms respectively, therefore, these minimum and maximum limits are obtained when LBN KPIs range from 0 up to their normalisation maximum. It is possible to observe the implemented normalisation mechanism effect and the accurate CF computation result into  $C_{NT}$ .



(a)  $C_{NT}$  computed only based on LBN blocking and delay both at RRM level.

(b)  $C_{NT}$  computed for LBNs and MBNs (with 100 ms delay and 2% blocking for MBNs).



(c)  $C_{NT}$  computed for LBNs, MBNs (as in (b)) and HBNs (with 150 ms delay and 2 % blocking for HBNs).

Figure 6.2 –  $C_{NT}$  theoretical computation results using an increasing number of network types.

Figure 6.2 (b) shows the impact of adding MBNs to the previous case (only LBNs). MBN CF KPIs were set to acceptable constant values (2 % for blocking and 100 ms for delay), thus, the corresponding impact should be also constant. This strategy is useful to easily identify and track the impact on the overall cost. In this case, the MBNs presence in the CF acts as a stabilisation factor. Note that  $C_{NT}$  starts above 0.15 and ends below 0.65. In this case LBNs and MBNs have

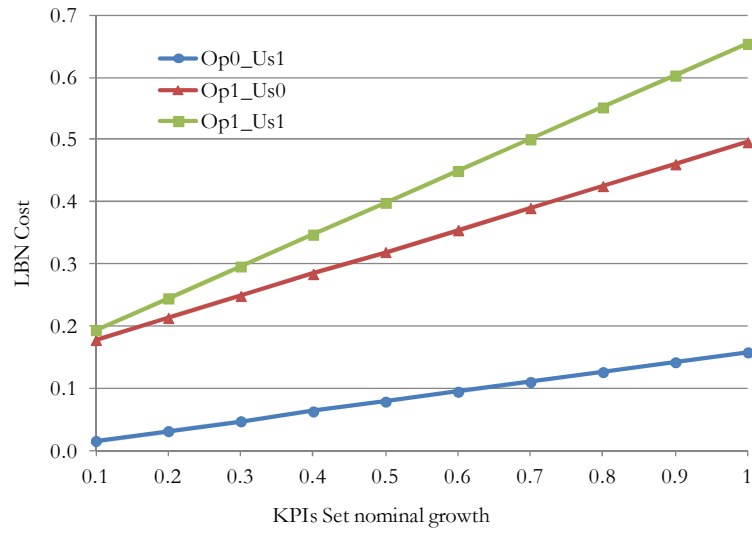
equal weights in the CF; however, if the MBN weight compared with the LBN one is set to be much higher, than  $C_{NT}$  converges to a constant value, yielding the MBN cost.

Figure 6.2 (c) represents the HBNs introduction into the CF, with a similar approach as in the MBN case. HBN KPIs were set as constant (2 % blocking and 150 ms delay), leading the overall  $C_{NT}$  to be more stable, since MBN and HBNs act as a steady anchor in the CF mechanism. Thus, only LBNs KPIs variations are observed in Figure 6.2 (c), where  $C_{NT}$  ranges from 0.23 up to 0.55.

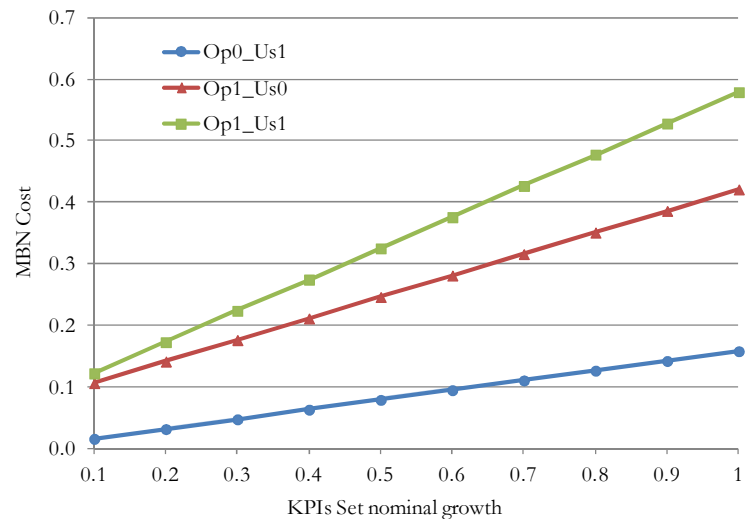
As already mentioned, the CF includes operators' and users' perspectives into the outcome. Thus, Figure 6.3, present the impact of operators and users weights together with network and users KPIs variations on LBN, MBN and HBN individual cost defined in (4.5), respectively. These different perspectives are based on (4.6) with different weights, for example: Op0\_Us1, stands for Operators and Users cost weights equal to 0 and 1 respectively; for the remaining cases the same logic applies. Note that operators' and users' KPIs weights are varying in a linear way for these three examples.

One may conclude that, in Figure 6.3 (c), all operators weighted curves present less cost, compared with LBN and MBNs, due to the fact that HBNs have a KPI sub-set, and are characterised by a relative low financial cost, therefore contributing to this lower cost. In Figure 6.3, only the Op0\_Us1 curve for the LBN, MBN and HBNs presents the same behaviour, because users' contribution to the CF overall cost, are RAT independent. Other curves are naturally different, given the nature of each particular RAT and its intrinsically KPIs, which produces different results (e.g., maximum normalisation allowed values).

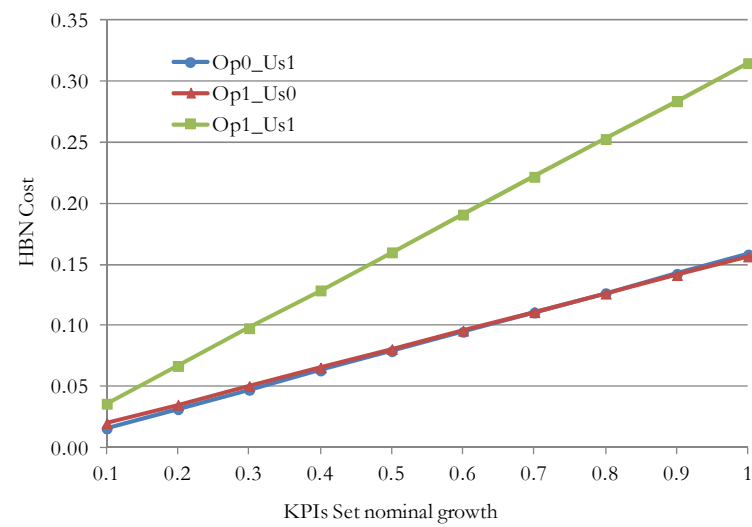
As conclusion of this analysis, several features are visible: the linear behaviour of the CF model, the normalised results in final and intermediate model costs, the weighting and contribution of different KPIs in the overall cost. Thus, one may conclude that the CF model corresponds to the initial RRM and JRRM requirements, which means it captures the multi-dimension problem of combining different BSs, RATs, and users using a set of KPIs. Note that, for all situations, the desirable/optimal cost assumed by the model is 0, the worst case corresponding to 1, this being applicable to all cases and levels in the CF model.



(a) LBN impact.



(b) MBN impact.



(c) HBN impact.

Figure 6.3 – RATs cost policies impact by setting all KPIs into a linear growth.

## 6.5 Theoretical Model Results

Based on the previous scenarios set, the model is capable of producing a considerable number of different results, a selection of the most relevant ones being presented in the next sub-sections.

### 6.5.1 Users' Mobility and Service Profiles Impact

For the High Mobility (HM) profile, the VHO probability (computed by (4.44)) reaches 66% for HBNs and 39% for MBNs, Figure 6.4. This means that users in a HM profile and the ones attached to HBNs will most probably experience a VHO to other RAT. For MBN, this probability is relatively less, since the MBNs coverage is higher and users will spend more time crossing an MBN cluster.

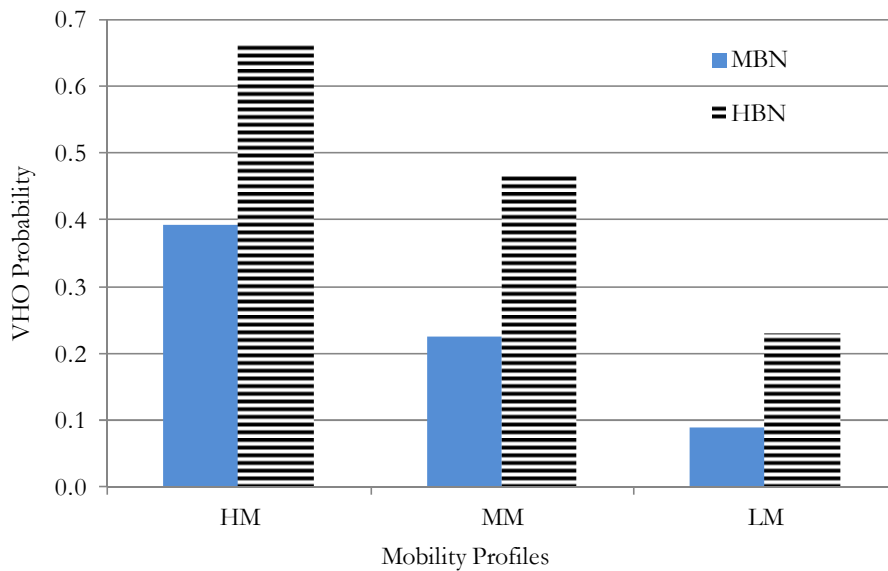


Figure 6.4 – Mobility profiles impact on VHOs probability for MBN and HBNs.

These results are very useful for JRRM designers, since it estimates the VHOs overhead knowing the scenario mobility profile. For example, a train station or business city centre will have different mobility profiles, with different impacts on JRRM signalling overhead to process VHOs. The crossing rate results follow the VHO probability, being useful to estimate the VHO load.

The users' capacity density (computed by (4.25)), which is the network equivalent number of active users per  $\text{km}^2$ , represents the heterogeneous network capacity for processing users' sessions for a given network QoS level. Figure 6.5 presents the results for the different switching

group ratio (CS/PS). One can see that, for PS-Centric, the number of users is less compared with the CS-centric case, due to the fact that usually CS-Centric based services (voice and video telephony) have effective longer sessions. Thus, the number of active users in the network will be higher, compared with the PS-Centric case.

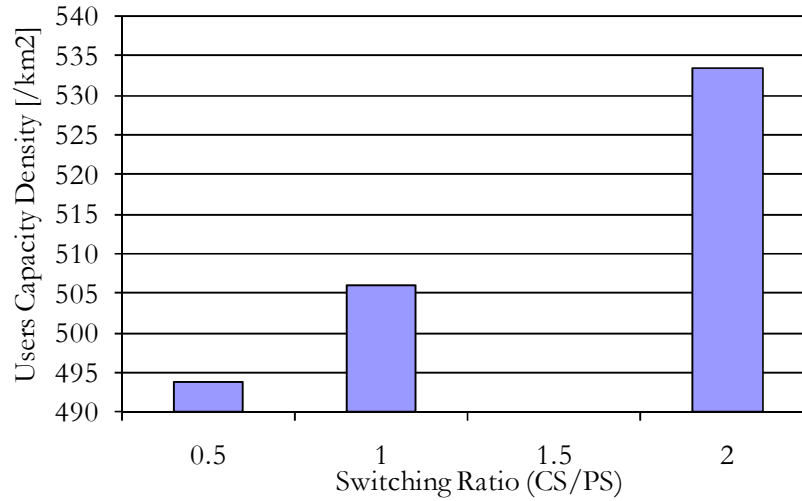


Figure 6.5 – Users capacity density as function switching type ratio.

Figure 6.6 presents the JRRM delay (computed by (4.34)) for the different switching trends. For the PS-Centric case, the JRRM overall delay increases (from 25 to 40 ms), due to intrinsically greedy PS based services over available radio resources. When moving towards a CS-Centric situation, the JRRM delay is lower compared with the Ref. case, as a consequence of the lower channels occupancy made by the voice service (assume to be in CS mode).

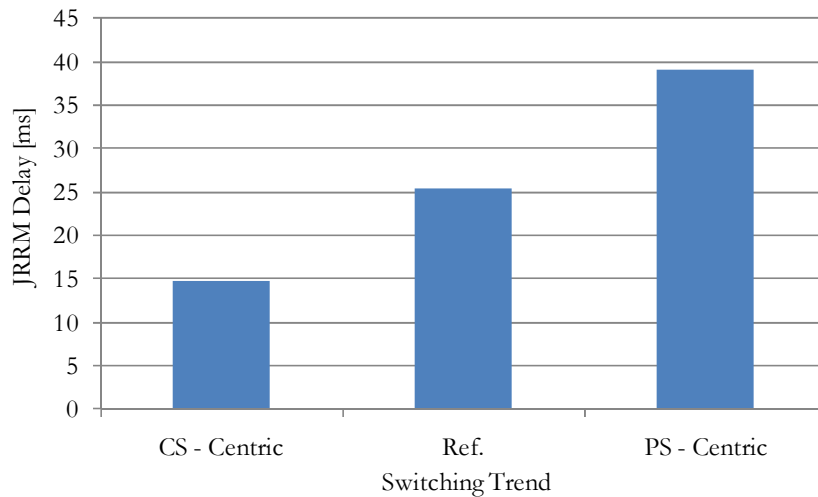


Figure 6.6 – JRRM Delay based on switching type trend.

### 6.5.2 RATs Coverage Impact

Concerning RATs cluster radius impact on VHOs, it is expected that HBNs are more susceptible

to having more VHOs, Figure 6.7. In the HCov scenario, the VHO probability is lower, because clusters sizes are larger, therefore, users' cluster cross events are less frequent, since they stay a longer time inside a given cluster (RAT type) borders.

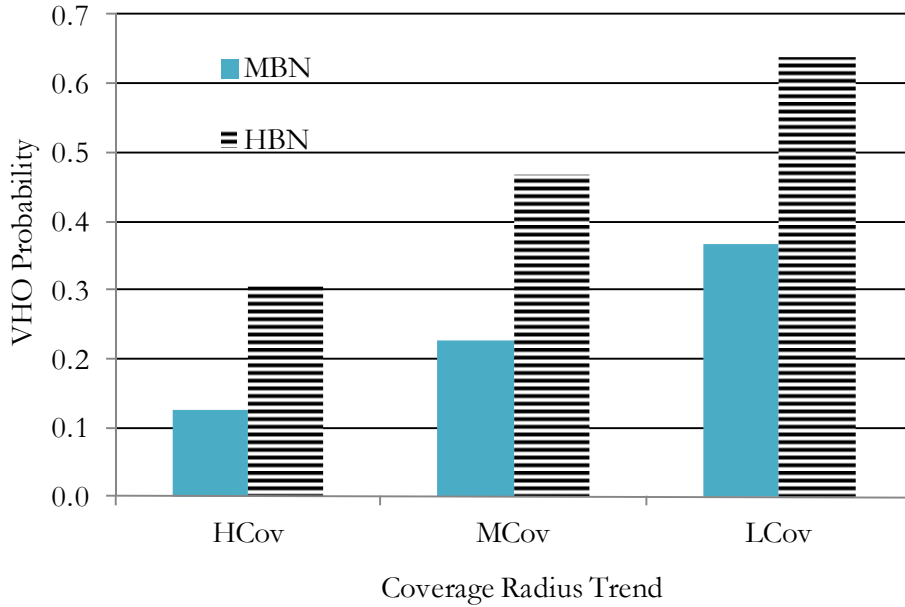


Figure 6.7 – VHO Probability as a function of coverage size.

Note that in the case of LBNs, they have adjacent and continues coverage, therefore, it does not make sense presenting VHOs probability, but rather HHO probability.

In Figure 6.8, MBNs and HBNs have an increasing VHO probability when coverage moves to the Macro-centric case, since they decrease their relative area in the cluster, having less users staying inside their coverage. Thus, MBNs and HBNs will have more crossing users to other RATs. The Macro-Centric scenario is dominated by LBN coverage.

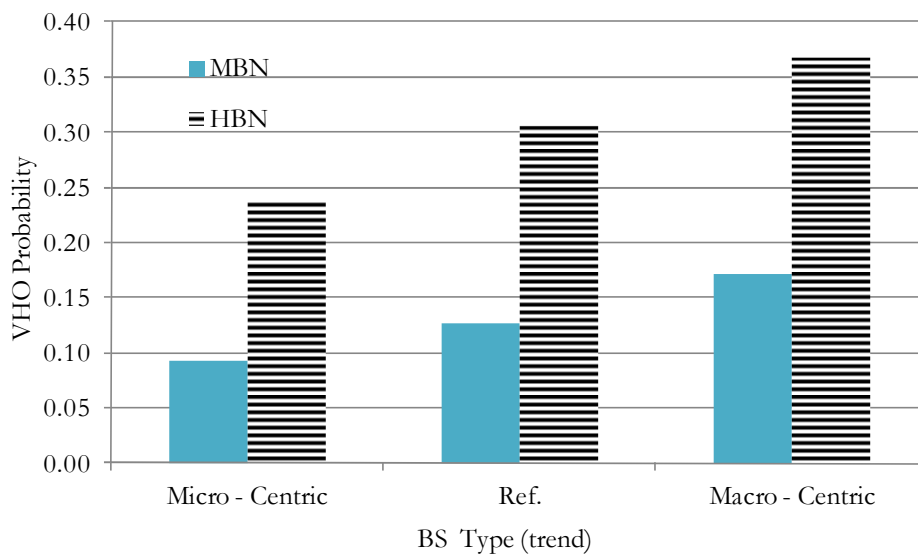


Figure 6.8 – VHO Probability as a function RATs clusters sizes.

Since LBNs have continuous coverage, according to the scenario and assumptions, one can also compute the LBN HHO probability (by (4.38)), Figure 6.9, decreases when going to Macro-centric scenarios, since LBNs increase their absolute area, users having more time inside their coverage. Thus, LBN HHOs decrease and the VHOs of MBN and HBNs increase, when moving to a Macro-Centric scenario.

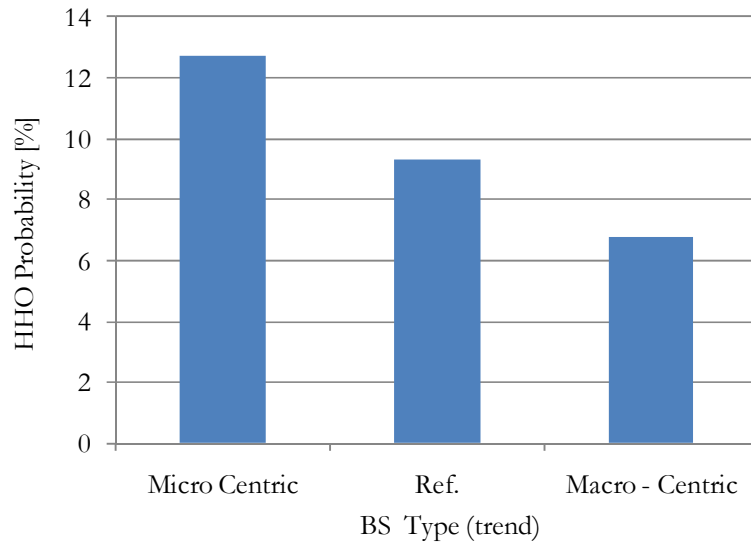


Figure 6.9 – LBN HHO Probability as a function RAT's clusters trends.

According to Figure 6.10, the JRRM delay results for 2 the CS/PS ratio produces much less JRRM delay compared with the  $\frac{1}{2}$  one. Note that delay starts on 30 ms and goes up to 200 ms (which in most cases is an unacceptable value), thus, one concludes that PS based services dominance in the network produce very high delays, leading to a very poor network quality. This is observed because PS services take/use more radio resources from available RATs (e.g., radio channels or bandwidth).

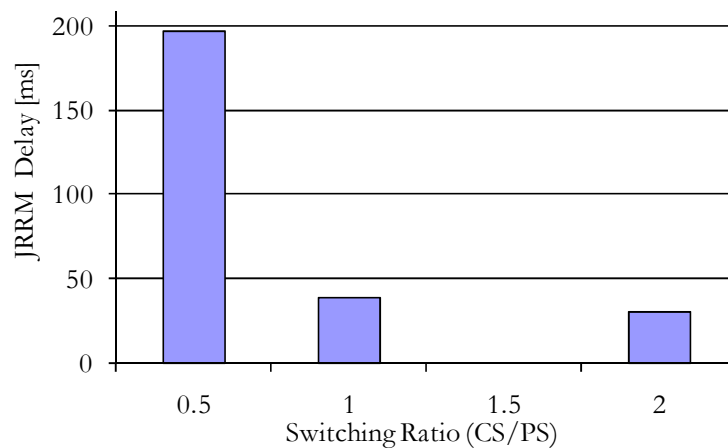


Figure 6.10 – Services penetration ratio impact on JRRM Delay.



### 6.5.3 JRRM Policies Parameters Impact

This sub-section presents the JRRM theoretical parameters variation results, by observing two dimensions simultaneously, one being the initial traffic and the other the VHO policy percentage distribution variation/trend. These variations are performed according to Table 6.18 and Table 6.19, expecting to have significant and different impacts on RATs QoS indicators.

In Figure 6.11 (a), it is possible to observe the LBN blocking variation. The worst case, from the LBN view perspective, is when initial traffic distribution and VHO policy push traffic to LBNs (LBN-Centric) in both axes, leading to an LBN blocking of about 13%. It is also possible to observe that the initial traffic distribution has more influence than the VHO variation policy, because the VHO percentage has less freedom on amplitude range. The best case is when the initial distribution tends to HBN-Centric, in which LBN initial traffic percentage will move from 10 to 4% of the total generated traffic. This may seem a small variation, however, with 4% LBN will handle less than 50% of the load of previous case (LBN-Centric), yielding the LBN blocking to be less than 1%.

Similar to LBN, Figure 6.11 (b) presents blocking for the MBN case. Observing the scenario setting, one can observe that MBN traffic distribution percentage is higher compared with LBNs. However, MBNs presents better  $P_b$ , since MBNs channel capacity is higher, which in this case is assumed to have 2.4 more channels, thus having better blocking for all cases. Also note that VHO percentage distribution axis does not have much impact on this indicator, by the fact that VHO policy variation uses MBN networks as a traffic source and destination, to/from LBNs and HBNs, thus, a reasonable stability is observed.

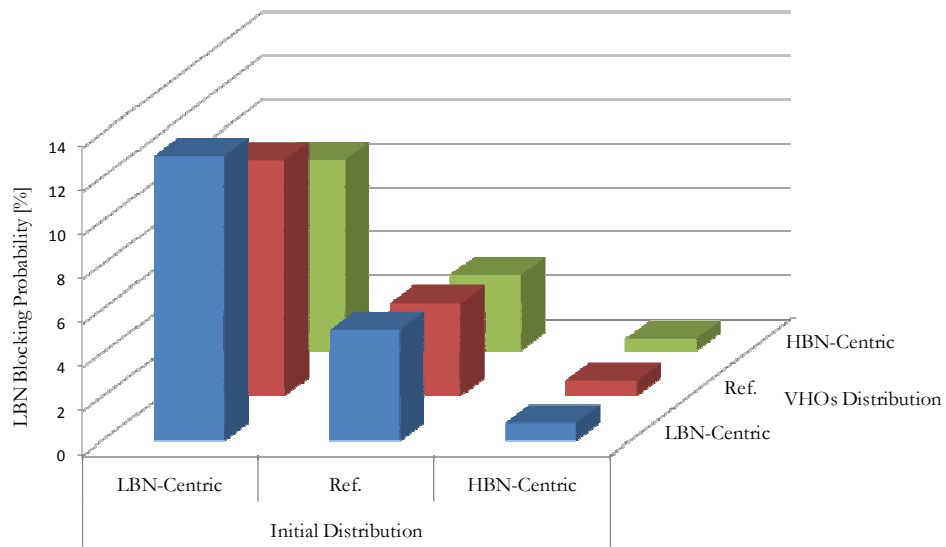
From the HBN viewpoint, blocking is negligible, being almost 0.

Another QoS indicator is delay, Figure 6.12 (a) presenting results for LBNs. Delay presents a parallel trend similar to blocking; however, note that delay is only “acceptable” for HBN-Centric case, which means that the offered traffic to LBN should be less, in order to reach the delay values that are under services constrains.

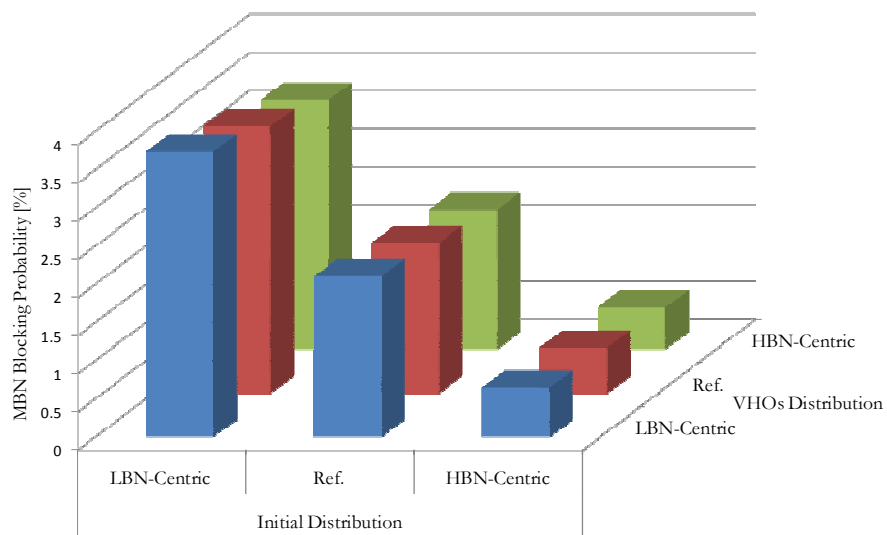
From the MBN viewpoint, Figure 6.12 (b), delay reaches acceptable values (<32 ms) only when the references distribution case is applied. Again, VHO traffic transfers are almost transparent to MBN, since there is, already mentioned, a compensation effect. Also note that even moving in the initial traffic distribution axis, from the Ref. to HBN-Centric, MBNs do not drop delay dramatically, since LBNs will also have some traffic release (not fully transferred to HBNs).

Considering delay from the HBN viewpoint, once again one, may neglect it, since it is under

1 ms.

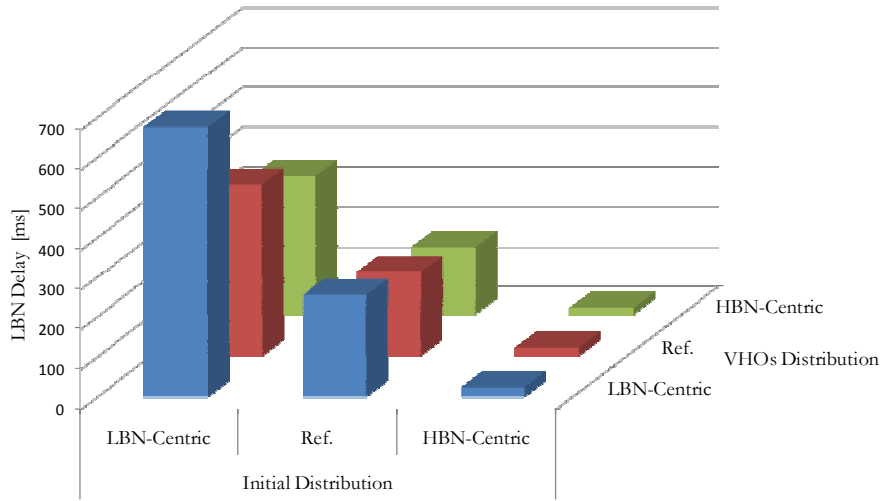


(a) JRRM policies impact on LBN Blocking.

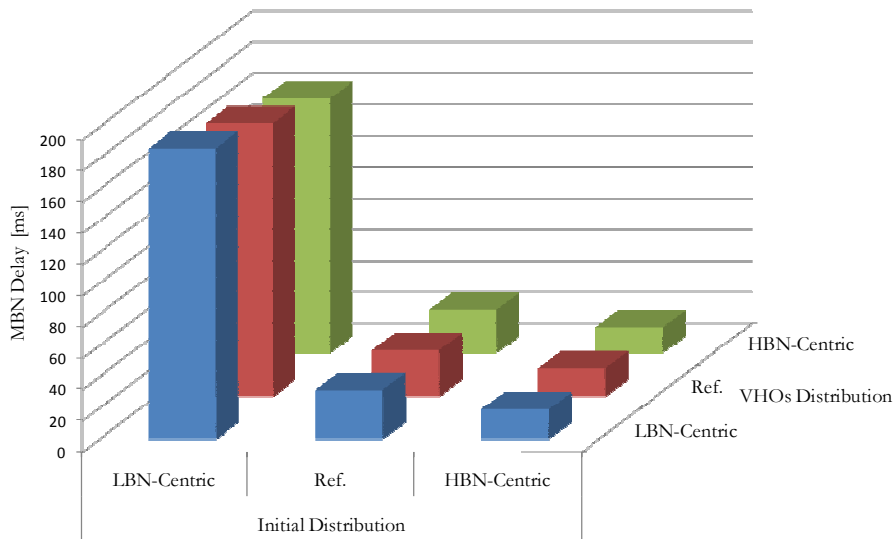


(b) Impact on MBN blocking.

Figure 6.11 – JRRM policies impact on blocking.



(a) Impact on LBN delay.



(b) Impact on MBN Delay.

Figure 6.12 – JRRM policies impact on delay

As conclusion of this theoretical analysis, one can point out the following remarks: theoretical model limits are under the expectations and output parameters, JRRM QoS follows the natural trends when input traffic or networks capacity parameters change, the geographical and users' mobility dependability is highlighted by the HHOs and VHOs results; also, the relation between load and key performance parameters, such delay and blocking, is notorious.

One concludes that HBNs have much more influence than other RATs since they can process much more traffic in their covered area, and therefore, decreasing the load in other RATs. Additionally, it is expected more JRRM signalling, due to VHOs over HBNs clusters borders, being strongly dependent on users' mobility profiles. The model is also capable to tackle the CS/PS traffic ratio, because it is sensitive to services heterogeneity. Results also show the impact

of RATs cell sizes and coverage trend dominance in JRRM expected signalling.

Finally, the JRRM tuning components defined in the theoretical model are also observed in the model results. These effects are shown by the initial traffic distribution and by the VHOs associated policy when rerouting traffic among RATs. Between these two parameters, the initial traffic distribution is the one that has more impact, the major one being when JRRM policies push towards HBNs-centric cases. These policies substantially increase JRRM performance quality indicators to much better levels (e.g., LBNs delay can drop from 600 to about 10 ms).

# Chapter 7

## Analysis of Simulation Results

This chapter aims to present and analyse relevant simulation results, produced according to the proposed scenarios. In Section 7.1, a brief comparison with the theoretical model and simulation results is made. In Section 7.2, the JRRM policies impact over QoS is discussed, Section 7.3 assesses the MIMO and mobility influence in JRRM QoS parameters. Section 7.4 discusses the services impact by looking into priorities and services penetration issues. Finally, Section 7.5 presents some special case studies, such as propagation impact on networks performance, results about a train station scenario, and concerns about energy power efficiency gains at RF and BSs/RATs levels as a driver for RRM.

## 7.1 Simulation and Theoretical Results Comparison

This section is dedicated to compare the developed theoretical model results with the simulated ones (using operators and users combined in the CF). To perform this comparison, one should first identify the common and relevant output parameters for both simulation and theoretical model. In a second step, comparable scenarios should be identified by using similar input parameters. Based on previous conditions, a set of input scenarios and output parameters were identified, Table 7.1.

Table 7.1 – Theoretical and simulation results comparison for different sub-scenarios.

Scenarios/ Output parameters			Mobility			Users Density		Services Penetration		
			LM	MM	HM	HUD	LUD	PS_30 CS_70	PS_50 CS_50	PS_70 CS_30
$\overline{R_{bf}}$ , JRRM bitrate [Mbps]	S	Av.	12.0	11.4	12.3	57.0	8.2	49	46	42
		SD	6.0	6.8	7.5	7.6	5.0	6	8	8
	T		28			37	18	30	33	39
$P_B$ , JRRM blocking [%]	S	Av.	0.5	1	1.3	13	0	9	1	0.4
		SD	0.03	0.7	0.5	2.2	0	5	0.1	0.06
	T		0.2			2.4	0.3	0.5	1.2	1.8
$\tau_{jcb}$ JRRM delay [ms]	S	Av.	8	7	24	201	0.2	189	1.6	0.1
		SD	3	5	14	47	0.1	15	0.8	0.05
	T		1.1 < <20			2 < <36	0.4 < <9	1.3 < <23	1.6 < <28	2.3 < <40
$N_{AU}$ , number of active MTs	S	Av.	54	55	53	61	38.7	52	46	45
		SD	7.5	6.7	7.5	6.8	5.7	7	9	9
	T		56			74	37	59	66	78
$T\rho_{N,LBN}$ $T_{CN,LBN}$ LBN load	S	Av.	0.114	0.116	0.183	0.23	0.103	0.185	0.111	0.045
		SD	0.040	0.090	0.017	0.02	0.014	0.019	0.010	0.003
	T		0.26			0.35	0.170	0.276	0.309	0.365
$T\rho_{N, HBN}$ $T_{CN, HBN}$ MBN load	S	Av.	0.024	0.021	0.022	0.042	0.019	0.019	0.027	0.039
		SD	0.009	0.012	0.013	0.014	0.001	0.010	0.010	0.030
	T		0.062			0.083	0.04	0.066	0.074	0.088

All remaining simulated results were obtained for a 1 hour observation of the network, after achieving a convergence status, i.e., the first initial 10 minutes of simulation are discarded, which is required to skip the natural initial ripple of time base simulations.

Before observing and analysing results, one must keep in mind that the theoretical model does

not consider issues that are simulated, such as: radio links propagation, coverage radius, power or link control, interference, BSs channels and load management, CF guidance policies, services bitrate adaptation to RATs propagation and load conditions, blocking and delay decisions made by RATs' CAC algorithms, users' mobility models, random traffic generation nature, users space distribution, and other minor details implemented by the simulator tool. Therefore, differences between results are expected, this comparison being a way to evaluate how different or how close these two approaches are. To simplify the comparison process in Table 7.1, results produced by the theoretical model (T) are confronted with the ones produced by simulation (S). For the simulation results besides the average (Av.), also the corresponding Standard Deviation (SD) is provided, to better evaluate differences between them.

One should stress that load from the theoretical model viewpoint is the ratio between users generated traffic over RATs capacity, therefore, it only provides RATs expected occupancy ratio, being different from the real power load computed by the simulator. Thus, when comparing load, the trend is really the interesting point, not the absolute values.

By observing Table 7.1, one can start by analysing the mobility scenario and conclude that the theoretical model for some output parameters is similar or is of the same order of magnitude compared with simulations, namely for JRRM delay (4.49), the number of active MTs (4.51), and RATs load. For JRRM bitrate (4.24) and JRRM blocking (4.53) one observes some differences, although not very significant. In this scenario, and for these output parameters, mobility variations in the model do not have impact, because only handovers statistics are considered, keeping other parameters constant. Observing all simulation results, some degradation in QoS is registered, when mobility levels rise, which is due to higher power control disturbances caused by MTs higher mobility profile. The JRRM bitrate level is roughly kept, although standard deviation rises.

For the users' density variation scenario, the idea is to evaluate the trends of different loads caused by a different number of users in the simulation area. Thus, in the LUD case, as expected, both frameworks provide the lowest values in all output parameters. In the other extreme, for high user concentration, one defines the HUD sub-scenario, where almost all output parameters reach their peaks as expected. One concludes that both simulation and theoretical model follow similar trends, however, for this high traffic case, the output values under study present a considerable gap between them. This occurs because the theoretical model was based on acceptable QoS levels, which means that the model produces more accurate results under "normal" network traffic conditions; thus, in this extreme case, simulation results are more reliable. Observing the simulation SD values, one may also conclude that for high traffic

scenarios, QoS parameters variation is less stable, which is coherent in all output parameter and acceptable, since high traffic situations drives more difficulties to RRM algorithms, therefore, more instability. Finally, the services penetration variations sub-scenario highlights fundamental differences between simulation and theoretical model. Observing these results, where PS and CS services penetration rates have different densities, it is clear that both frameworks produce opposite trends in all output parameters, except for the MBN load, because CS and PS have different impacts on QoS. For example, the simulator has a priority list that selects PS services to the most suitable RAT, and PS services ON/OFF activity effect is computed and simulated at radio level, having impact on bitrate adaptation according to RF conditions. In the theoretical model, all these previous effects are not considered, thus only nominal bitrates are considered, and PS and CS services intrinsic different natures are not distinguished, all services being processed as one huge stream of bits that should be handled by BSs/RATs.

## 7.2 JRRM Policies

### 7.2.1 CF KPIs Based Policies

To evaluate the JRRM-CF based policies over output parameters, such as JRRM blocking, delay, Bitrate and the number of active MTs, the results presented in the next figures compare JRRM output parameters, when different JRRM policies are applied using the CF, described in Section 4.1.2. One should note that the offered random generated traffic (service mix) is the same on average for all simulations, the reference scenario being used (urban hotspot).

Figure 7.1 presents the JRRM average delay results (4.49) for the different JRRM-CF policies, based on Cumulative Distribution Function (CDF) curves, generated by PS services. JRRM delay may happen due to different reasons: no radio resources available when service session initiates (lack of channels or load rise); interference when a packet is being transmitted or; bandwidth or channel unavailability (HBN case).

By observing Figure 7.1, one can conclude that when the simulation is performed neglecting the CF (NoCF case), the JRRM delay presents the worst situation (ranging from about 0.6 up to 1s delay), since there is no guidance to select the most suitable BS/AP, when HO is performed (HHO and/or VHO). However, when the CF is based on blocking and delay KPIs, the result is



quite better, ranging from 0 up to 60ms (BD case), followed by the policies that considers blocking, delay, bitrate and delay, in the CF (ALL, DO, BO, BrD); note that in these cases the conflict of interests is highlighted, since blocking and delay based services have inherent impact on each other in the network. The remaining cases (BrO and BrS ranges from 0.1 up to 0.9s) suffer a higher JRRM delay, since they are focused on other KPIs, which do not have direct impact on JRRM delay or blocking.

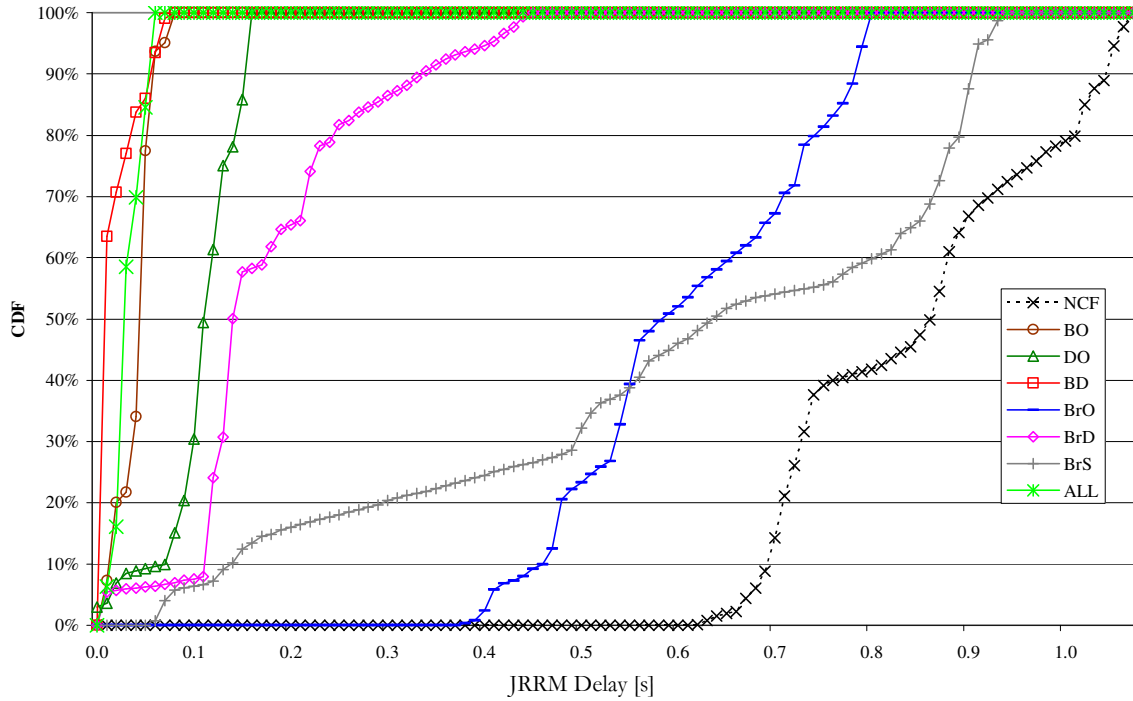


Figure 7.1 – Policies variation impact on JRRM average delay.

In a similar way to the previous case, Figure 7.2 presents the JRRM blocking (4.48), generate by voice and video-telephony services. Blocking happens when the CAC process, running on each RAT detects that the selected BS (based on the service priority list) does not have channels available for a particular service, or when the load is above a configurable threshold, 70 % used for all cases. In the case of the HBN, it is assumed that blocking exists for CS based services, since congestion control is assumed. In this case, a minimum of 1 Mbps is guaranteed to users, and if only less than this is available, users are blocked or delayed. Therefore, here the best effort strategy is not assumed in the HBN group. Note that most policies present blocking values above the usual expected one, because the offered traffic is set to high levels, in order to better highlight potential differences among JRRM policies.

Observing Figure 7.2, the policies that present better results concerning JRRM blocking are the BrO and BD, being related to BS and MT's bitrate, and JRRM blocking and delay. They generate a JRRM blocking under 1 %, for 100 and 40 % of the simulated cases for BrO and BD,

respectively, which is very good, because all remaining policies are above 2% for all simulated cases.

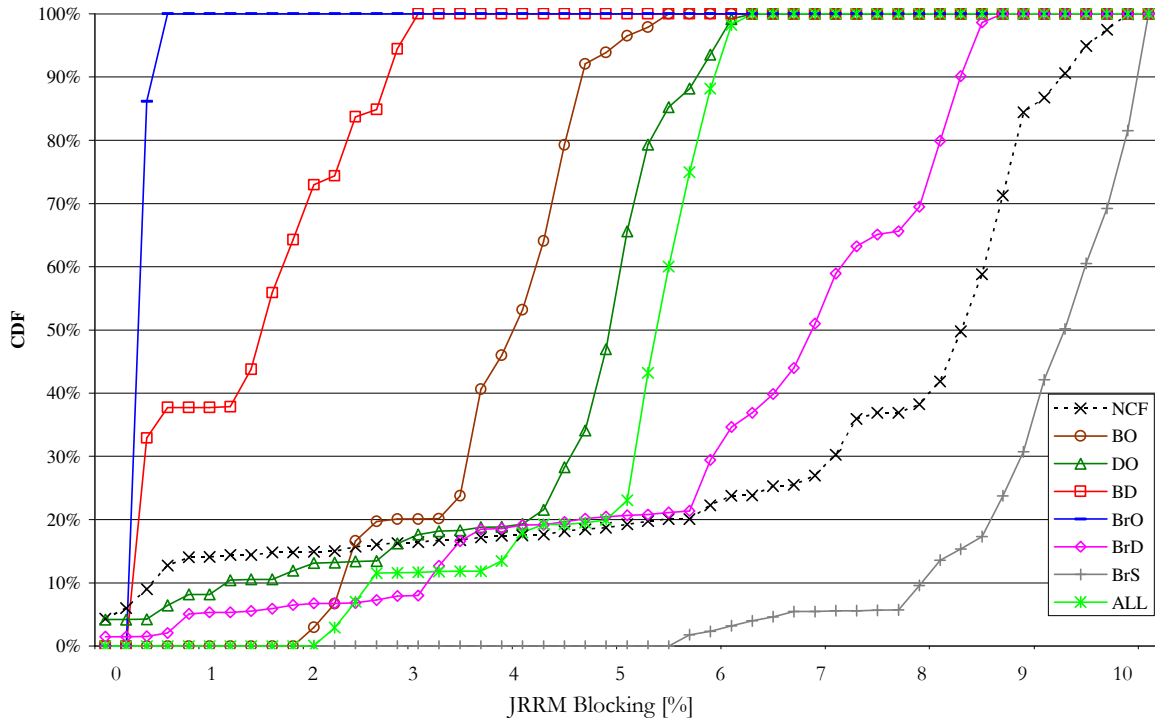


Figure 7.2 – Policies variation impact on JRRM blocking.

The BrO policy pushes MTs connections to HBNs, since they offer higher bitrates, unloading MBN BSs. Note that the BrS policy presents the worst results (even worst than NCF), because it is concerned with the bitrate and the service cost, which are conflicting in some cases. This policy also generates more attached MTs, on average, thus, higher JRRM blocking and delay being natural.

Blocking and delay are caused mainly by BSs' channels unavailability, since the simulated scenario is a urban hotspot, thus, coverage and BSs power/load are not the main problem.

Figure 7.3 shows the CF policies' influence on the number of simultaneous active MTs in the scenario (4.51). Observing the CDF curves, one may conclude that differences among tested policies are not substantially significant, the highest being about 5 users, between BD and NCF policies. Nevertheless, the BD and BO curves are the ones that present less active MTs, being followed by the other policies; the ALL and BrS policies, produce good results. One may conclude that blocking oriented policies are more MT restricted than delay or bitrate oriented ones.

One relevant observation is that the BD policy produces good results on JRRM delay and blocking, however, this may be achieved because it produces slight less MTs, thus, it is possible

that a couple of MTs have relevant impact on JRRM QoS.

Finally, the interval range of active MTs shown in the curves (network active period) reveals that all policies supports more than 40 up to about 70 active MTs.

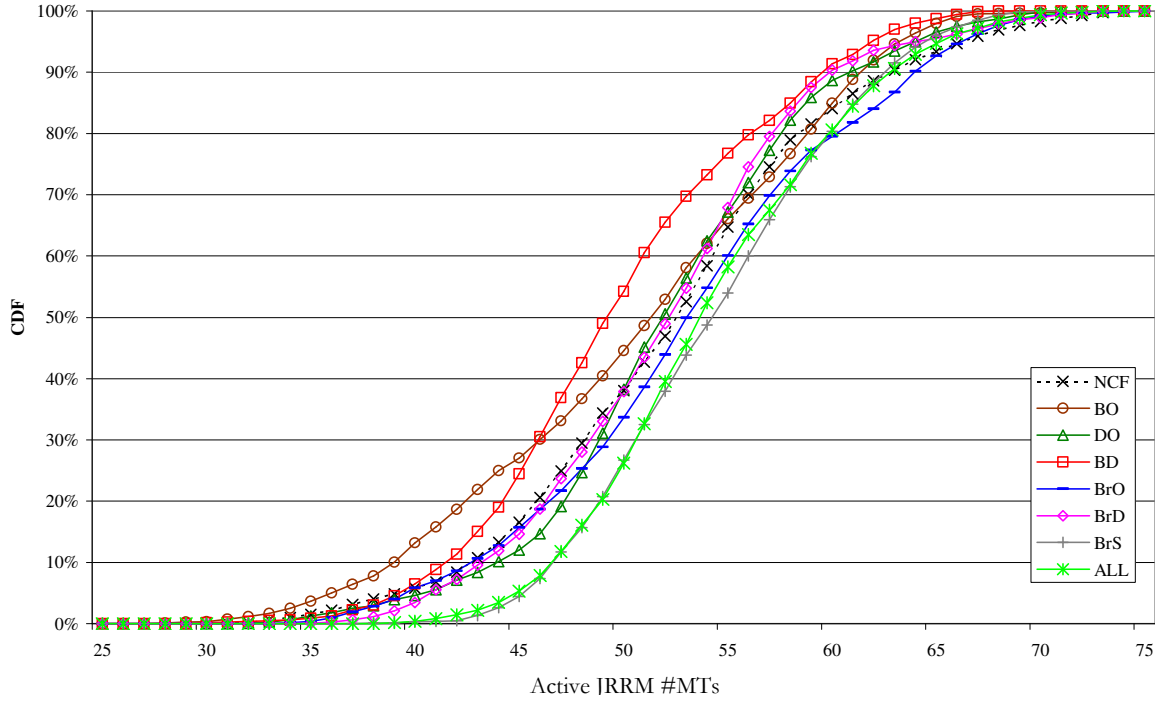


Figure 7.3 – Policies impact on JRRM active MTs.

Figure 7.4 shows some CF policies' influence on the JRRM overall bitrate (4.53). Similar to the number of MTs, the BO and BD policies present less JRRM bitrate, which can be related, since less active MTs can produce lower bitrates (although this is not straightforward, because MTs can have different services with different nominal and minimum bitrates).

The BrS, BrO and NCF policies produce good results by maximising JRRM Bitrate, thus, one may conclude that bitrate based policies and the NCF produce good results for JRRM Bitrate; however, this is achieved by strongly sacrificing JRRM QoS parameters as previously shown. One may also conclude that, on average, users' individual bitrate (including channel coding overhead) is about 0.5 Mbps or less. Naturally that voice users (about 54%) have quite less individual bitrates, thus, data users are, on average, quite above the 0.5 Mbps. The observed range, for this scenario at JRRM Bitrate, is from 1 up to 32 Mbps.

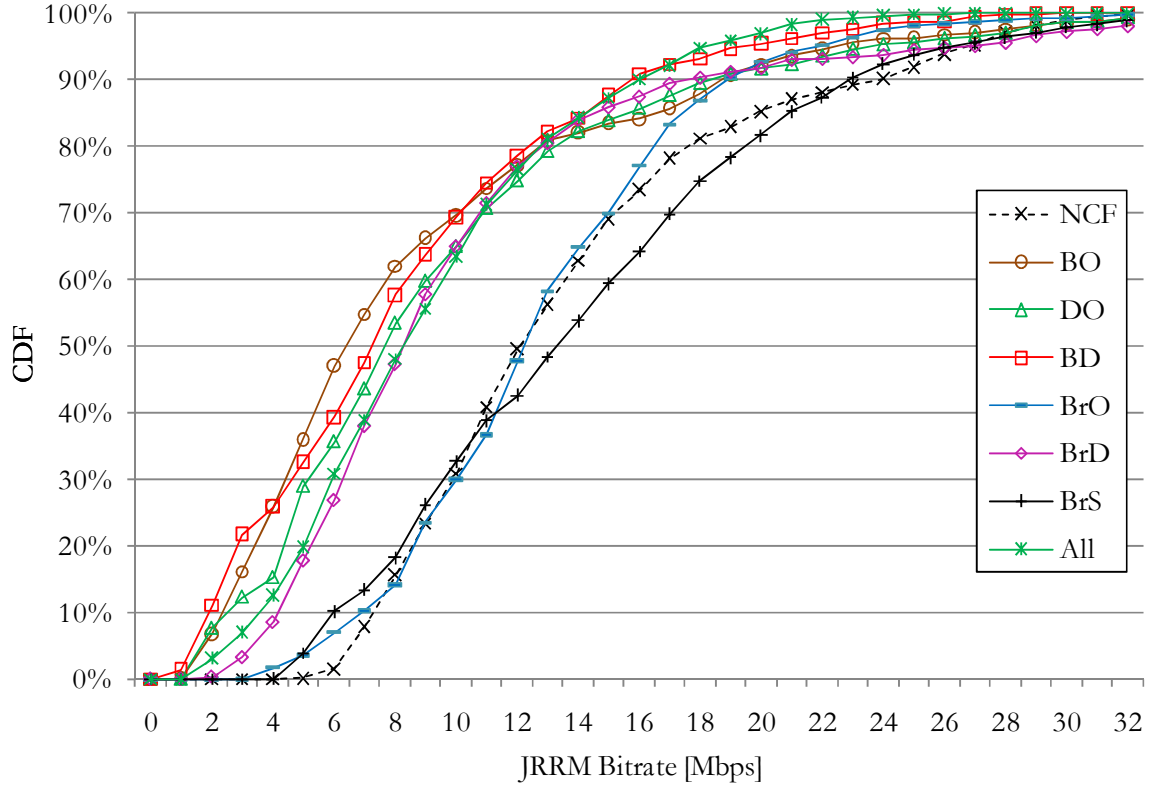


Figure 7.4 – Policies impact on JRRM bitrate.

The previous policies results are also presented in Table 7.2, where statistical indicators, obtained at JRRM level are shown, such as average, standard deviation, maximum and minimum values. This table helps to understand better the previous results, by showing the KPIs variation range and limits.

By observing the SD column, it is possible to evaluate the magnitude range of a given policy and KPI. One concludes that JRRM Bitrate and the number of active MTs have similar values, which means that traffic variation magnitude, translated to active MTs, is followed by the overall JRRM Bitrate. The NCF policy, presents the highest value for blocking and delay, because it is a non guided policy, therefore, it does not converge to a guided trend or resource orientation, thus, generating more fluctuations in the overall network.

From the operators' perspective, one concludes that BD generates good results, since it minimises delay and blocking; however, this can be seen by users as a policy that decreases the overall bitrate, not necessarily the user individual performance.

Note also that when comparing these results with usual and acceptable performance real live networks, one concludes that BD and BO perform better, since they present results in the range of 1 to 4% for blocking and below 50 ms for delay. This is achieved while keeping the number of active MTs closer to other policies results, expect for the overall bitrate result.

Table 7.2 – JRRM KPIs summary results.

JRRM Output KPIs	CF Policy	Average	SD	Max.	Min.
Blocking [%]	NoCF	6.8	2.99	9.8	0
	BO	3.7	0.82	5.2	1.8
	DO	4.3	1.55	6.0	0.0
	BD	1.3	0.93	2.8	0.2
	BrO	0.3	0.06	0.4	0.2
	BrD	6.1	2.13	8.4	0
	BrS	9.0	1.01	10.6	5.4
	ALL	4.9	1.07	6.1	1.9
Delay [s]	NoCF	0.845	0.132	1.065	0.617
	BO	0.041	0.016	0.073	0.008
	DO	0.107	0.037	0.159	0
	BD	0.017	0.020	0.072	0
	BrO	0.609	0.123	0.800	0.377
	BrD	0.180	0.098	0.445	0
	BrS	0.605	0.285	0.936	0.055
	ALL	0.032	0.014	0.053	0.003
Bitrate [Mbps]	NoCF	13.6	6.0	41.7	4.8
	BO	8.7	6.9	47.0	1.0
	DO	9.4	6.6	34.7	1.0
	BD	8.2	5.6	29.4	0.6
	BrO	13.2	6.1	34.4	2.5
	BrD	7.8	6.2	35.0	2.0
	BrS	14.6	6.0	36.5	3.9
	ALL	9.1	6.5	27	1.5
#MTs Active	NoCF	52.8	7.9	74	31
	BO	51.1	8.5	73	28
	DO	52.6	6.8	73	32
	BD	50.3	6.9	68	30
	BrO	53.7	7.9	76	34
	BrD	52.5	6.8	75	34
	BrS	54.9	6.0	71	38
	ALL	54.8	6.3	74	39

After analysing the previous set of results, one concludes that among the considered JRRM policies, BD seems to be the policy that presents a better compromise one network performance offered to PS and CS services, because it combines both BSs main characteristics at the CF: blocking to CS services and delay to PS ones. Other policies, such as BrS, perform better for the overall bitrate; however, they are worse for other JRRM QoS. Thus, one concludes that, based on the selected CF KPIs, operators can expect different results and trends. Combining all KPIs in the CF, defined as the ALL policy, JRRM results show that QoS performance presents intermediate results, since it combines different trends.

## 7.2.2 Users' and Operators' Oriented Policies

This sub section present results related to one of the innovative concepts introduced in this thesis, the users' and operators' JRRM perspectives, described previously. These results explore the comparison between operators and users KPIs, focusing on the ones that can present more opposite interests. In Figure 7.5, as in previous cases, the JRRM evaluation is based on the overall JRRM blocking. In this particular case, the KPI Bitrate only (BrO) was used, since it is a KPI that has clearly opposite interests between users and operators.

From Figure 7.5, one can conclude that when the JRRM CF is guided by the operator's perspective, the JRRM blocking is better compared to users' interests being taken into account. This is somehow expected, since on the one hand, operators try to locate users at lower bitrate steps (decreasing the connection impact on the network), while on the other, users try to have a higher bitrate, leading to a more congested network, in this case, increasing blocking in the network. Note that these simulations were performed under HUD scenario, therefore, generating high traffic demands, which explains the high values for blocking (above 2%), which in real networks are not acceptable values.

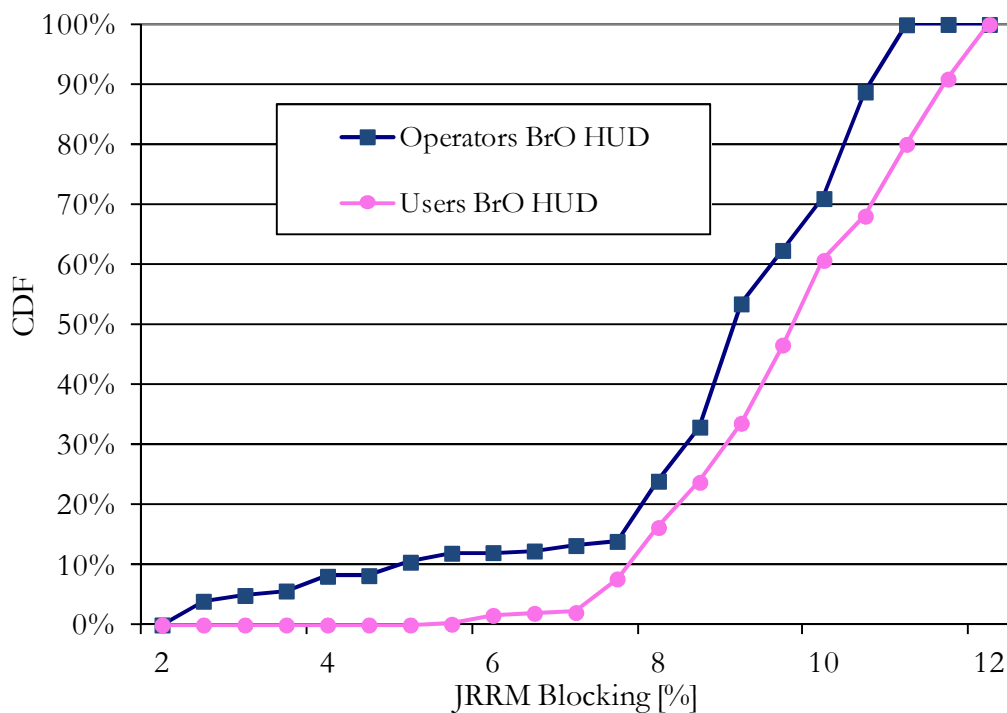


Figure 7.5 - JRRM blocking probability comparing operator's and user's perspectives using only bitrate KPI and HUD.

In Figure 7.6, the JRRM blocking result is presented, applied to the MUD case and setting the CF to be guided by the blocking only KPI (BO). Again, the previous effect is observed, however, in this example users' density is smaller, therefore, blocking is also smaller, converging now to usual

and acceptable values, below 2%. Note when the CF is guided only by operators, blocking stays under 0.1 %, but if it is guided only by users it goes up to 1.4%.

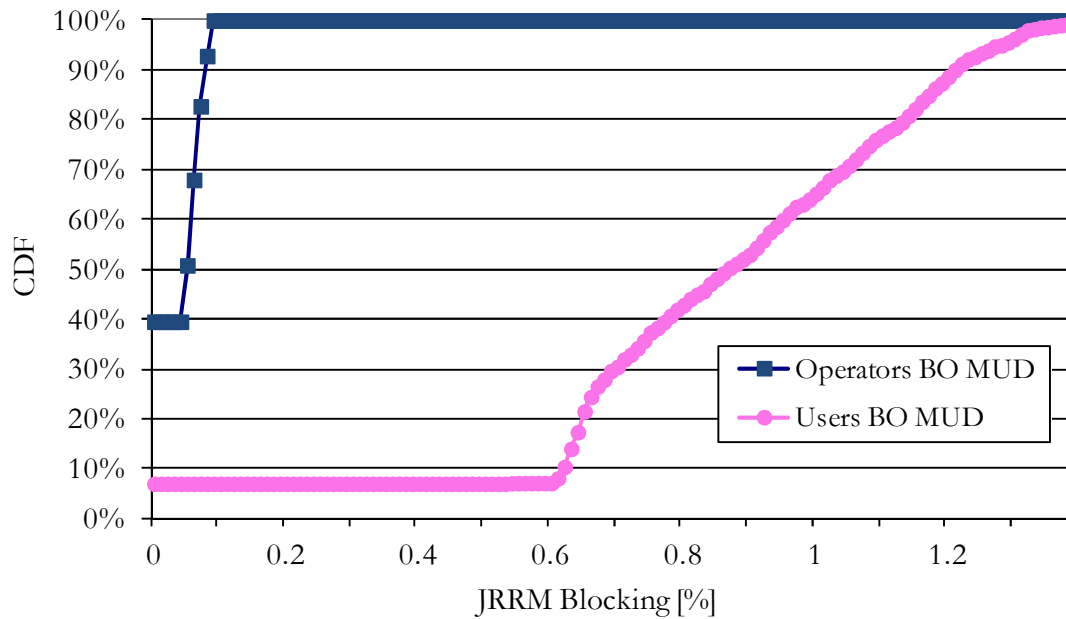


Figure 7.6 - JRRM blocking comparing operators' and users' perspectives using only blocking as KPI and MUD. Figure 7.7 presents another JRRM performance indicator, the overall JRRM delay. Using the CF with the BO configuration policy, the relative difference between users and operators perspectives is substantial: roughly, when users guide the CF, they double delay. Thus, using the CF guided by the operators' perspective produces better results.

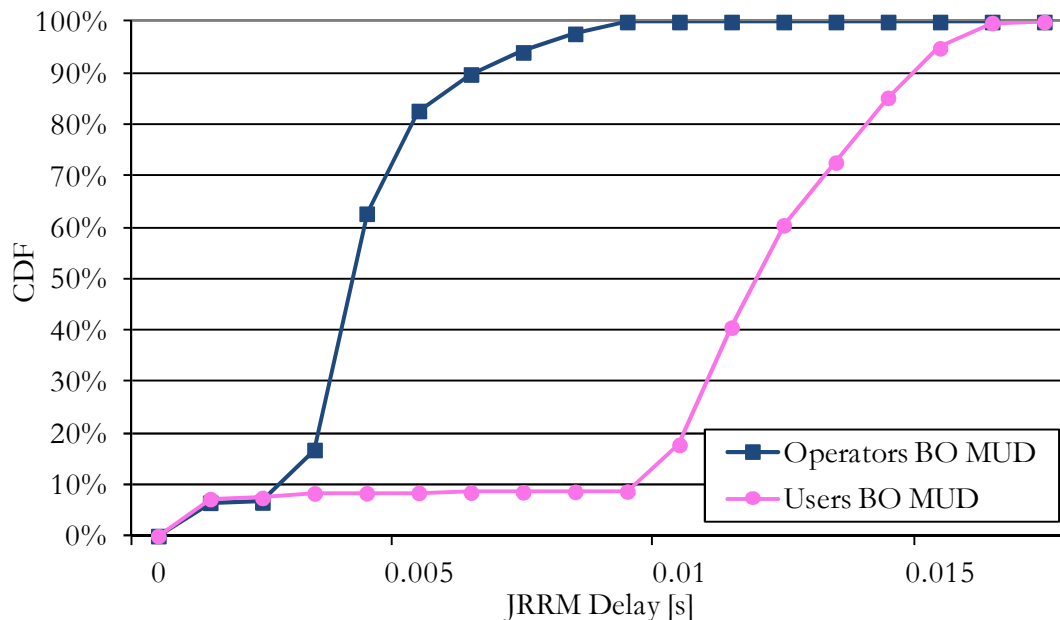


Figure 7.7 - JRRM delay comparing operator's and user's perspectives using only blocking KPI and MUD.

Another interesting parameter to explore in the CF set is the financial network cost. For example,

BSs and/or APs installation costs for a user are not perceived, however, for an operator this is definitely a key issue. Like the previous examples, Figure 7.8 and Figure 7.9 present the JRRM blocking and delay, obtained when the CF guides the JRRM entity only based on the cost for each perspective. In Figure 7.8, the operators result is better (0% blocking) compared to the users results (maximum for JRRM blocking 0.15 %).

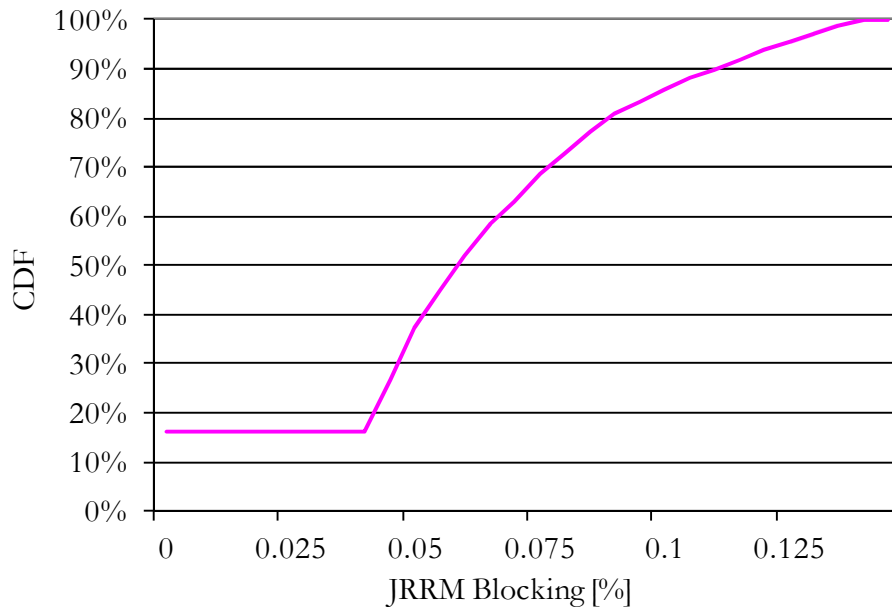


Figure 7.8 - JRRM blocking for user's perspective using only the Cost KPI (MUD).

Figure 7.9 presents the JRRM delay, in the case that CF is guided by the Cost KPI and for the MUD case. Again, when the CF is guided by operators' interests the JRRM performance is better (staying under 0.3 ms), compared with users' ones (up to 0.6 ms), roughly doubling delay.

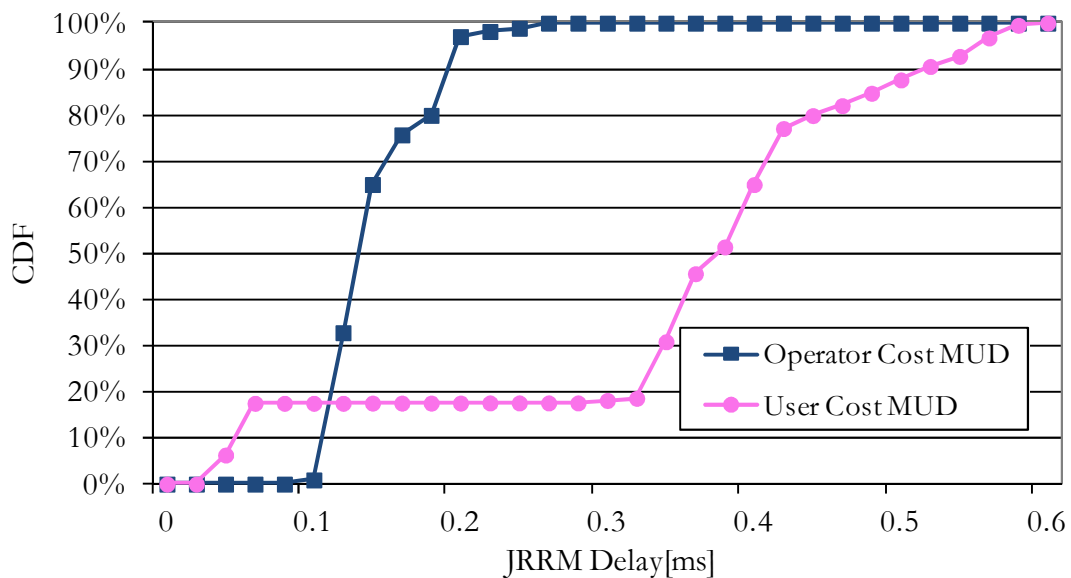


Figure 7.9 - JRRM delay comparing operator's and user's perspectives using only Cost KPI.

The Cost policy produces such good results compared with other KPIs because Cost attracts



users to HBNs (very low cost compared with other RATs), which have less coverage compared with LBNs or even with MBNs. This releases radio resources in other RATs types, increasing the overall JRRM performance.

Exploring a bit further the BrO policy, Figure 7.10 presents other results, by showing the number of active MTs at JRRM level (4.51), when the CF is guided by operators, users and for MUD and HUD traffic levels. The best case is when networks are managed only by the operators CF component, which is also confirmed by the JRRM QoS indicators (e.g., delay). Again, the CF users' guidance memory effect can be the reason, since the BrO policy managed by the operators CF component is more consistent in time, therefore, leading the algorithm to better BSs/RATs.

Additionally, differences are expected in the number of users for MUD and HUD cases. Although, this difference is present, the number of effective active users in HUD compared with MUD is not so high. One reason is the fact that in the HUD case some new attempts to start a service may be blocked or delayed according to results presented in Figure 7.5.

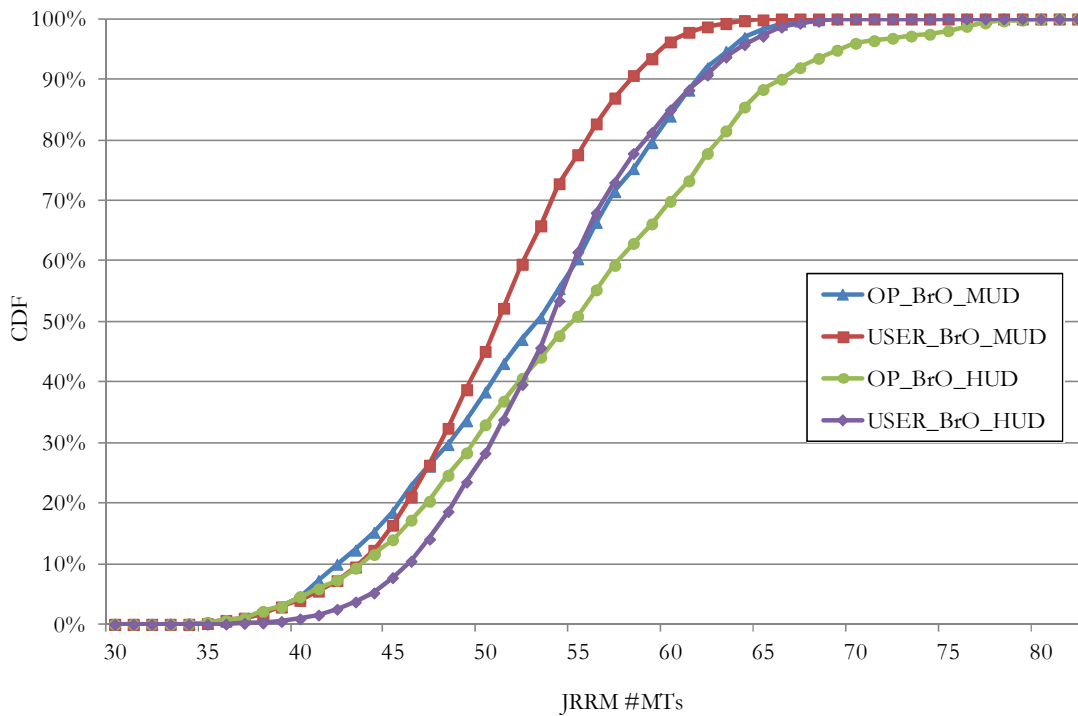


Figure 7.10 - JRRM number of MTs comparing operator's and user's perspectives using BrO policy for MUD and HUD sub-scenarios.

Using the same previous policies, Figure 7.11 presents results for the JRRM bitrate, clearly showing differences between MUD and HUD, and also between operators and users. For, some bitrate levels, especially for the high cases (in HUD), users' policy overcomes operators; the MUD users' policy being almost always the best for all traffic levels.

One may conclude that a higher number of active MTs do not necessary mean higher JRRM

bitrates, because in the scenario one has six services and three different RATs. This is because different services have also different nominal bitrates, being managed in a dynamic manner after a BS attachment. This is also dependent on the radio channels constraints and RAT type, therefore, the growth of active MTs and the overall bitrate does not have a linear direct relation.

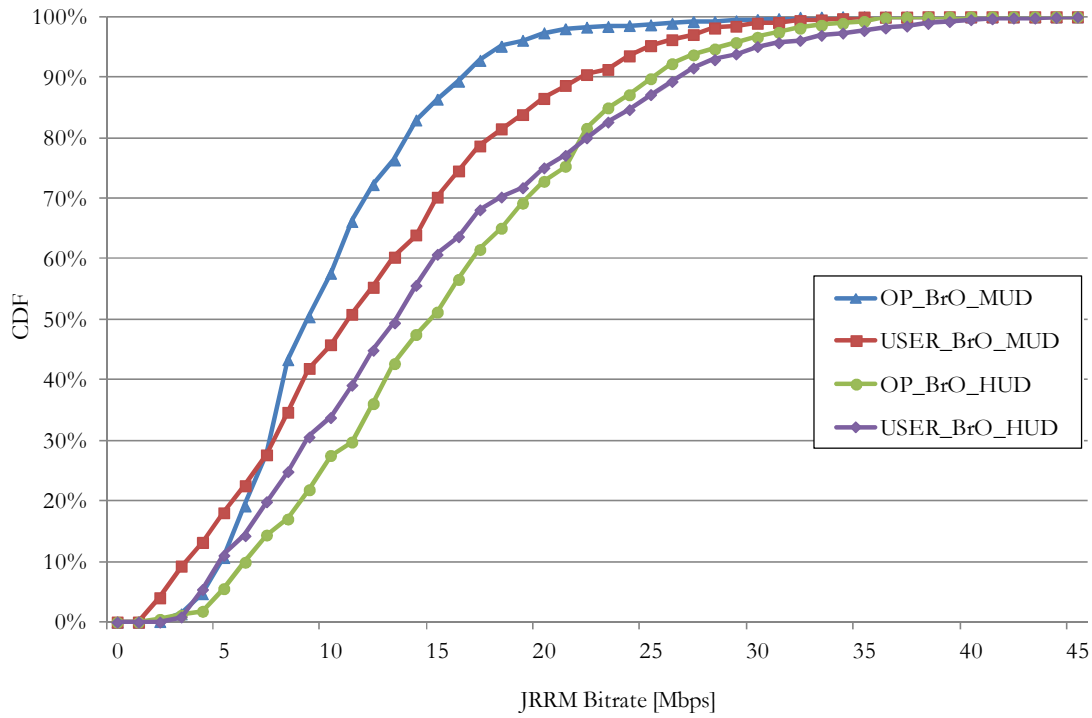


Figure 7.11 - JRRM bitrate comparing operator's and user's perspectives using BrO for MUD and HUD sub-scenarios.

As a conclusion of this section, one observes that when the CF model is guided only by operators or users, the overall JRRM performance indicators change, in some cases in a significant manner. In general, it is recommended to use the operators CF component to achieve better JRRM overall results. The Cost KPI has a huge impact on JRRM performance, because it is a policy that attracts MTs to HBNs in a higher number (at least one order of magnitude). Differences between MUD and HUD scenarios are also visible in QoS and performance indicators.

### 7.2.3 JRRM QoS Based on the Fittingness Factor

Based on a set of KPIs defined by the CF, and on the FF algorithm, one has extracted some RRM and JRRM performance parameters, for different cases where the FF algorithm is guided by different CF KPIs. Among simulation results, for the different policies or used KPIs, Table 7.3, Channels is the KPI that produces better results for all output parameters, because it is a

policy that in fact links MTs to the most suitable BS in terms of radio resources availability. For the worst case, one observes that the first row (NO\_FF) corresponds to a case where the FF is not being used, the JRRM bitrate presenting the lowest value. This is due to the fact that MTs are not guided to the highest bitrate RAT. The JRRM blocking, caused directly by voice and video services, in the NO\_FF case present the worst result. By observing the output parameters presented in Table 7.3, one can conclude the following:

- The number of VHOs caused by the FF (#VHO\_FF) reaches the maximum when the FF is guided by the Cost KPI, which is computed by the CF algorithm. Remember that in this case the most attractive RAT is the HBN group (the cheapest RAT). Thus, many MTs will be moved to HBNs and consequently produce the highest JRRM average bitrate (70 Mbps) and simultaneously the worst JRRM average delay (consequence of RRM in HBN). Note also that the LBN load indicator presents the lowest value (0.209) for this policy, again for the same previous reason.
- When Delay and Blocking are used as KPIs directly by the CF and indirectly by the FF, they produce roughly the same amount of VHOs, JRRM bitrate, and RATs load. Nevertheless, among them, Blocking present the best result at JRRM delay and blocking levels.
- Load and Channels KPIs better results for JRRM bitrate, delay and blocking (0 %), nevertheless one observes that Channels is better, since this KPI produces less VHOs and JRRM delay, compared with others KPIs proposed. The difference between both is related to the abstraction level, load includes not only channels occupancy, but mainly power and propagation issues. Channels only look at radio resources, therefore being more sensible to BSs radio resources real availability.
- To compare the FF algorithm simulation results with the theoretical model, the reference scenario (Hotspot urban area) was computed by the model. The achieved results are also presented in Table 7.3 (bottom row). Note that theoretical results (although under the order of magnitude of other policies) are more similar to the ones produced by the KPI Load, because the theoretical model uses also load as a fundamental parameter to generate results overall JRRM results. Nevertheless, considering the underlined complexity (high number of variables and their relation), it is very important to observe that the theoretical model can produce results in the same order of magnitude, compared with ones produced by the simulator.

Since the FF model produces interesting results, it is used to analyse and explore other relevant output parameters generated by the simulator. These results are based on the previous CF

policies. For performance reference analysis the NO\_FF sub-scenario is also presented.

Table 7.3 – Simulation average results using the Fittingness Factor for different CF KPIs compared with the theoretical model for the reference scenario.

Fittingness Factor KPI/CF guide	FF #VHO	Average Number of Active MTs	JRRM Bitrate [Mbps]	JRRM Delay [ms]		JRRM Blocking [%]	LBN Load	MBN load
NO_FF	0	50	24	4.03		6.7	0.2379	0.0214
Delay	213	53	49	7.52		4.3	0.2352	0.0342
Blocking	258	48	55	0.94		2.1	0.2378	0.0383
Cost	9178	55	87	39.32		2.3	0.2097	0.0405
Load	956	53	61	4.52		0.0	0.2330	0.0345
Channels	98	56	53	0.58		0.0	0.2783	0.0348
Theoretical results for the reference scenario	Theoretical #VHO	55	56	LBN [ms]	MBN [ms]	0.4	0.208	0.025
	902			13	0.19			

One interesting output parameter is the LBF, defined by (4.54). This parameter measures how balanced LBNs and MBNs are: when LBF is close to 1, LBNs and MBNs are properly balanced (by computing their power loads). By observing Figure 7.12, which presents LBF in the time domain for the different CF KPIs, one conclude that LBNs and MBNs are more balanced when Cost and Blocking are used as KPIs, because when Cost is used, HBNs become more attractive, the FF algorithm triggering VHOs from LBNs and MBNs to HBNs, or even from LBNs to MBNs. In this case, both networks become empty and more balanced, offering more capacity by exploring HBNs capabilities. When the Blocking KPIs is used (green curve), sometimes it overcomes the Cost performance, because BSs presents similar levels of QoS for the Voice users (majority in the scenario). The third policy that provides a good result in the LBF is the BSs load (light blue curve), in a few cases overcoming the Cost and Blocking CF polices, producing a high number of VHOs, since BSs'/RATs load change significantly.

Note that these results may change if the tuning parameters associated to the FF model mechanism are changed, for example the  $\Delta_{VHO}$  (VHO threshold parameter) and  $T_{VHO}$  (period of time that a VHO triggering condition holds). Produced results use  $\Delta_{VHO} = 0.1$  and  $T_{VHO} = 3$  s as default values. These parameters influence the FF behaviour, thus, having an impact on the number of VHOs generated and on the final performance. These changes were not fully studied by this thesis. Finally, the NO\_FF case (red line) is several times in the worst situation.

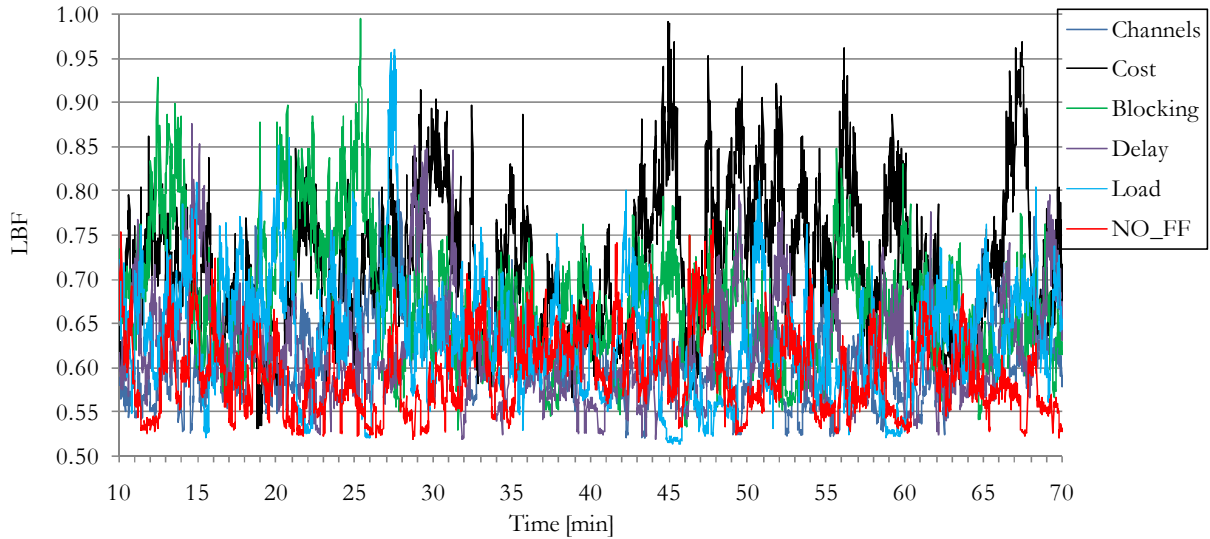


Figure 7.12 – LBF based on the FF and different CF policies (in time).

Based on the previous results for the LBF, Figure 7.13 presents statistical results where average and standard deviation is shown for each FF/CF policy. With these results, it is easy to distinguish and rank the selected policies. It is clear that when the FF algorithm is off, the LBF presents the worst result, depending only on the priority table, which is a service-RAT fixed mapping, thus, not adaptable to real-time load changing conditions as the FF model is.

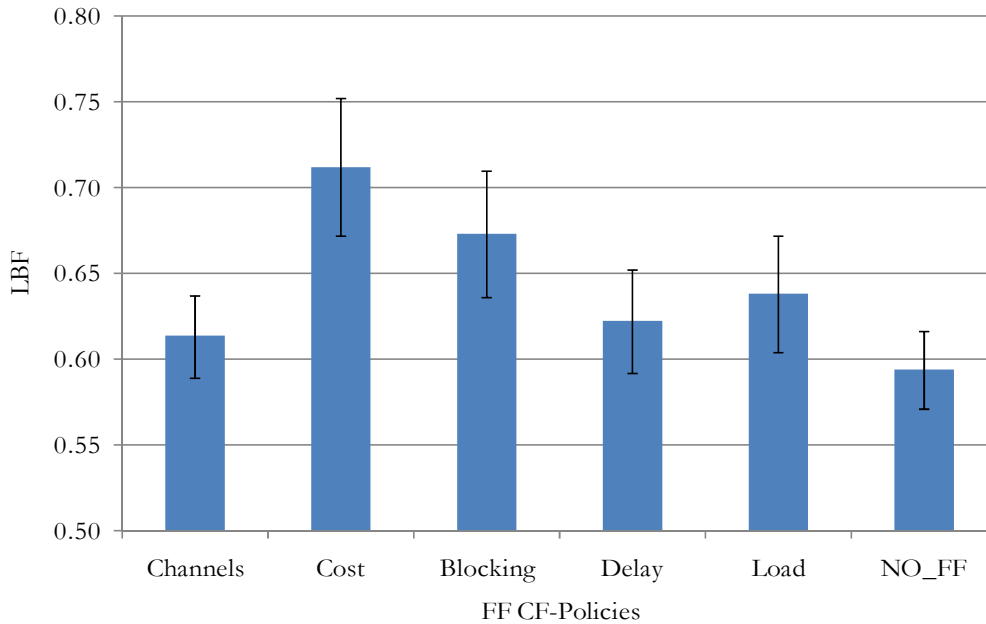


Figure 7.13 – LBF average and standard deviation for the FF and different CF policies.

For the Cost oriented policy, the standard deviation presents the highest value for LBF, because more VHOs are performed by the FF (according to Table 7.3), which causes more disturbances/changes in the BSs load, leading to more instability in the LBF parameter.

Since the FF algorithm is pro-active for triggering VHOs, it is interesting to evaluate its impact in

the overall number of VHOs, which is performed by computing the number of VHOs triggered by the FF algorithm  $N_{FFVH}$  (4.58), and the overall JRRM number of VHOs,  $N_{VHOsim}$  (4.57) ratio. Results for each adopted policy on this ratio are provided in Figure 7.14, where average and standard deviation values are shown. Note that standard deviation values are very small for all policies, which means that the impact of FF VHOs is kept almost constant among simulations, the overall impact being quite stable and predictable. This ratio for the NO\_FF policy is zero, because the FF algorithm is turned off, thus, the number of VHOs produced by the FF is zero. The highest ratio is generated by the Load policy (70%); because BSs load has a natural instability, and the FF algorithm triggers several VHOs, when probably they are not well justified. Many VHOs do not necessary mean good results, according to the LBF results the Load CF policy is in third place. The Cost based policy also produces a very high VHO ratio (second highest), however, producing good results in other QoS indicators, since it handovers MTs to HBNs, therefore taking, the intrinsic HBN advantage in capacity. For other policies, such Blocking, Delay and Channels, the FF model generates a relatively low number of VHOs, less that 10% of the total that is generated.

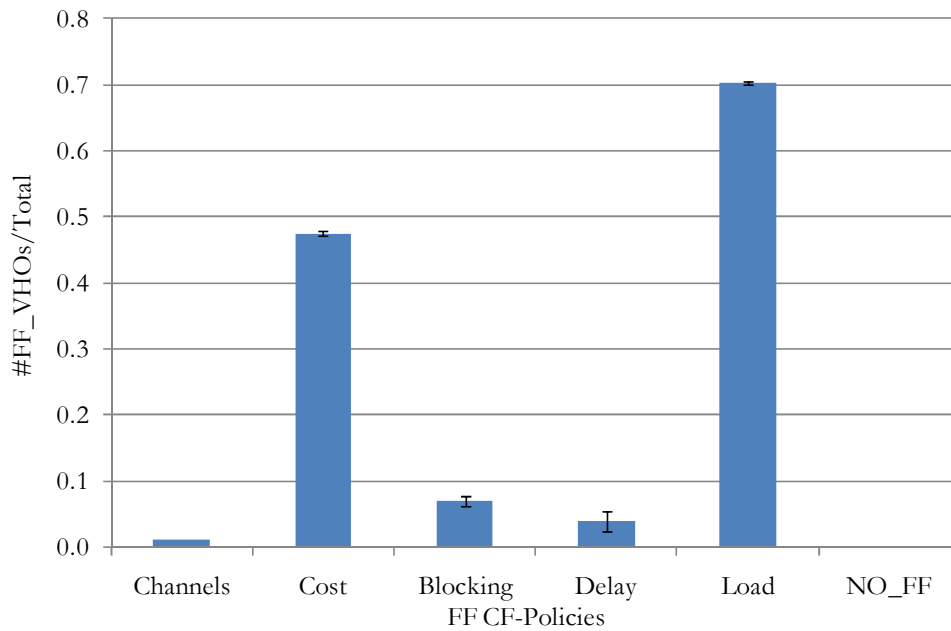


Figure 7.14 – Number of FF VHOs over the total average ratio and associated SD.

Another JRRM output parameter generated by the simulator is the number of BSs reachable by MTs,  $\overline{N_{BSMT}}$ , described in (4.52), is very dependent on the scenario configuration, BSs density, or even users' mobility and geographic distribution. In the case under study, the reference scenario, this parameter is roughly 2. Observing results presented by Figure 7.15, one concludes that the Cost and Blocking KPIs oriented policies are capable to increase slightly this parameter compared with others. These results have some similarities with the LBF ones, since these

policies attract more users to HBNs, which in the end MTs explore more the HBNs coverage up to the limit, while keeping the LBNs and MBNs coverage.

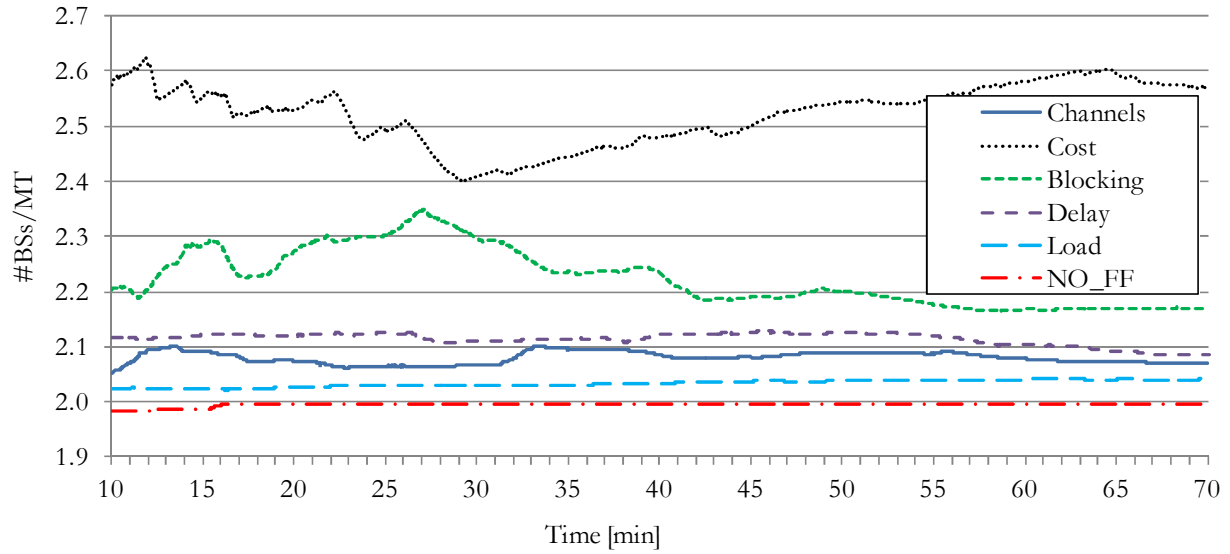


Figure 7.15 – The number of BSs reachable by MTs in time for each FF/CF policy.

Similar to previous parameters, Figure 7.16 also presents the summary results by highlighting the average and standard deviation for the number of BSs reachable by MTs and for each management policy KPI tested under the FF algorithm. The lowest result is again the one with no guidance, the NO\_FF. It is also noted that the standard deviation is quite small for almost all FF policies: only for the Cost and Blocking standard deviation it presents higher values, this being explained by the influence that these policies have on the capability to attract MTs to HBNs, therefore, being less stable. This effect is already observed in Figure 7.13.

In order to provide a temporal view about the JRRM bitrate behaviour as function of the adopted FF/CF policies, one has plotted in Figure 7.17 the overall generated JRRM bitrate based on the reference scenario it is possible to see some peaks related with data services connected to HBNs.

Observing the FF/CF policies in time, one can conclude that the Cost policy, followed by the Load one, present the first and second best result, respectively. The worst result is again generated when the FF algorithm is turned off. The overall performance of the remaining policies, Channels, Load and Delay, are located between the previous ones, although then are some peaks produced by these policies. The 150 Mbps level is overcome for some minutes in a few simulations, the 200 Mbps is reached in few moments, and the 250 Mbps is only overcome once, by the Load policy. This may be because load at LBNs and MBNs BSs can be very dynamic, leading to network capacity limits.

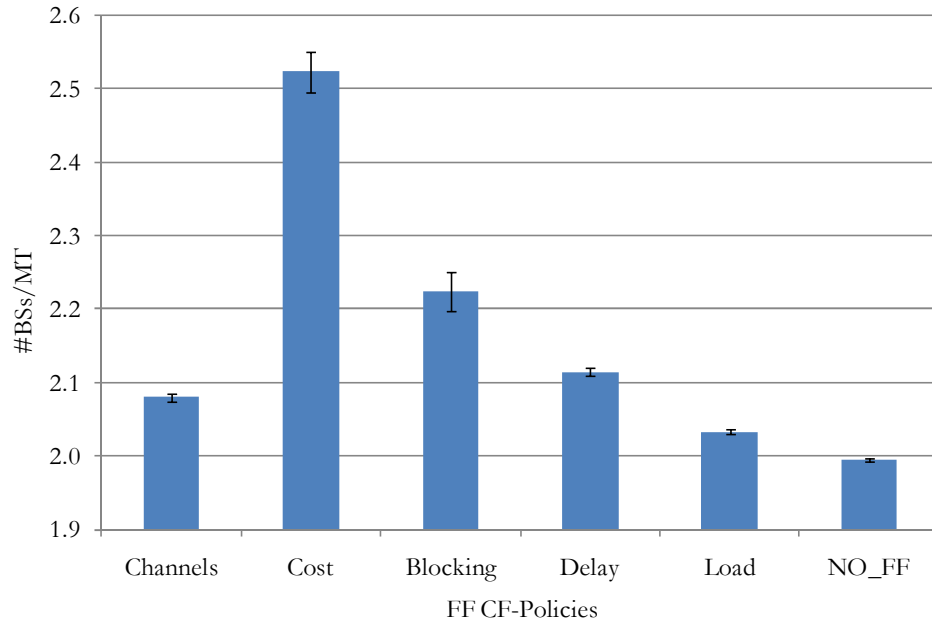


Figure 7.16 – Average and standard deviation for the number of BSs reachable by MTs and for each FF/CF policy.

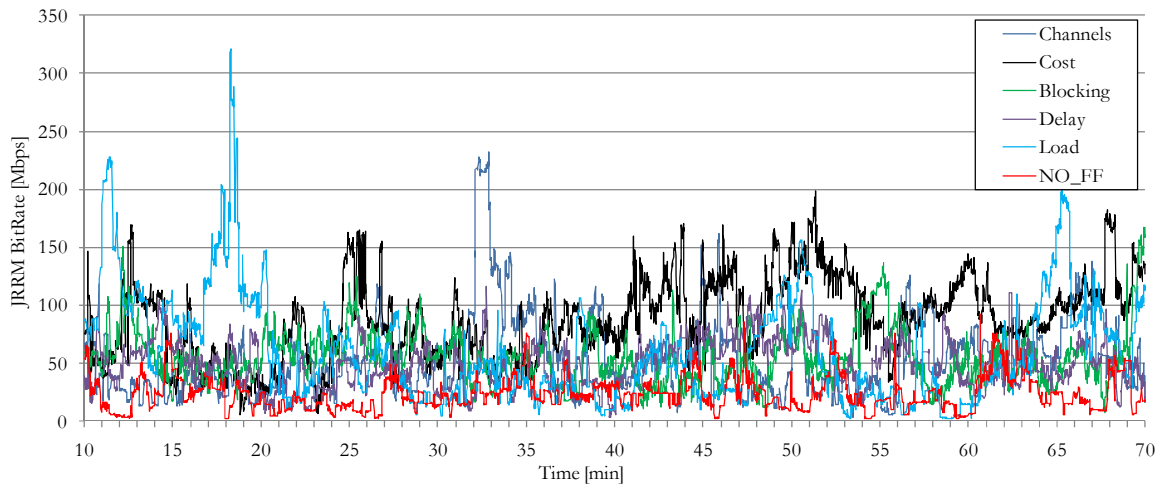


Figure 7.17 – JRRM Bitrate in time for FF using CF-Policies.

Figure 7.18 results help to clarify the ones presented by Figure 7.17, where average and respective standard deviation for each FF/CF policy are highlighted. Load and Cost policies present the highest standard deviation values, the origin of this statistical result can be observed in Figure 7.17, where JRRM Bitrate dynamics is plotted in time.

Note that for the NO\_FF case, the standard deviation is the lowest, explained by the absence of a pro-active algorithm, the FF.



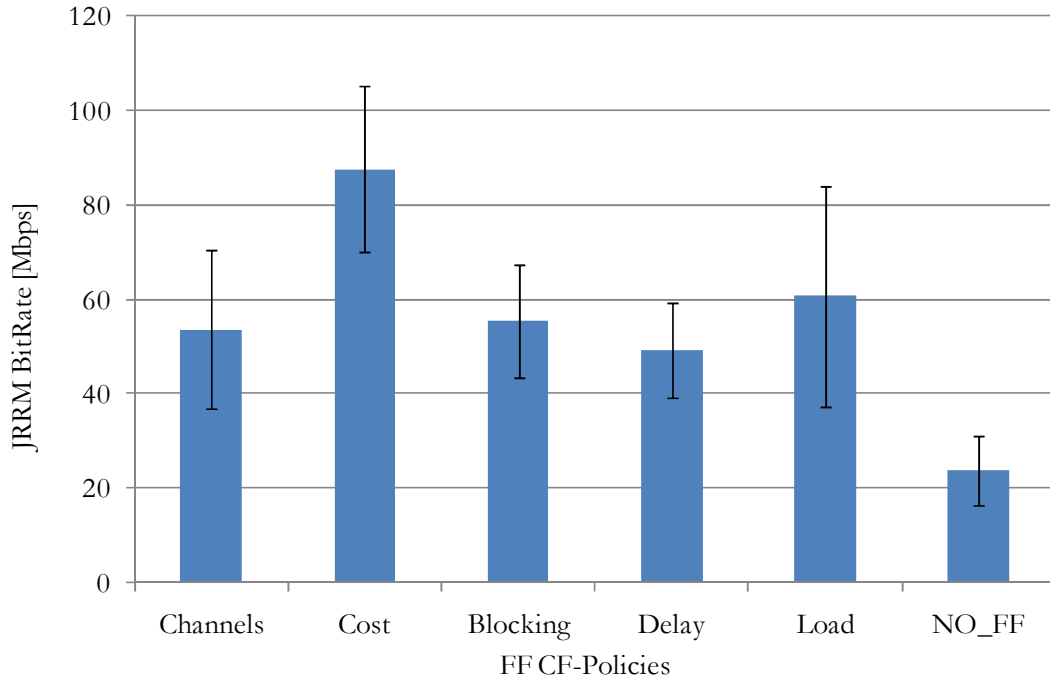


Figure 7.18 – JRRM Bitrate statistics for the FF algorithm using CF-Policies.

Other feature implemented in the simulator is the number of active MTs per each service, being also studied under the FF algorithm analysis. Figure 7.19 is an example for the KPI “Channels”, where the number of active MTs/service is presented in time. It is possible to observe the effect of services distributions percentages (Table 6.1), defined in the reference scenario. Other related results for the remaining policies are described in Annex-E.

Figure 7.20 shows the summary of all results described in detail in Annex-E, where the average and standard deviation values for each service and FF/CF policy are presented. It is possible to have a different perspective by viewing which policies can, on average, accommodate more active MTs/services. For speech, Channels and Load policies allow more users, because BSs with more channels available and/or less load will be more available to accommodate more Speech-MTs. The Cost policy is the third for Speech, but it is the leader for data services, because this policy has the trend to handover MTs to HBNs or MBNs.

From the standard deviation for all services and policies, it is possible to notice that the speech service presents the highest value, because it is more than half of active MTs (56% - according to the scenario, Table 6.1), therefore, the number of speech users generate a wide dynamic range compared with other services with quite lower percentage, e.g., video (4%).

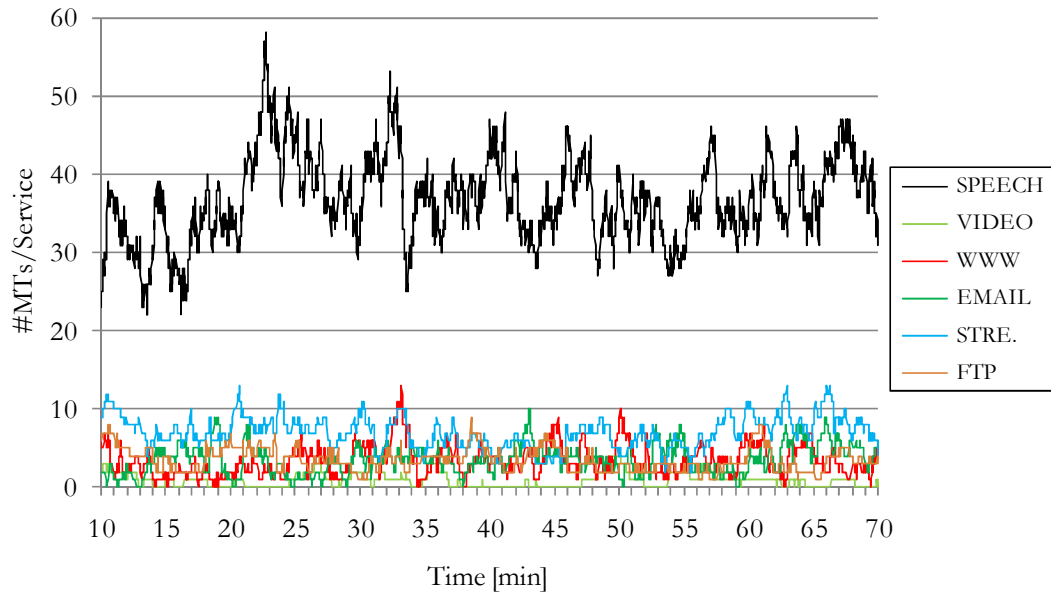


Figure 7.19 – The number of active MTs per service for FF CF-Channels (viewed in time).

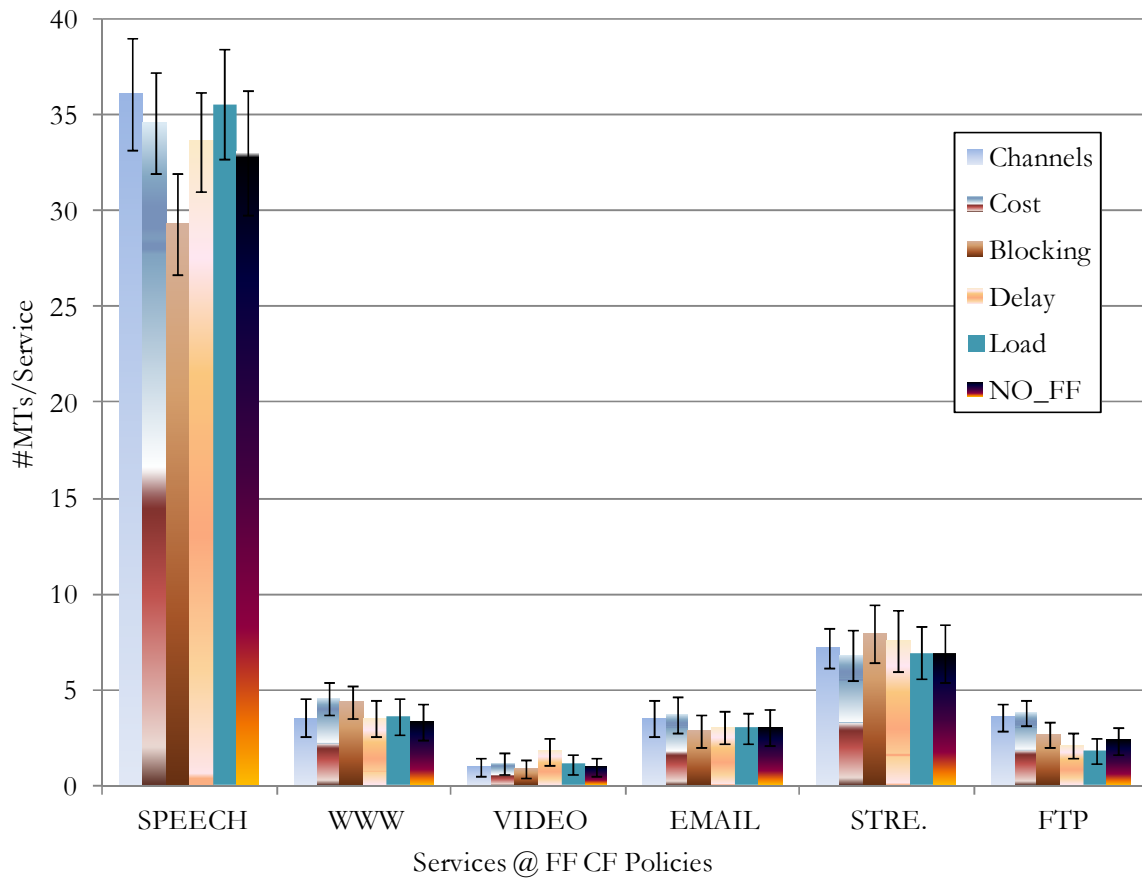


Figure 7.20 – Number of active MTs per service statistics for each service and FF/CF policy (average and standard deviation).

Compared with other policies the NO\_FF policy presents similar values for the number of active MTs in each different service, nevertheless JRRM QoS for this policy, as presented before, is the worst. One concludes that, although processing roughly the same amount of MTs, the FF

algorithm is able to increase the overall JRRM QoS, and users' average bitrate experience in a heterogeneous network.

Also note that, although in the input reference scenario configuration some services have similar distribution or penetration percentages, results show that there are some differences in the output number of active services, because some services have relatively less activity time. For example, in the reference scenario, E-Mail and Streaming, have both 10% in the service penetration bouquet, however, results show significant differences between these two services. Comparing Streaming with E-Mail, the former is more time consuming, generating also more data volume, thus, the number of active MTs using Streaming is higher compared with E-Mail associated active MTs.

In conclusion one observes that the CF can easily be integrated in the FF algorithm as input, being it self a JRRM algorithm. Results produced by the FF and guided by different CF/FF policies show that Cost and Blocking (BO) policies generate better results in JRRM QoS and performance indicators. Therefore, these policies are recommended to be used by JRRM entities in cellular heterogeneous networks.

One also concludes that results produced by the theoretical model are of the order of magnitude or similar to the ones produced by the FF in the simulator, for the reference scenario.

## **7.3 MIMO and Mobility Impact**

### **7.3.1 MIMO Influence**

In this section, the MIMO impact on JRRM performance is presented. Results are based on the reference scenario, using the HUD case in order to highlight potential differences between MIMO and SISO based systems. Simulations were performed using the same CF policy, which considers the following JRRM KPIs: Delay, Blocking, Bitrate and the number of active MTs, all for operators and users combined.

In Figure 7.21, the CDF curves represent the JRRM delay performance comparing SISO and MIMO based scenarios. As expected, the MIMO case performs better. When observing these curves, one can conclude that, in this environment, MIMO systems reduce JRRM delay roughly by half. These results are based on the RMG model described previously, for these assumed

scenarios. Although, not directly comparable, the RMG increases the MT's data rate by a factor of two compared to SISO. The JRRM delay ranges from 70 up to 160ms when MIMO is applied, and for SISO cases it goes from 165 up to 310ms.

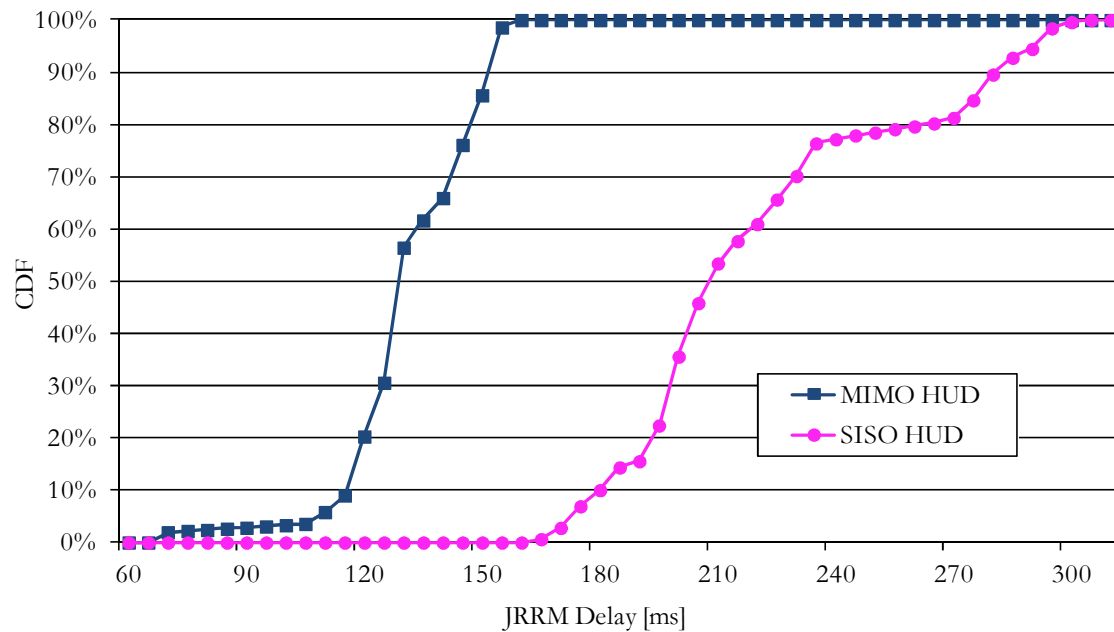


Figure 7.21 - JRRM delay comparing MIMO and SISO in a HUD situation.

Figure 7.22 presents the JRRM blocking performance. Once again, the MIMO based scenario performs better. The high blocking levels, are due to the fact that they are based on a HUD scenario.

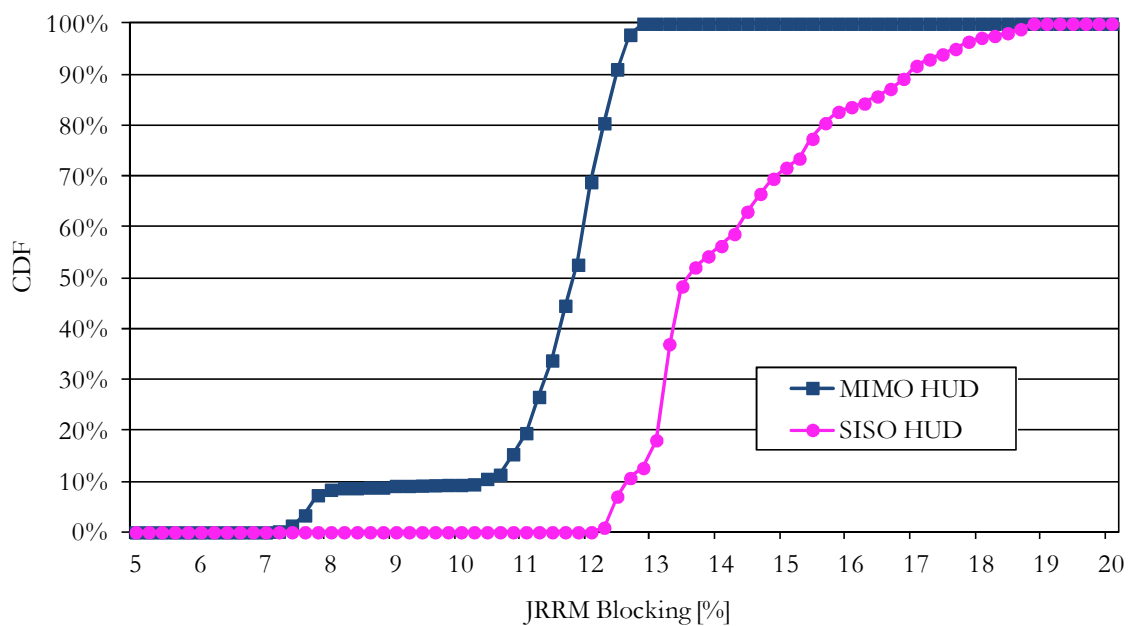


Figure 7.22 - JRRM blocking comparing MIMO and SISO in a HUD situation.

This very high traffic demand scenario decreases the overall JRRM QoS to levels that are away

from the ones that are normally acceptable (usually under 2%). When observing these results, keep in mind that the JRRM blocking is generated by CS services (voice and video calls), which in this case do not take direct advantage from MIMO systems. However, CS oriented services indirectly take advantage from MIMO, since PS services (when using MIMO) occupy radio resources in a shorter period of time. Thus, MIMO has an indirect impact on the JRRM blocking, by reducing this metric down to 7 %, Figure 7.22.

Another interesting parameter to be analysed is the overall number of simultaneous and active MTs, Figure 7.23. One may observe that the difference is not substantial, although MIMO, most of times, takes the best result. Therefore, one can also conclude that MIMO equipped networks can accommodate the same number of active MTs, while increasing substantially the overall JRRM QoS, which can be translated as network increased capacity.

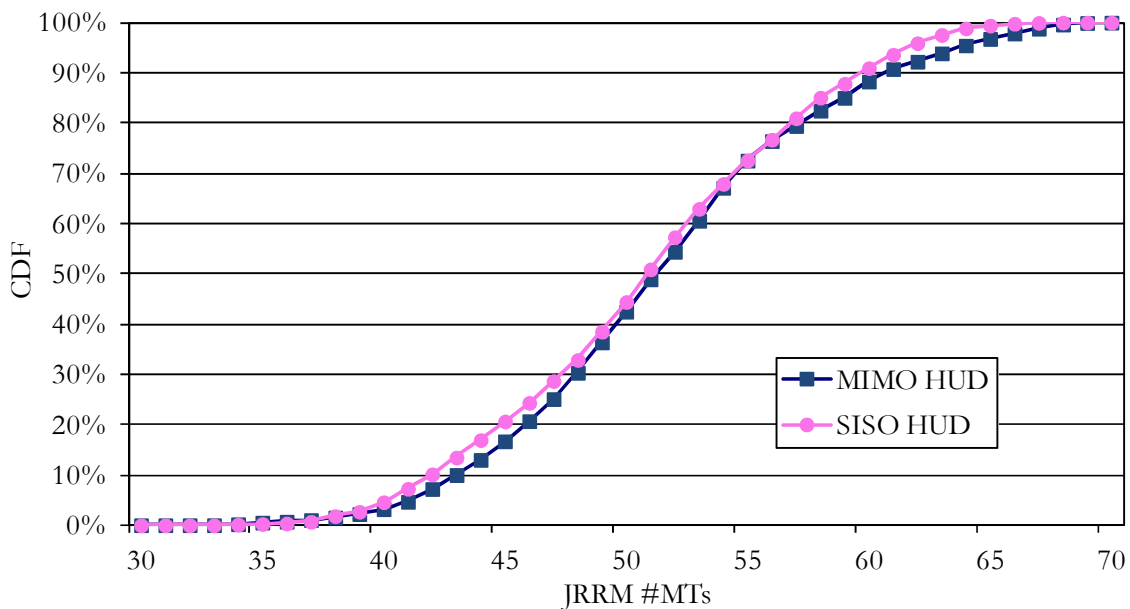


Figure 7.23 - JRRM #MTs comparing MIMO and SISO in a HUD scenario.

Observing the JRRM bitrate behaviour for the HUD scenario, and comparing SISO and MIMO performance scenarios variation, Figure 7.24, MIMO performs better. This is due to the fact that PS based services increase their radio interface bitrates by (roughly) 2 up to 4, due to the assumed MIMO systems under study, which leads to better networks overall QoS, even in HUD scenario. Another effect generated by MIMO systems is the increase of the JRRM Bitrate to high values, benefiting from MIMO-HBN BSs, which, in this case, can contribute with very high bitrates, especially in urban hotspot cases. For the SISO case, JRRM bitrate stays under 40 Mbps, having a median above 10 Mbps. For the MIMO case, JRRM bitrate has maximum values above 200 Mbps, although the median is about 60 Mbps.

To conclude this section, MIMO systems, as expected, have a notorious increment on the PS

services performance, because they are bitrate variation tolerant. Thus, any change at BSs radio resources occupancy time by PS services, leads to changes in the overall networks QoS metrics. Naturally, that MIMO systems decrease this occupancy time, decreasing delay, blocking and generating more JRRM bitrate, while keeping the number of active MTs, if not increasing.

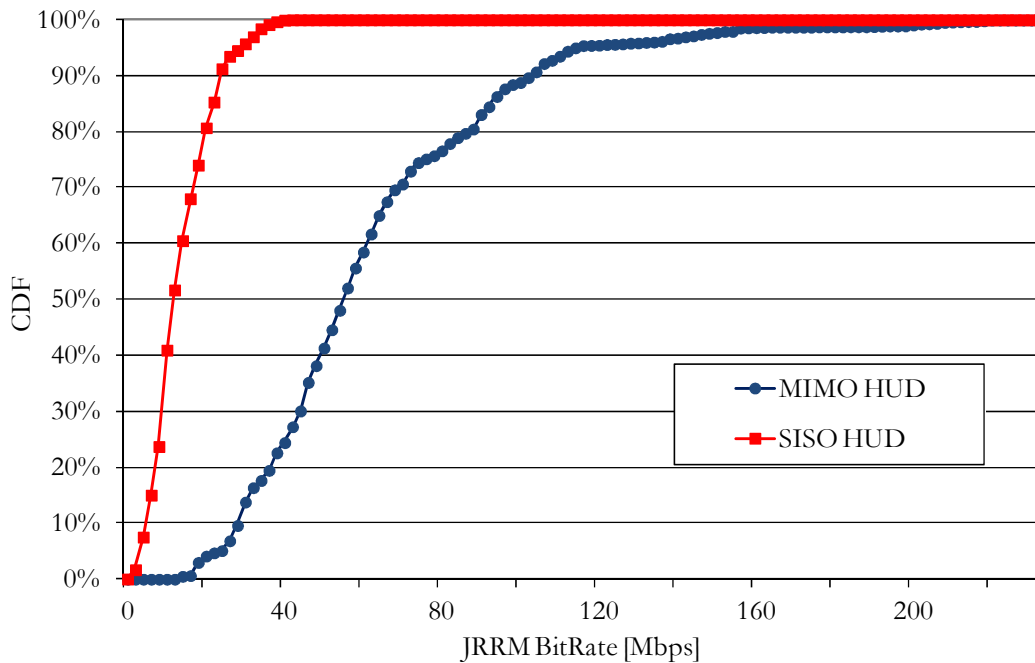


Figure 7.24 - JRRM bitrate comparing MIMO and SISO in a HUD scenario.

### 7.3.2 Mobility Profiles

In order to isolate the MIMO impact and associated MTs mobility profiles have on performance, only one JRRM-CF policy was simulated, using the reference scenario, corresponding to the one that presents better results in Section 7.1. This policy combines delay and blocking KPIs (BD policy).

Results presented in Figure 7.25 and Figure 7.26 compare different mobility profiles, using SISO and MIMO systems. The SISO mobility results, besides being useful to compare with MIMO ones, are also valuable to analyse the mobility impact on JRRM performance. One should note that the offered random generated traffic (service mix) conditions are constant for all simulations.

By observing Figure 7.25, one can conclude that when MIMO systems are assumed to be installed in MTs, JRRM delay performs better, since PS services (e-mail, streaming, FTP and www) are supported over higher bitrates bearers, thus, the time required to transmit packets (specially the ones with high volume) is reduced. Additionally, the HM profile also performs

better (relatively), probably due to the fact that MTs in a HM profile take more advantage of HHOs and VHOs. Therefore, PS services, based on their session data oriented traffic behaviour, are more easily handover to better BSs (the ones with less cost, base on the JRRM/CF policy computation). One can also conclude that, regardless of the mobility profile, MIMO produces better results, staying below 15 ms of JRRM delay. Remember that handovers signalling delay are not considered. For the SISO case, the worst situation goes up to 45 ms, corresponding to LM profile.

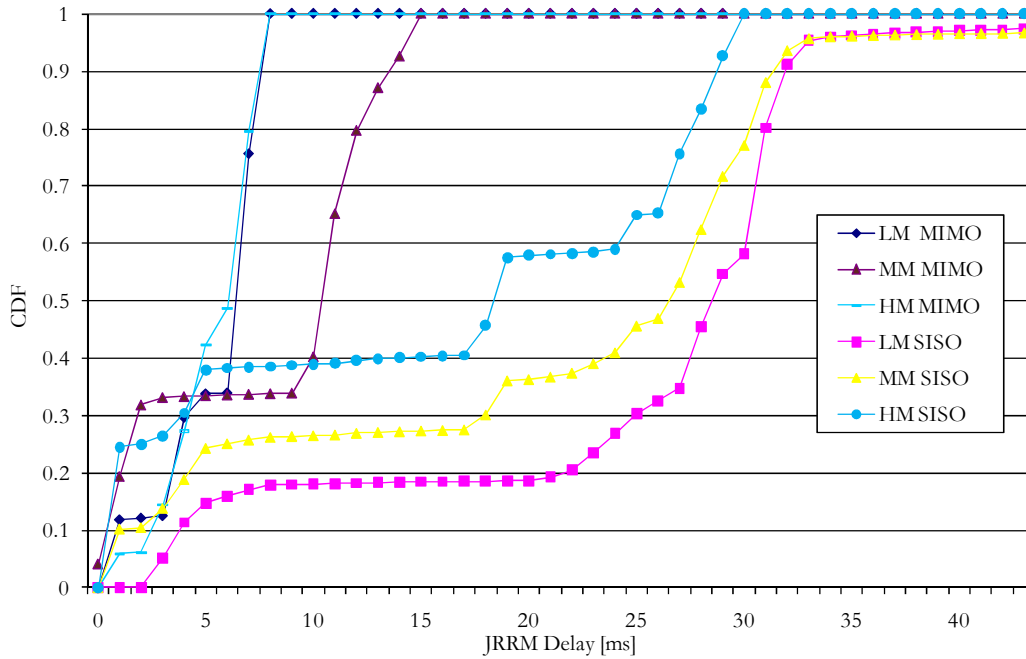


Figure 7.25 – Mobility and MIMO impact on JRRM average delay.

From the results presented in Figure 7.26, one observes an opposite trend to the previous case (from the mobility profiles viewpoint). The MIMO effect is kept, the SISO and MIMO curves are again clearly separated. Although CS services do not take direct advantage of MIMO radio bearers (at least in these simulations), they take an indirect and positive advantage, since PS services, takes less time using radio resources, releasing radio resources earlier to new CS calls.

Concerning MTs mobility profiles, JRRM blocking has better performance in the LM cases. These mobility results have different trends, compared with the JRRM delay performance, since these services (CS based services with long duration) are more expose to handovers (HHOs and VHOs), thus, to the CAC and the blocking process.

The best case is the LM MIMO, where JRRM blocking goes up to 0.8 %, while the worst one corresponds to HM SISO, where the maximum goes up to 4 %. MMs cases are separated roughly per 1.5 %.

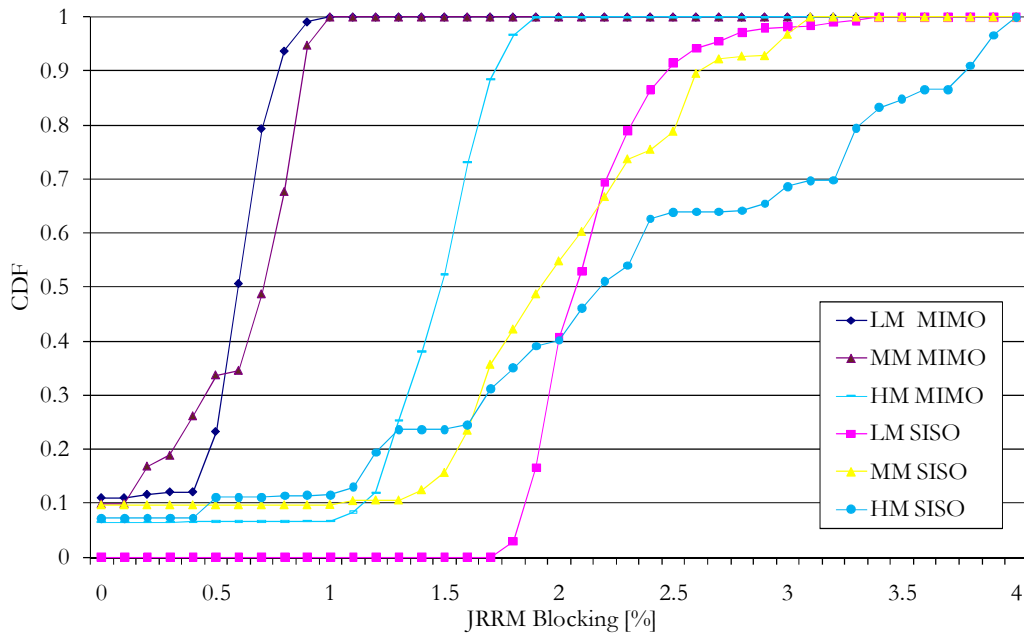


Figure 7.26 - Mobility and MIMO impact on JRRM blocking.

Figure 7.27 presents the number of active MTs in the JRRM domain, by comparing different mobility scenarios, and crossing them with MTs equipped with SISO and MIMO systems. Although one observes more active MTs when the HM profile is considered, the difference among the various mobility profiles does not present a significant impact on the overall number of active MTs. This is due to users being uniform distributed, randomly moving in the scenario, and the number and services sessions being in equilibrium, which means that arriving and departure users sessions at BSs are kept stable. However, SISO and MIMO have some impact on the number of active MTs. The “worst” case is for LM SISO, and the “best” is for HM MIMO. Nevertheless, these differences are explained by users SISO MTs being more easily blocked or delayed, therefore MIMO scenarios present a few more active MTs.

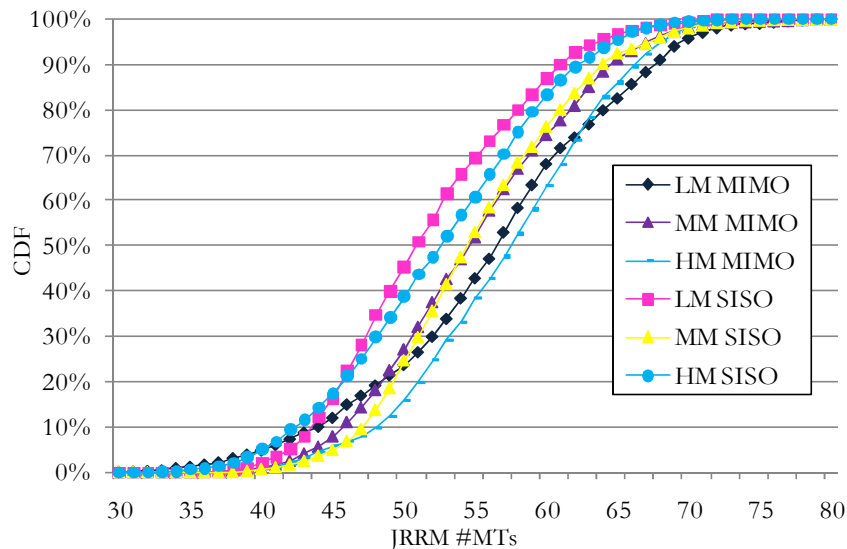


Figure 7.27 - Mobility and MIMO impact on JRRM number of active MTs.



Similar to previous scenarios, Figure 7.28 present results for the overall JRRM bitrate. As expected, the MIMO “group” take the highest values. One concludes that high mobility profiles generate lower JRRM bitrate, and low mobility generates higher bitrates, because mobility has an effect on the radio channel conditions, and fast and slow power control or link adaptations mechanisms (among different RATs) have more difficulties to keep channels under good conditions (signal power and interference stability) in high mobility profiles, leading to low bitrate situations. Thus, SISO combined with HM profile is the case that generates lower bitrate, MIMO LM being the one that presents the highest values.

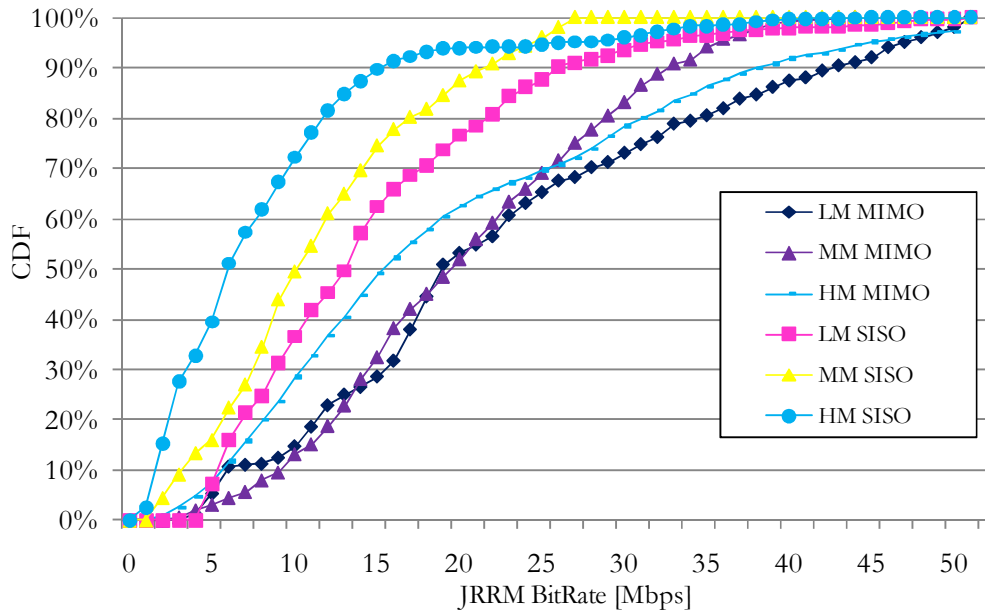


Figure 7.28 - Mobility and MIMO impact on JRRM Bitrate.

As a final conclusion of this section, one observes that users' mobility profiles have impact on the JRRM QoS and performance, especially on JRRM delay, blocking and bitrate. MIMO systems associated to fixed and fast users also generate the expected trends, having a clear positive impact on results.

## 7.4 Services Impact

### 7.4.1 Priorities Policies

Based on Table 6.12 previously proposed services/RATs priority variation, keeping the BD policy, and analysing associated results presented in Figure 7.29 and Figure 7.30, one can observe

that the HBN Centric scheme leads to better JRRM performances, since HBNs by nature have more capacity, thus, if HBNs have priority among others RATs, the overall JRRM performance is improved, since LBNs and MBNs are less loaded. The HBN Centric scenario keeps JRRM blocking below 1.8%. In the other extreme, the LBN Centric case rises up to 8% (note that half samples are above 7%), while MBN Centric and Reference cases range from 0 up to 3.5%.

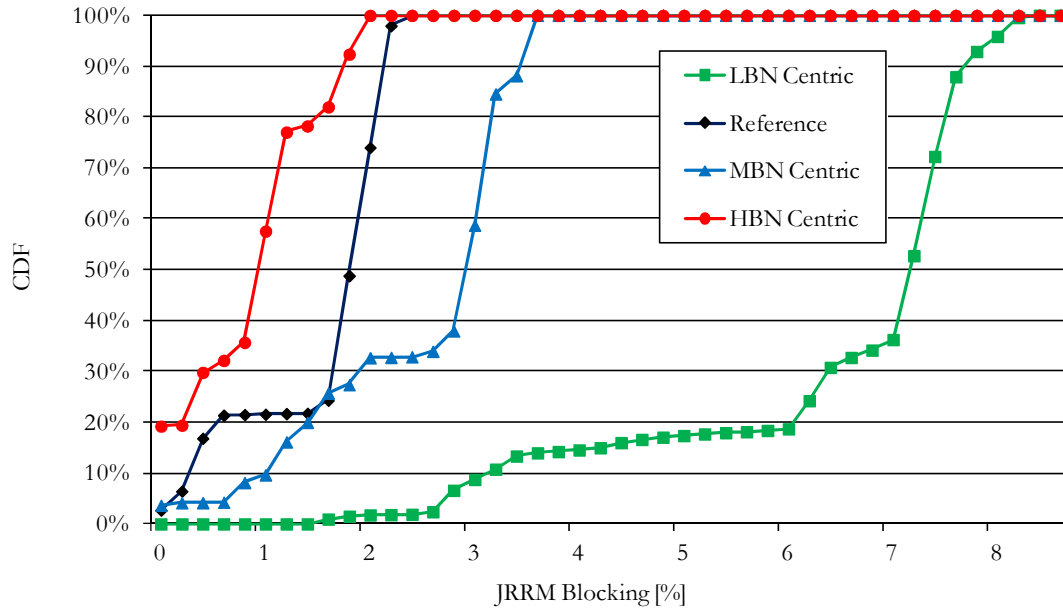


Figure 7.29 – Service priority mapping impact on JRRM blocking.

The second best is the Reference mapping scheme, which seems the most balanced services/RATs priority scheme. For this reason, the “Reference” case presents relatively good JRRM performance results. The MBN centric case has slightly worst results, but not so bad compared with the LBN centric situation; this is probably due to the fact that PS oriented services have the first priority into MBNs which seems the most suitable type of networks for PS services. The LBN Centric presents the worst result, since this trend can easily overload LBNs QoS usual limits (e.g., blocking above 3%). Additionally, the fact that LBNs have more coverage leads to more users to handle, mainly being voice MTs.

From the JRRM delay viewpoint, results are quite similar, HBN Centric and Reference being below 17 ms, while the MBN performs below 30 ms. In the other extreme, the LBN Centric goes up to 200 ms. Simulation QoS results for HBN and LBN Centric situations is presented by the theoretical model results, in Figure 6.12.

The impact of priority policies into the number of #MTs is presented Figure 7.31, where HBNs and MBNs centric cases allow less active MTs. The LBN Centric case is almost coincident with the Reference scenario. Compared with others, the difference between LBN Centric and the remaining others comes from LBNs having higher coverage area, capturing more MTs. The

maximum number of active MTs (about 75) is reached by all services/RATs mapping policies, because in high traffic demand moments MTs/services are handover to other RATs (guided by the CF), maximising the scenario capacity.

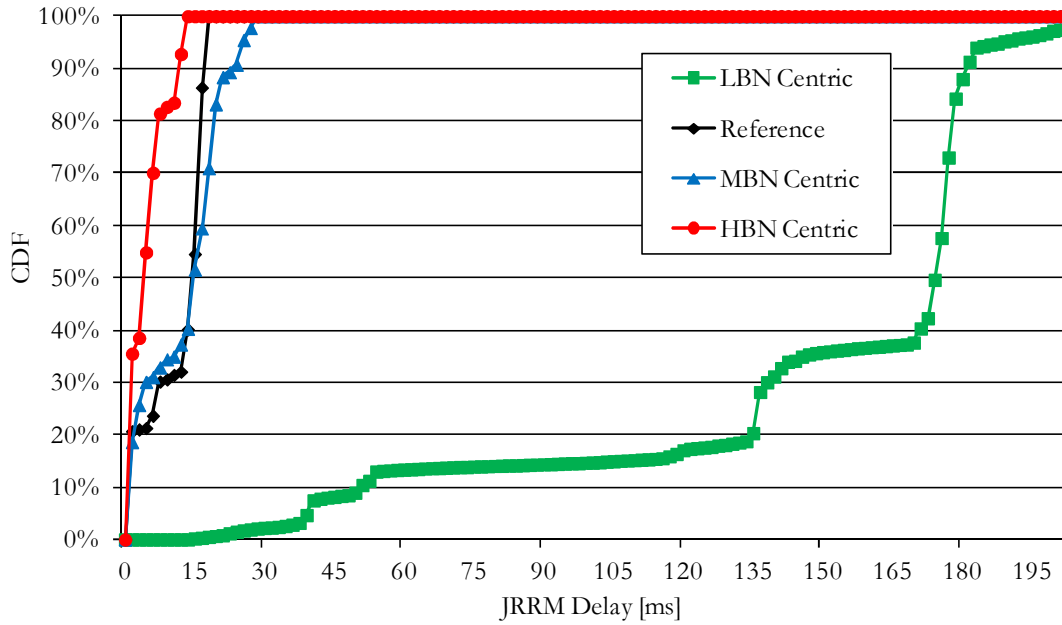


Figure 7.30 – Service priority mapping impact on JRRM delay.

Another relevant point is that among the services set, voice has the highest percentage, and therefore more associated to LBNs (roughly coincident with the reference case).

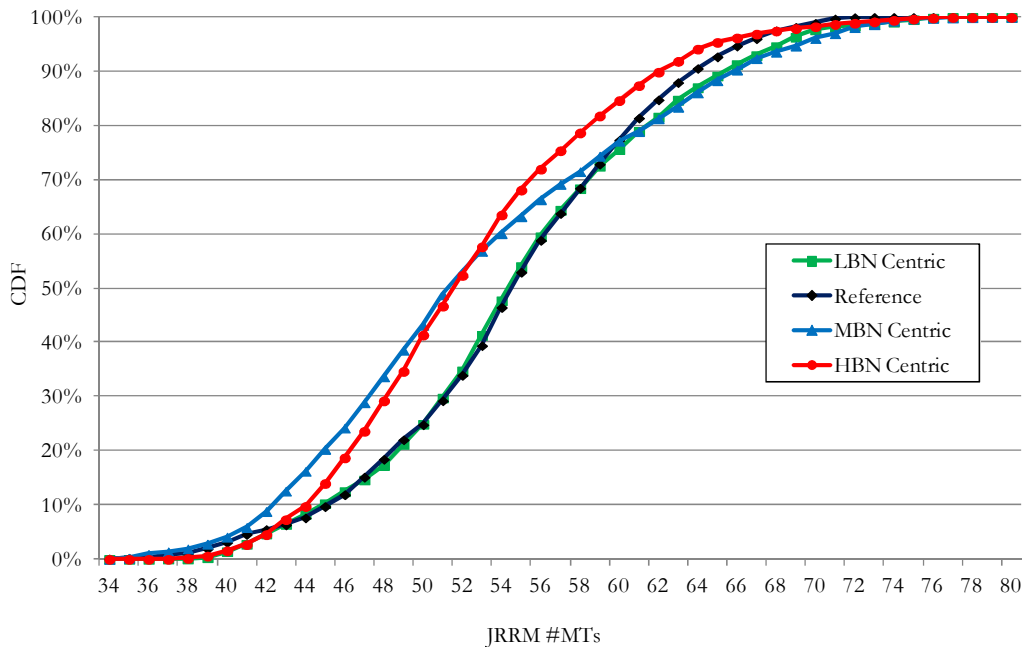


Figure 7.31 – Service priority mapping impact on the number of MTs active at JRRM.

Finally, the impact of priority policies onto JRRM bitrate is presented in Figure 7.32, where it is clear that the LBN Centric policy generates lower JRRM bitrate, since LBNs are intrinsically low bitrate networks. Therefore, LBNs can connect more MTs and cover relatively wide areas;

however, this is achieved with less overall throughput. Observing MBNs and HBNs Centric policies, one concludes that MBNs can produce higher bitrate compared with HBNs, because MBNs have a larger area, therefore, reaching more MTs/users in space. Thus, HBN Centric policy does not produce the highest JRRM overall bitrate, as expected, due to low coverage.

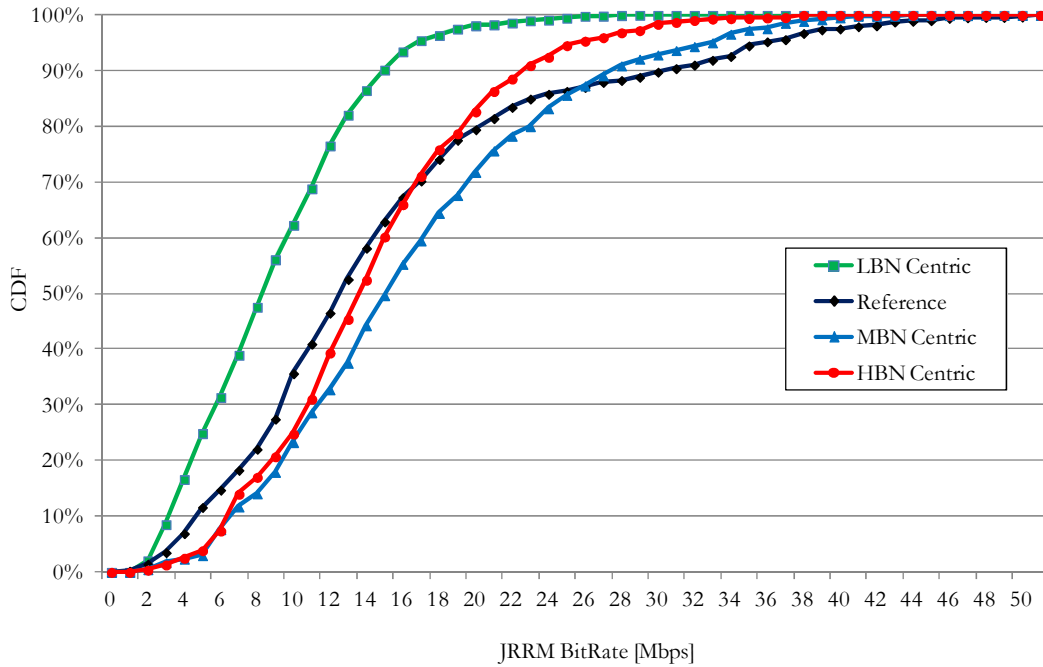


Figure 7.32 – Services/RATs priority mapping impact on the JRRM Bitrate.

As a final remark, one concludes that HBN Centric generates the best JRRM QoS, however, due to its low coverage nature it does not perform so well in covering MTs. The MBNs Centric and Reference cases seem to be the most suitable ones, because they present good results in the study metrics, since they distribute services in a more balance way. It is also clear that the LBN Centric strategy should be avoided, in order to increase networks overall performance.

## 7.4.2 Services Penetration Trends

In order to evaluate the JRRM dependence on the dominant switching type CS or PS, two scenarios were defined: the CS centric (CS\_CENTRIC) where voice and video-telephony service average time duration was doubled (from 60 to 120 s), and the PS centric (PS\_CENTRIC) by increasing the BHCA parameter of all PS oriented services from 1 to 2.

By observing results presented in Table 7.4, one can conclude that the CS\_CENTRIC scenario has a huge negative impact on JRRM performance, since voice and video-telephony users get radio resources for a longer period of time, doubling the CS generated traffic; producing a huge

JRRM blocking and packets delay.

Concerning JRRM blocking results, it is possible to find a match with the Erlang B model (traffic and blocking probability). For example, from the Erlang B model, if one takes 30 channels and 5% blocking one obtains about 24 Erl, and if one goes from 33 up to 48 Erl (two times more traffic), the blocking probability falls between 20 and 40 %. In this case, the JRRM Blocking simulated results range between 22 and 36 %.

In the PS\_CENTRIC scenario, results are quite different (better compared with CS\_CENTRIC), since PS oriented services, besides having less penetration in the reference scenarios, use network radio resources in a “burst” manner, occupying resources in a very short period of time, taking also advantage of high bitrate data networks capabilities.

The average number of JRRM active MTs for the CS and PS CENTRIC cases are quite similar; however, there is a slight difference in the maximum and minimum values. The PS\_CENTRIC case presents higher variations, since PS sessions duration is more unstable compared with CS ones, thus, the number of active users in a given moment can be higher or lower, compared to CS\_CENTRIC extremes.

Different services penetration trends were also simulated. One concludes that performance is reduced when the CS services penetration increases. However in, the PS\_50\_CS\_50 scenario, the JRRM blocking probability is zero, i.e., in this case an optimal balance between CS and PS occur, producing very good JRRM QoS results, both on blocking and delay.

For the number of JRRM active MTs, on average the PS\_30\_CS\_70 scenario has more active users, since CS services keep users connected during much more time, however, leading JRRM QoS to worst performance results. On the other end, and for the same reasons, the PS\_70\_CS\_30 scenario has less active users.

An MT is considered active when the service session is still active, which does not necessarily mean that the MT is fully active by continuously receiving packets. This fact explains the difference in JRRM QoS, although the number of active MTs is roughly the same.

The JRRM bitrate follows the natural trend of PS services which means that, when more PS based services are requested by users, the overall bitrates rises, thus, the JRRM bitrate for PS\_CENTRIC is higher compared with CS\_CENTRIC. Similar, for the service bouquet when PS services have more penetration, the JRRM bitrate increases, therefore, the PS\_70\_CS\_30 scenario presents higher values (better ones).

Table 7.4 – Simulation statistical results for services penetration sub-scenario.

Simulation JRRM Results /Scenarios	Blocking [%]			Delay [s]			#MTS			Bitrate [Mbps]		
	Average	Max	Min.	Average	Max	Min.	Average	Max	Min.	Average	Max	Min.
CS_CENTRIC	33	36	22	2.4	3.6	0.4	62	71	53	9.4	25	0.9
PS_CENTRIC	6	8	4	0.1	0.15	0.01	61	78	48	14	38	1.9
PS_70_CS_30	0.1	0.15	0.05	0.001	0.002	0.0003	41	59	30	20.7	51.2	2.9
PS_50_CS_50	0	0	0	0.0008	0.001	0.00001	46	66	33	10.1	34.6	0.7
PS_30_CS_70	9	11	2	0.3	0.8	0.01	49	61	38	9.4	28.8	0.5

This section presents the impact that services switching type has on JRRM performance, being clear that CS services concentration decreases networks QoS. From previous results, it is recommended that a proper balance among different services should be accomplished, although not easily generating good results. Nevertheless, this can be implemented by manipulating services billing policies that invite/guide users to generate a given services distribution when using cellular networks.

## 7.5 Other Case Studies

### 7.5.1 Building Propagation Issues

Based on Table 6.15, one can expect that increasing the building attenuation factor, BSs power control algorithms will increase BSs load, decreasing JRRM performance by load rising effect. However, in this urban scenario, power management is not the problem, compared with channels availability (as mentioned previously). Results, shows the opposite of what one can initial expect. JRRM QoS performance increases, the real reason for this being the coverage reduction, since some indoor users/services can not be served. Thus, the number of active users decreases when the building penetration factor increases, as presented in Table 7.5. These users reduction decreases the JRRM blocking and delay indicators.

From JRRM blocking results, one can see that when the buildings penetration factor is assumed to be 5 dB, BD\_BL\_L case (relatively low value compared with reality), then JRRM blocking reaches high values, presenting also high variation around the average, more users reach the network (indoor ones). However, in the medium case, BD\_BL\_M, JRRM blocking presents

acceptable values. Finally, the BD\_BL\_H case presents very low values, since the number of reachable MTs/users decreases, thus, reducing the need for radio resources. For the JRRM delay metric, previous effects are also detected.

The JRRM bitrate increases when the assumed building loss decreases, because MTs/PS services radio channels are managed with a slight less attenuation, enabling services a slight increase in their bitrate, or BSs load decrease, and therefore, allowing more MTs.

Table 7.5 – Simulation statistical results for building penetration sub-scenario.

Simulation JRRM Results /Building loss	Blocking [%]			Delay [ms]			#MTs			Bitrate [Mbps]		
	Average	Max	Min.	Average	Max	Min.	Average	Max	Min.	Average	Max	Min.
BD_BL_L	4.1	6.1	1.1	42	110	5	54	66	41	15.2	29.2	1
BD_BL_M	0.9	1.1	0.2	12	15	1	50	61	39	10.5	37.5	0.9
BD_BL_H	0.05	0.1	0	2	3	0.5	47	57	34	9.4	41.8	1.1

As a relevant conclusion related to buildings penetration attenuation and their effect on networks performance, one can conclude that when buildings penetration loss increases, less indoor areas are covered, therefore, there is less traffic demand, and the overall network QoS increases. The opposite is also valid, meaning that when buildings penetration loss decreases more traffic arrives to networks and QoS decreases. However, this is not a real benefit since operators/networks should also cover indoor users.

### 7.5.2 Train Station Results

Three different traffic loads were generated and simulated for the train station scenario by the JRRM simulator, Low Traffic (LT), Medium Traffic (MeT) and High Traffic (HT), Table 7.6. This study is based on a service set and corresponding different traffic load levels described in Section 6.1.2. As expected, the number of active users rises according to the traffic load, however, for the HT case, blocking also rises, leading to a relative reduced increase on the number of active users, namely voice and video users.

It is possible to observe that JRRM blocking and delay, as expected, increases when higher traffic loads are computed. The number of HHOs and VHOs are 0, since users' mobility is not considered in the train station scenario and no proactive optimisation algorithm is running under JRRM. Note that the number of users supporting video in HT case is less than in the MeT one,

which is an exceptional trend. This happens because these video requires higher bitrate and power compared to other applications, thus, these services are blocked more easily in a load rising network conditions.

Table 7.6 – Train Station JRRM results.

Traffic Load	JRRM parameters			Average number of users per service					
	#Act. Users	Block. [%]	Delay [ms]	Speech	WWW	Video	E-Mail	STR.	FTP
LT	48.6	0.0	0.15	29.9	3.8	2.3	3.6	5	4
MeT	62.6	2.3	0.20	37.9	4.0	4.4	4.2	8	4
HT	69.4	9.4	0.28	40.8	6.7	3.1	4.8	8	6

The JRRM Bitrate is about 250 Mbps, on average, which is acceptable considering the presence of 5 HBN BSs in the train station platform. The JRRM delay is acceptable, since it is below 1 ms, which is tolerated by any of the considered services.

### 7.5.3 Energy Efficiency

Based on the scenario framework defined in Section 6.1.3 for the EE gains evaluation, different simulations were performed. EE results are presented by Table 7.7, where each service is individually evaluated (this means that all active users are performing only a particular service), additional all services combination are evaluated.

The average RF power required in each situation is also presented, for both cases with and without the EE KPI policy awareness by the FF/CF. As one can observe, RF power decreases when the FF algorithm is guided by the EE metrics, which means that MTs are moved to a more EE efficient RAT releasing radio resources at LBNs, thus, saving power in LBN BSs.

Table 7.7 – LBN RF Power Levels and Services Traffic Load.

Services	EE [ON/OFF]	BS RF Power [W] Traffic Load Profiles		
		Low	Medium	High
Voice	OFF	1.9	2.9	2.9
	ON	1.4	1.5	1.9
WWW	OFF	4.5	4.9	5.3
	ON	2.4	3.0	5.2
FTP	OFF	3.3	3.5	5.4
	ON	2.3	2.7	5.0
ALL	OFF	6.8	6.6	6.2
	ON	3.8	5.3	6.0



The RF power gain  $G_{RF}$ , is shown in Figure 7.33. Results for EE gains at system level,  $G_{SL}$ , are presented by Figure 7.34. The corresponding system level EE gains results are computed according to the model presented in Section 4.4, for the micro-cell power model conditions presented in Table 6.7.

When traffic rises, EE gain decreases, because the number of VHOs triggered by the FF also decreases, due to less power margin offered by JRRM/RRM BSs. The only exception is voice, since it takes less radio BSs resources, thus, networks can offer EE gains even when voice traffic increases. Other effects become important, e.g., handover receiving RATs becoming more loaded, therefore, less power efficient, since more intra-cell interference becomes also significant. Another effect is in the communication distance, since MBN networks, by comparison with legacy ones, may become less power efficient for long ranges or high bitrate services become out of coverage, leading potential VHO situations to be less interesting or impossible.

By observing Figure 7.33, one concludes that only the voice service increases its EE for the Medium load case. This happens because voice has less impact on the network load (compared to data), providing a margin to increase EE even in Medium load case; however for the High case, voice users trigger VHOs, providing less EE gain. For the WWW and FTP services, differences on EE gains curves are due to their session density, duration, or burstiness intrinsic natures. When all services are simulated simultaneously, the RF EE gain decreases with the traffic load, but it can achieve relatively high gains in the Low traffic case, because in this traffic scenario VHOs have high power margin, producing EE gains (being coherent with WWW and FTP trends).

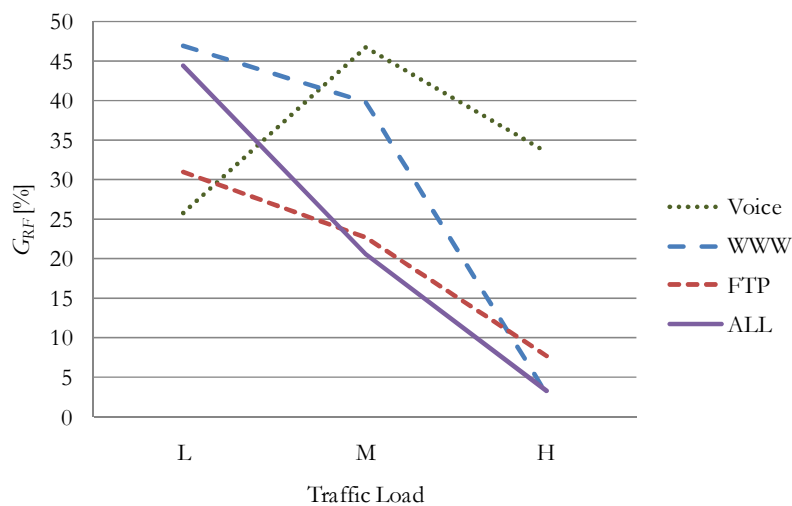


Figure 7.33 – RF EE gains for each simulated case.

As mentioned previously, the simulator provides BSs RF power, therefore, being possible to compute the EE gain at RF interface by comparing JRRM algorithms off and on. Using these

results and taking advantage of the previous BS power model, it is possible to compute EE gains at BS system level.

The results presented in Figure 7.34 follow the previous RF gains, but for some cases the non-linearity of the model can be observed ( $\Delta_p$  factor); for example, in the Low case, when all services are combined, it presents higher gains compared to the WWW single case. For the WWW and FTP services, differences on EE gains curves are due to their session density, duration, or burstiness intrinsic natures. Anyway, for the all services case, EE ranges from about 1 up to 13 %, which means that one can cut 13% in LBNs CO<sub>2</sub> emissions and network energy operation costs.

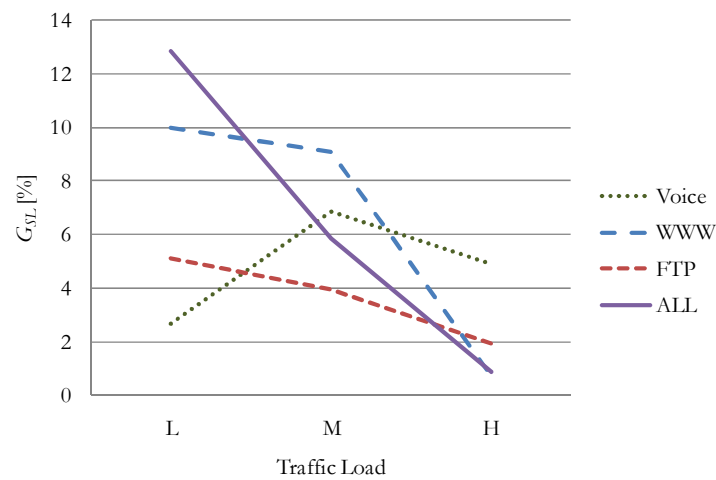


Figure 7.34 – EE at system level gains for each simulated load traffic case.

Figure 7.35 shows the total average number of active users generated by the tool for both BSs under simulation and for all previous situations. FTP and WWW are very similar, as expected. These results confirms previous effects, since it is shown that real transported services rises according to the plan defined in the scenario.

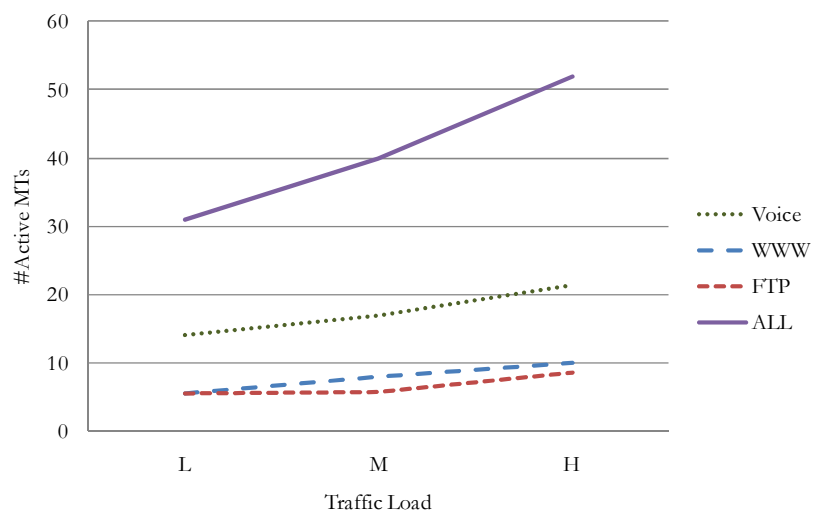


Figure 7.35 – EE at system level gains for each simulated load traffic case.

As conclusion, this section proposes VHOs to be used as one more technique in the battle for power consumption reduction in mobile cellular heterogeneous infrastructures, being applicable in a JRRM environment. The FF algorithm triggers VHOs guided by EE metrics, such as W/bps. The capability to distinguish packets overhead and users' data in a multi-RAT environment is assumed.

Results for voice, WWW, and FTP show EE gains at RF levels ranging from 5 up to 46%, being achieved for High and Low traffic cases, respectively. EE gains for micro-cell BS power consumption, at the system level, range from 1 to 13%, achieved for High and Low traffic cases, respectively. Thus, one may conclude that in very high traffic load conditions, VHOs will have a very short margin to decrease power consumptions, since BSs will be closer to congestion. Nevertheless, for Low traffic and Medium traffic loads, EE gains presents interesting values that should be considered.



# Chapter 8

## Conclusions

This chapter aims at presenting the main conclusions of this thesis, highlighting major results, and suggesting further work for the future. In Section 8.1, a brief summary of the thesis is done, and in Section 8.2 the main thesis novelties are highlighted. In Section 8.3, major results are discussed and summarised. Finally, in Section 8.4, the proposed future work is addressed.

## 8.1 Summary

This thesis is organised in 8 chapters. Chapter 1, besides a brief history of the last 3 decades in mobile communications, presents the main objectives, the novelty and contributions of this thesis, as well as the research path and strategy plan.

In Chapter 2, a basic description about local wireless and cellular systems is provided, devoted mainly to systems architectures and radio interface, relevant to this work. Also, services and applications were classified and described, to be used as a service bouquet. Finally a fundamental comparison between families of systems is discussed, useful to distinguish differences among RATs.

In Chapter 3, a JRRM and RRM survey is presented, where different RRM and JRRM algorithms are described, being very important to identify and understand relevant management mechanisms and frameworks at a heterogeneous environment. RATs grouping strategy is also defined in this chapter, highlighting major RATs differences defined in Chapter 2. Also, implementation aspects are covered, being relevant for simulation work development.

Knowing that managing radio resources in mobile and wireless heterogeneous networks is a multi-dimensional problem, Chapter 4 proposes different schemes and algorithms to deal with a huge amount of parameters, which can be seen from users' and operator's perspectives, and also contextualise by different RATs. Solutions to handle this complex problem are presented. A theoretical model, capable of capturing JRRM fundamental parameters, is also proposed, such as: users, services characterisation, users mobility profile, BSs/RATs characteristics, BSs density, cells organisation, individual RATs QoS, and a few JRRM policies impact on traffic. This theoretical model was kept simple to balance the trade-off among attractiveness, practicability, flexibility, adaptability to real scenarios and of course sensitive to heterogeneous environments and fundamental JRRM policies, by producing relevant JRRM QoS results.

In Chapter 5, previous algorithms and concepts are defined in a more pragmatic way, their implementation in the developed simulation platform tool being also described. Fundamental assessment procedures are also described.

In Chapter 6, two main points are addressed: reference scenarios definition and selected results produced by the proposed theoretical model. A set of reference scenarios is defined to provide guidelines to simulation strategies and results evaluation. Parameters variation is proposed to access their impact in the simulation platform and by the theoretical model. Relevant theoretical results are presented in this chapter.

In Chapter 7, comparable results from simulations and the theoretical model are presented, followed by a deep analysis over key output simulation results obtained by exploring all proposed reference scenarios variations. Local conclusions and explanations are taken in each analysis and simulated scenario.

Finally in the current chapter, thesis novelties, main conclusions, and future work are addressed.

## 8.2 Novelty

This thesis claims novelty in some new ideas or models that are proposed to manage heterogeneous networks. An example, is when users QoS experience or particular preferences are used or combined with operators interests or key network indicators (implemented by the proposed CF model), when computing high network layers decisions both at RRM or JRRM levels. Another innovative feature, proposed by the CF model, is the fast and simple manner that new KPIs are removed or included into management policies criteria, even the number or RAT types that are managed under the JRRM entity, all capable to be changed in real time and for any time scale. The CF computational result is offered to RRM and JRRM mechanisms and algorithms, which easily sense the network performance at BS, RRM and JRRM levels. This generates a normalised multi-RAT network management capability. Therefore, new BSs/RATs and users KPIs can be easily included in current and future networks, keeping the model updated even in the future or with new unforeseen RATs. An example of this important feature was the energy efficiency KPI, being a modern and fundamental indicator, which was included in the model after its definition, and, from the JRRM viewpoint, no changes were made, only the network management driver being changed.

Additionally, this thesis claims other innovative aspect, the RRM/JRRM theoretical model. This model is capable of including in a simple and relatively realistic manner, several relevant heterogeneous network issues that are hard to find (in literature), modelled by simple analytical approaches, which are the following: users' multi-service, generate traffic and mobility definition, multi-RATs capacity, HHOs and VHOs event rates, JRRM basic tuning policy parameters, and QoS statistics like delay and blocking both at RRM and JRRM levels. Thus, a mobile operator may use the model to estimate QoS at RRM and JRRM levels, when deploying heterogeneous networks in different multi-service traffic densities/mobility and multi RAT coverage scenarios.

Finally, this thesis also addresses RAT's energy efficiency by proposing fundamental metrics,

focussed on the way that networks radio protocol overhead and useful data are related, and can be analysed from the energy efficiency viewpoint. This matter is very important for current network operational costs, having also significant impacts in the environment (CO<sub>2</sub> emissions).

### **8.3 Major Results**

Besides the innovative perspective presented previously, this section presents other major results related to specific achievements obtained throughout this work, which are summarised in the following paragraphs.

After performing a state of the art exercise targeting management techniques over heterogeneous networks, it was identified that few parameters are being used to trigger RRM/JRRM actions, such as users' coverage or BSs loads, being computed in a unstructured manner. A set of KPIs is proposed and adapted/normalised to different RATs. After this step, a model to compute multiple KPIs, different policies in network management and stakeholders, is required. Moreover, this model should be able to support different network time-scales, not neglecting the implementation requirements, providing results to RRM/JRRM entities in due time. Thus, the CF model design was based on these requirements. One concludes that all of them were developed and tested, supporting an infinitive number of different management policies combinations. The model allows future new KPIs and RATs that can also be added or just adapted into this model. One may also conclude that different JRRM algorithms can use this CF model, an example being the FF model, implemented and studied in this thesis, which can use the CF result as a fundamental metric criterion to trigger and manage the VHO process. Results produced by the FF, guided by different CF/FF policies, show that Cost and Blocking (BO) policies generate better results in JRRM performance indicators, therefore, these policies are recommended to be used by JRRM entities in cellular heterogeneous networks.

In cellular networks studies, mobility is a key feature, hence , it is addressed and evaluated in different ways. First, a set of mobility models was studied, in Annex A, several candidates being presented; based on this study and using simplicity as criterion, the random walk was selected and implemented; furthermore users' speed is combined and modelled by the triangular distribution model. Three mobility profiles are defined: static, slow and fast; these profiles addresses mainly indoor, pedestrian and vehicular users, respectively. Furthermore, multi mobility scenarios combinations are defined, such as low, medium and high mobility cases. These mobility



variations have impact on the VHO probability in different RATs, mainly at HBNs. As final conclusion, users' mobility profiles have impact on the JRRM QoS and performance, especially on Delay, Blocking and Bitrate.

MIMO systems were also included in the study (implementing the RMG model), by assuming a relation with mobility profiles, e.g., low space antennas MTs are assumed to be used by static and pedestrian users. Thus, fast MTs (vehicles installation or laptops) present more antennas space, leading to better network delay performances, because MIMO systems offer higher bitrates to PS services, compared with SISO ones. However, network blocking increases in high mobility scenarios, because CS services generate blocking not affected by high bitrates, provided by MIMO gains. The associated MIMO systems associated to fixed and fast users also generates the expected trends, MIMO having a clear positive impact on results.

Handover is also a key mechanism studied by this thesis, being used to keep MTs connected under a given constrain. Handovers at RRM level are called horizontal, and at JRRM level are the vertical ones when another BS-RAT is selected. The CF is used to rank all BSs, when RRM/JRRM needs to decide the next BS for a given MT. This decision depends on the defined management policy criterion, which can be changed by the JRRM operator in real time. For that, the operator can change or enable/disable KPIs just by changing the KPI's weights parameter and observe the short/long term effect of these new policies into the handover mechanism. An example of this effect can be observed when applying the FF algorithm, by initially attaching MTs to a given RAT group, and then observe the FF trigger handovers to the BS/RAT that is indicated as more suitable by the CF/KPI policy.

Many JRRM algorithms, policies and strategies can be based on this CF, since all BSs and MTs are marketed by their own cost on the network. Thus, it is easy to compare and classify the most relevant nodes in the radio network, enabling the creation of candidate lists for a given criterion.

Other JRRM policies based on the CF that present better results concerning JRRM Blocking probability, are the ones based only on the Bitrate only KPI (BrO) and the one focussed on Blocking and Delay (BD); these policies are concern with BS and MTs bitrates, and JRRM blocking and delay. The BrO policy pushes MTs connections to HBNs, since they present higher bitrates, unloading MBN BSs. Note that since the BrS policy is concerned with the bitrate and the service cost, these two being conflicting in some cases, this policy leads to a bad result concerning JRRM Blocking. This is due to the fact that BrS policy has more MTs attached, on average, hence a higher JRRM Blocking and Delay results are natural. Combining all KPIs in the CF, defined as the ALL policy, JRRM results show that QoS performance presents intermediate

results; since it combines different trends. Note that JRRM Blocking and Delay are caused mainly by channels unavailability, since in urban hotspot scenarios coverage and BSs power/load are not a relevant issue.

Concerning the stakeholders, one observes that when the CF model is guided only by operators or users, the overall JRRM performance indicators changes, in some cases, in a significant manner. In general, it is recommended to use the operators CF component to achieve better JRRM overall results.

The CF oriented policies have also influence on the number of simultaneous active MTs. The BD and BO policies are the ones that present less active MTs, being followed by other management policies. The BrS policy, applied to this JRRM parameter, produces good results. Thus, one may conclude that blocking oriented policies are more MT restricted than delay or bitrate ones.

The Cost KPI has a huge impact on JRRM performance, because it is a policy that attracts MTs to HBNs in a large number (at least one order of magnitude). Differences between MUD and HUD scenarios are also visible in QoS and performance indicators.

Globally, one may conclude that JRRM policies based on this CF model can enhance the JRRM capabilities and sensitivities, or even guide JRRM algorithms to a given goal or desired trend.

The initial attachment process to a given BS/RAT can be based on a priority table, where users' services are mapped onto RATs. This is considered also as a JRRM policy, where for a given service the most suitable RAT group is indicated as the first priority, and so on and so forth. It is recommended that this table, besides matching services in a suitable way, also contributes to balance RATs load traffic, meaning that, services/RATs priorities should be distributed. Thus, this table has impact on the overall performance, if no other JRRM algorithm is active, being responsible for the load distribution factor within the JRRM domain.

This thesis also addresses MIMO systems, by implementing the so called RMG model; this provides the capacity gain that a given MIMO link has over a SISO system throughput. The MIMO gain is computed at the radio interface throughput, combining the MT mobility profile (associated to the number of antennas as previously described), and the BS-MT distance. Knowing the MIMO gain and radio interface throughput, packets transmission time can be computed and systems delay performance is naturally enhanced. One may conclude that this model is very easy to implement, and to adapt to a simulation tool where services throughput can be changed. Results associated to MIMO show the increase in QoS when MIMO option is selected, mainly in PS services. Results also demonstrate the combination of different research

areas (link and system level, usually separated and working apart), integrated into one single simulation tool, and that MIMO equipped MTs present median packet delay and blocking that can vary by a factor higher than 2.

Apart from simulation models, a new analytical model to evaluate JRRM QoS parameters was proposed and described. JRRM performance indicators, like VHO probabilities, average bitrates, and global delay, among others, were evaluated based on trend scenarios and on the model itself. The model aims to be used as an alternative to the simulation tool, thus it, needs to be simple to use and simultaneously cable to include relevant features concerning the heterogeneous networks and the JRRM framework. One concludes that results produced by the theoretical model are of the order of magnitude or similar to the ones produced by simulation, for the reference scenario. Additionally, one concludes that the theoretical model limits according to expectations and output parameters, JRRM QoS change according to the input traffic or networks capacity parameters, the geographical and users' mobility dependability is highlighted by the HHOs and VHOs results, also the relation between load and key performance parameters such as delay and blocking is notorious.

Analysing the previous presented results one concludes that HBNs have much more influence than other RATs, since they can process much more traffic in their covered area, and therefore decrease the load in other RATs; additionally, it is expected more JRRM signalling due to VHOs over HBNs clusters borders, being strongly dependent on users' mobility profiles. The model is also capable to tackle the CS/PS traffic ratio, because it is sensitive to services heterogeneity. The model results also show the impact of RATs cell sizes and coverage trend dominance in JRRM expected signalling. Finally, the JRRM tuning components defined in the theoretical model are also observed in the results. These effects are shown by the initial traffic distribution and by the VHOs associated policy when rerouting traffic among RATs. Between these two parameters, the initial traffic distributions is the one that has more impact, the major one is when JRRM policies push towards HBNs-centric cases. These policies substantially increase the JRRM performance quality indicators to much better levels (e.g., LBNs delay can drop from 600 to about 10 ms).

The latest feature introduced and studied is the energy efficiency in wireless networks. This thesis addresses the RAT efficiency by distinguishing, at radio interface, RATs transmitting data overhead. Since different RATs presents also different efficiency levels, then JRRM guided by the EE cost metric can handover MTs to the most efficient RAT, keeping under control load and QoS. Thus, this scheme releases power into the less efficient RAT, leading to energy saving gains.

The FF algorithm triggers VHOs guided by EE metrics, such as W/bps. The capability to

distinguish packets overhead and users' data in a multi-RAT environment is assumed. Results for voice, WWW, and FTP show EE gains at RF levels ranging from 5 up to 46%, being achieved for High and Low traffic cases, respectively. EE gains for micro-cell BS power consumption, range from 1 to 13%, achieved for High and Low traffic cases, respectively. Thus, one may conclude that in very high traffic load conditions, VHOs will have a very short margin to decrease power consumptions, since BSs will be closer to congestion. Nevertheless, for Low traffic and Medium traffic loads, EE gains presents interesting values that should be considered.

Concerning the scenarios set, one concludes that relevant situations were considered, for example the high traffic urban city centre, combined over layered RATs and users mobility multiple profile and multi service experience, all being possible to combined in a single challenging scenario, leading to a realistic situation used in simulations. Moreover, a similar approach is taken when using the theoretical model, meaning that a urban dense synthetic scenario was defined and used to compare some results. A special case, like the train station scenario, is used to work jointly and compare results with other colleagues in European framework research projects. A complete distinguished scenario is used, demonstrating that the proposed models can be used to study and evaluate JRRM performance for a considerable different scenario.

Concerning RATs traffic distribution percentage, one concludes that HBN Centric generates the best JRRM QoS, however, due to its low coverage nature, it does not perform so well in covering MTs. The MBNs Centric and Reference cases seems to be the most suitable ones, because they present good results in the study metrics, and they distribute services in a more balance way. It is also clear that the LBN Centric strategy should be avoided in the future in order to increase heterogeneous networks overall performance.

## **8.4 Future Work**

Naturally, this work can be continued by exploring several other topics that can be investigated in the future. Examples of these topics are proposed below.

Analysing new scenarios, e.g., motorways impact on results, by exploring MTs' high speed and evaluate handovers impact on QoS. Another approach can be changing others parameters, like the number of BSs, their inter-site distance, and installation (e.g., antennas configuration, BS and buildings height relation). Scenarios can be further analysed, like the train station, such as mobility investigation and interaction with surrounding BSs/RATs.

Other future and interesting scenarios to be explored should include emerging and future RATs, such as LTE and LTE-A.

This thesis can also be followed by introducing new and more sophisticated algorithms to manage heterogeneous networks at the JRRM level, solving problems for relatively high time scales, such as planning and self-organising techniques. These algorithms can be based on artificial intelligence techniques, which can change the network configuration based on the proposed cost function performance metrics at RRM, JRRM and users levels.

Another future and relevant research activity that can be further extended is the network energy efficiency topic. In this area, using the proposed cost function, further aspects, such as traffic variation and multi RAT cooperation, can be deeply studied in order to better understand the energy saving margin that networks have, while keeping end users under the minimum QoS. These techniques/algorithms can for example take advantage of traffic load variation by reducing BSs bandwidth or even shutting down radio carriers in a dynamic and automatic way.

New networks concepts, such as cellular network virtualisation, can be also proposed as future work, since the management of future virtual operators can be based on the same cost function framework by adding new KPIs, such as virtual operators' contract violation rate or bandwidth occupation ratio, to be used by virtual networks/hardware management entities.

Finally, for future work one can add new RATs, e.g., the IEEE 802.15 based systems (personal area networks wireless systems), bringing new challenges, like communication range, traffic aggregation into the MTs used as gateway, interference and mobility into the problem.



# **Annex A**

## **Mobility Models**

In order to simulate JRRM mechanisms, one should use models that represent MTs' mobility behaviour, hence, triggering some JRRM algorithms forced by the MT displacement, e.g., VHO. In Section A.1, different mobility models are briefly presented. In Section A.2 and Section A.3, the adopted mobility modes are described. Finally, in Section A.4, some assessment work is described.

## A.1 Models Discussion

A mobility model should attempt to mimic the movements of real MTs. Changes in speed and direction must occur, and this should happen within a reasonable number of time slots or frames. For example, one does not want MTs to travel along straight lines at constant speeds throughout the course of the entire simulation, as it is obvious that this is not a real situation. Different mobility models can be identified as follows:

- Random Walk Mobility Model [CaBD02]: a simple mobility model based on random directions and speeds;
- Random Waypoint Mobility Model [YoLN03]: the model includes pause times between changes in destination and speed;
- Random Direction Mobility Model [RoMM01]: MTs are forced to travel to the edge of the simulation area, before changing direction and speed;
- Triangular Vehicular Distribution Mobility Model [Chle95]: it considers a triangular distribution for speed;
- Highway Traffic Mobility Model [CvGa98]: this model presents two way directional highways, with multiple entrances and exits;
- Gauss-Markov Mobility Model [LiHa99], [Tole99]: a model that uses one tuning parameter to vary the degree of randomness in the mobility pattern;
- Probabilistic Version of the Random Walk Mobility Model [JaZh98], [FCSC02]: it uses a set of probabilities to determine the next position of an MT, being assumed that it moves along roughly a straight line (with occasional backtracking) for a significant period of time, before changing direction;
- City Section Mobility Model [Davi00]: it moves MTs along streets, respecting the speed limits and safe distance between them;
- Boundless Simulation Area Mobility Model [Haas97]: this model does not have a memory-less mobility pattern, establishing a relation between the current speed and direction and the next ones;
- Exponential Correlated Random Mobility Model [HGPC99]: a model that was one of the first group mobility models using a motion function to simulate MTs movement;



- Reference Point Group Mobility Model [HGPC99], [PGHC99]: it defines an individual mobility pattern for the entire group, as well as for each MT in the group;
- Nomadic Community Mobility Model [Sanc02]: it models a group of MTs moving to a new location, where each MT has an individual mobility inside the group;

JRRM being the focus of this thesis, the mobility model to be selected must comply with, at least, the following criteria:

- the model should be close to reality;
- the computational complexity and load should be relatively low;
- it should allow speed variance and users mobility profiles (slow, fast, pedestrian, vehicular).

Based on the previous selection criteria the Random Walk Mobility Model [CaBD02] was selected. However, in order to introduce a more realistic behaviour, speed is modelled by the Triangular Distribution Mobility Model [Chle95], enabling different speeds across an MT displacement.

The other mobility models were “rejected” due to their high degree of specification, environment dependence and commitment, or characteristics.

## **A.2 Random Walk Mobility Model**

The Random Walk Mobility Model [CaBD02], Figure A.1, was developed to mimic the heretic behaviour of MTs giving a memory-less mobility patterns, as each step is calculated without any information of the previous one. At regular time intervals, both angular direction (uniformly distributed in  $[0^\circ, 360^\circ]$  and speed of MTs are updated.

MTs bounce at the border of the simulation area, in such a way that they can never roam outside this area. If the MT's speed or direction is updated frequently (short time intervals or distances), then it does not wander far off from the starting position. This effect can be useful when, e.g., one is simulating a semi-static network. If one wants to simulate more dynamic networks, larger values for the time interval or distance travelled should be used.

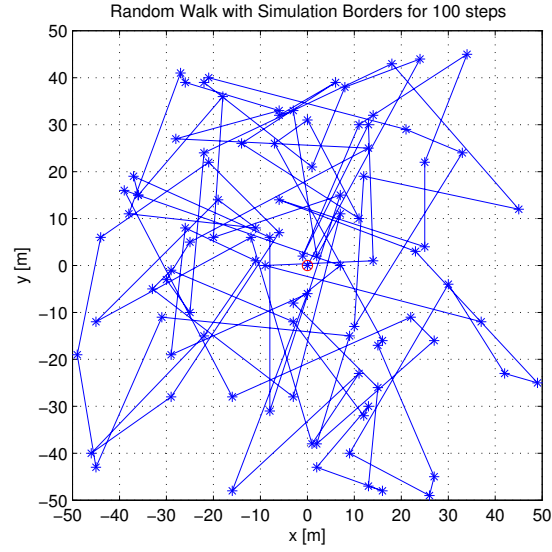


Figure A.1 - Random Walk mobility pattern (extracted from [CaBD02]).

### A.3 Triangular Distribution Mobility Model

The model presented in [Chle95] considers a triangular distribution for speed, where the density function is given by:

$$f(v) = \begin{cases} \frac{1}{\Delta^2} [v - (V_{av} - \Delta)] & , \text{if } V_{av} - \Delta \leq v \leq V_{av} \\ -\frac{1}{\Delta^2} [v - (V_{av} + \Delta)] & , \text{if } V_{av} \leq v \leq V_{av} + \Delta \\ 0 & , \text{otherwise} \end{cases} \quad (\text{A.1})$$

Five different mobility types, Table A.1, with average

$$V_{av} = \frac{V_{\max} + V_{\min}}{2} \quad (\text{A.2})$$

and deviation

$$\Delta = \frac{V_{\max} - V_{\min}}{2} \quad (\text{A.3})$$

are considered for the speed, Figure A.2.

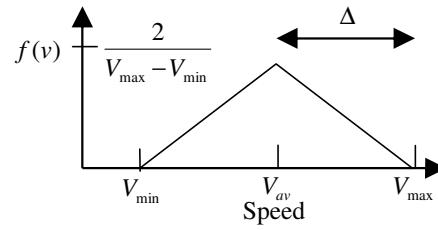


Figure A.2 - Velocity probability density function (extracted from [Chle95]).

Table A.1 - Mobility type speed characteristics (adapted from [Chle95]).

Mobility type	$V_{av}$ [m/s]	$\Delta$ [m/s]
Static	0	0
Pedestrian	1	1
Urban	10	10
Main Roads	15	15
Highways	22.5	12.5

## A.4 Model Assessment

The developed mobility model was validated. Figure A.3, presents the speed histogram resulting from simulations. The speed triangular density shape is very clear, thus, one may conclude that the speed random generator complies with the model specifications. Note that other parameters involved (direction, distance) were already validated. For the MT' direction generator, a uniform generator is used. The validation of the uniform generator is presented in Annex-C.

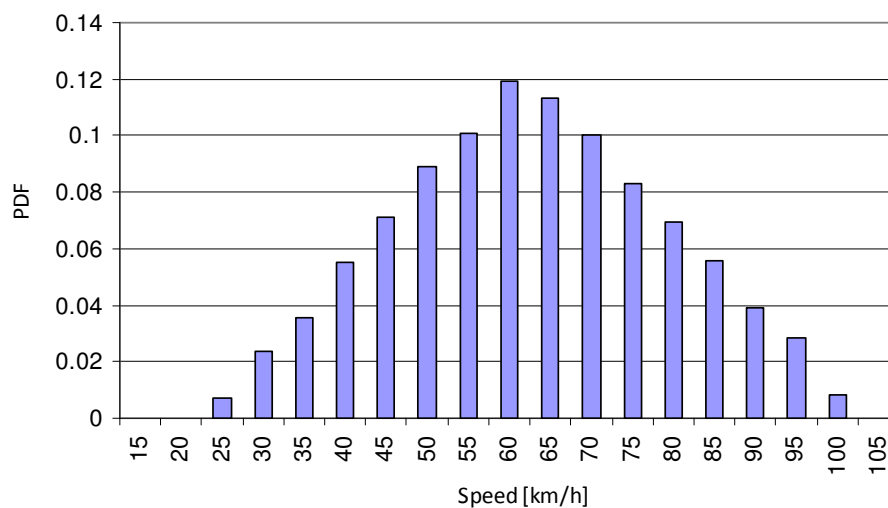


Figure A.3 - Triangular PDF of the speed (from 20 up to 100 km/h) using 10 000 samples.



# **Annex B**

## **Propagation Models**

The propagation models adopted and used in this thesis are described in this annex. These models are used for cellular and wireless local networks propagation estimation. Section B.1 describes the propagation model used to estimate radio losses in LBNs and MBNs. In Section B.2, the HBNs propagation model is also defined. In Section B.3, the used interference model is also described.

## B.1 COST 231 Walfish-Ikegami Model

For a good estimation of the received average power, one uses the well know COST 231-Walfisch-Ikegami propagation model for microcell environments [DaCo99]. This model has the following input parameters:

- $h_{BS}$ : BS height;
- $h_B$ : Building height;
- $h_{MT}$ : MT height;
- $w$ : Street width;
- $f$ : Frequency;
- $d$ : Distance between BS and MT;
- $d_B$ : Building separation;
- $\Psi$ : Street orientation angle.

The following default values are recommended:

- $b$ : [20, 50] m
- $w$ :  $b/2$
- $h_B$ :  $3 \text{ m} \times [\text{number of floors}] + \text{roof}$
- $\Psi$ :  $90^\circ$

The path loss, when in LoS, is given by:

$$L_p[\text{dB}] = 42.6 + 26 \cdot \log(d_{[\text{km}]}) + 20 \cdot \log(f_{[\text{MHz}]}) \quad (\text{B.1})$$

The path loss in the case of NLoS is given by (all path loss values are expressed in dB):

$$L_p = \begin{cases} L_0 + L_{rts} + L_{msd} & , L_{rts} + L_{msd} > 0 \\ L_0 & , L_{rts} + L_{msd} \leq 0 \end{cases} \quad (\text{B.2})$$

where:

$$L_0[\text{dB}] = 32.4 + 20 \cdot \log(d_{[\text{km}]}) + 20 \cdot \log(f_{[\text{MHz}]}) \quad (\text{B.3})$$

$$L_{rts}[\text{dB}] = -16.9 - 10 \cdot \log(w_{[\text{m}]}) + 10 \cdot \log(f_{[\text{MHz}]}) + 20 \cdot \log(\Delta h_{\text{Mobile}}) + L_{ori}[\text{dB}] \quad (\text{B.4})$$

$$\Delta h_{\text{Mobile}} = h_{MT}[\text{m}] - h_{\text{Building}}[\text{m}] \quad (\text{B.5})$$

$$L_{ori}[\text{dB}] = \begin{cases} -10 + 0.34 \cdot \Psi_{[^\circ]} & , 0^\circ \leq \Psi < 35^\circ \\ 2.5 + 0.075 \cdot (\Psi_{[^\circ]} - 35) & , 35^\circ \leq \Psi < 55^\circ \\ 4.0 + 0.114 \cdot (\Psi_{[^\circ]} - 55) & , 55^\circ \leq \Psi \leq 90^\circ \end{cases} \quad (\text{B.6})$$

$$L_{msd}[\text{dB}] = L_{bsb}[\text{dB}] + K_a[\text{dB}] + K_d \cdot \log(d_{[\text{km}]}) + K_f \cdot \log(f_{[\text{MHz}]}) - 9 \cdot \log(d_{B[\text{m}]}) \quad (\text{B.7})$$

where:

$$L_{bsb}[\text{dB}] = \begin{cases} -18 \cdot \log(1 + \Delta h_{Base}) & , h_{BS}[\text{m}] > h_B[\text{m}] \\ 0 & , h_{BS}[\text{m}] \leq h_B[\text{m}] \end{cases} \quad (\text{B.8})$$

$$\Delta h_{Base} = h_{BS}[\text{m}] - h_B[\text{m}] \quad (\text{B.9})$$

$$K_a[\text{dB}] = \begin{cases} 54 & , h_{BS} > h_B \\ 54 - 0.8 \cdot \Delta h_{Base} & , d \geq 0.5 \text{ km and } h_{BS} \leq h_B \\ 54 - 0.8 \cdot \Delta h_{Base} \cdot \frac{d_{[\text{km}]}}{0.5} & , d < 0.5 \text{ km and } h_{BS} \leq h_B \end{cases} \quad (\text{B.10})$$

$$K_d = \begin{cases} 18 & , h_{BS} > h_B \\ 18 - 15 \cdot \Delta h_{Base} / h_B & , h_{BS} \leq h_B \end{cases} \quad (\text{B.11})$$

$$K_f = \begin{cases} -4 + 0.7 \cdot \left( \frac{f_{[\text{MHz}]}}{925} - 1 \right) & \text{for medium size cities and suburban} \\ & \text{centres with moderate tree density} \\ -4 + 1.5 \cdot \left( \frac{f_{[\text{MHz}]}}{925} - 1 \right) & \text{for metropolitan centres} \end{cases} \quad (\text{B.12})$$

$L_0$  is the free space attenuation,  $L_{rs}$  is "roof-to-street diffraction and scatter loss",  $L_{ori}$  is the attenuation caused by main street orientation with respect to the direct radio path and  $L_{msd}$  is the "multi-screen diffraction loss".

Some parameters have a validity range, Table B.0.1.

Table B.0.1 - Valid parameters range.

Frequency, $f$ [MHz]	[800, 2000]
Distance NLoS, $d$ [km]	[0.02, 5]
Distance LoS, $d$ [km]	[0.02, 0.2]
BS antenna height, $h_{BS}$ [m]	[4, 50]
MT antenna height, $h_{MT}$ [m]	[1, 3]

## B.2 Double Breakpoint Model

The free space propagation model is not applicable to many practical situations. However, due to its simplicity, it is common to use it for estimations, in this case the distance exponent  $\gamma=2$  is changed to better match practical situations. A breakpoint model can be applied in relation to obstructed conditions, at which a distance exponent  $\gamma \neq 2$  is used for the first metres, and a larger  $\gamma$  for distances above the breakpoint.

For outdoor environments with an antenna height of a few metres and distance of a few hundred meters, a "double" breakpoint model gives a good characterisation of the path loss for urban environments in the presence of obstruction. The double breakpoint model [PrPr01] has a first breakpoint at 1m (reference distance for isotropic loss) and a second one at 100 m. Note that frequencies covered by this model matches with IEEE 802.11 family, thus, this model is used for HBN propagation estimation.

For 2.4 GHz, the path loss is as follows:

$$L_p(f = 2.4\text{GHz})_{[\text{dB}]} = 40 + \gamma 20 \log(d_{[\text{m}]}) \quad d \leq d_{\text{break}} \quad (\text{B.13})$$

$$L_p(f = 2.4\text{GHz})_{[\text{dB}]} = 40 + \gamma_1 20 \log(d_{\text{break}[\text{m}]}) + 10\gamma_2 \log\left(\frac{d_{[\text{m}]}}{d_{\text{break}[\text{m}]}}\right) \quad d > d_{\text{break}} \quad (\text{B.14})$$

while for the 5GHz band it is:

$$L_p(f = 5\text{GHz})_{[\text{dB}]} = 46.38 + \gamma 20 \log(d_{[\text{m}]}) \quad d \leq d_{\text{break}} \quad (\text{B.15})$$

$$L_p(f = 5\text{GHz})_{[\text{dB}]} = 46.38 + \gamma_1 20 \log(d_{\text{break}[\text{m}]}) + 10\gamma_2 \log\left(\frac{d_{[\text{m}]}}{d_{\text{break}[\text{m}]}}\right) \quad d > d_{\text{break}} \quad (\text{B.16})$$

where  $\gamma_1$  and  $\gamma_2$  are set to 2.

## B.3 Interference Models

For LBNs and MBNs, the signal to interference ratio  $\rho_I$  in DL is based on the following expression [3GPP00c]:



$$\rho_I = \frac{G_p \cdot P_s}{\alpha \cdot I_{Intra} + I_{Inter} + N_0} \quad (\text{B.17})$$

Parameter  $I_{Intra}$  includes also interference caused by traffic and common channels. In the multi-operator case,  $I_{Inter}$  may include the interference coming from the adjacent operator. The orthogonality factor  $\alpha$  takes into account the fact that in DL one does not have perfectly orthogonality due to multipath propagation; an orthogonality factor of 0 corresponds to perfectly orthogonal intra-cell users, while for the value of 1 intra-cell interference has the same effect as inter-cell one.  $G_p$  and  $P_s$  stands for receiver processing gain and received signal power, respectively.

The interference margin adopted for LBNs and MBNs link budget computation algorithm follow results presented in [EsPe06], where the interference margin was studied for different UMTS environments. According to [EsPe06], the interference margin was generated by following a uniform distribution in [0.5, 3.5] dB.



# **Annex C**

## **Traffic Source Models**

This annex presents the traffic source models implemented for each service simulated in the thesis. From Section C.1 to C.4, different services and corresponding source models are presented. In Section C.5, the radio adaptation is explained.

## C.1 Mobile Communications Voice Model

In [VaRF99], a new model for voice is described, based on measurement including not only the ON-OFF behaviour, but also the effect of the voice encoder, compression device and Air Interface (AI) characteristics in mobile communications; therefore, this model is expected to produce accurate results.

The model described in [VaRF99] and [RaMe01] uses a four-state model (Table C.1): when the source is in state  $k$  it generates packets of size  $S_k$  each 10 ms, for a burst duration of  $\tau_k$ ,  $k = 1, \dots, 4$ . In the long time average, the probabilities that a packet is of size  $S_k$  are measured to be  $P_k$ . The burst duration  $\tau_k$  is modelled as a random variable; with mean value  $m_k$ , with the Weibull Probability Density Function (PDF) as follows:

$$f(x) = \beta_k \cdot \lambda_k \cdot (x \cdot \lambda_k)^{\beta_k - 1} \cdot e^{-(x \cdot \lambda_k)^{\beta_k}} \quad (\text{C.1})$$

where  $1/\lambda_k$  is the scale parameter and  $\beta_k$  is the shape parameter, both taking the values defined in [VaRF99].

Table C.1 - Voice Source Model Parameters (partial extracted from [VaRF99]).

State $k$	Packet size $S_k$ [Bytes]	Measured Probability $P_k$	Measured mean burst duration $m_k$ [packet]	Weibull parameter $\lambda_k$	Weibull parameter $\beta_k$
1	2	0.5978	29.8	0.03	0.75
2	3	0.0723	2.5	0.45	0.80
3	10	0.0388	1.8	0.80	0.70
4	22	0.2911	38.8	0.05	0.90

After a  $k$  state, a new state is selected with probability  $Q_k$  where [RaMe01]:

$$Q_k = \frac{\frac{P_k}{m_k}}{\sum_{j=1}^4 \frac{P_j}{m_j}} \quad (\text{C.2})$$

Figure C.1 summarises the voice source model, and shows also that all voice sources have the same repetition rate, but, depending on AI settings, they might have different phase offsets.

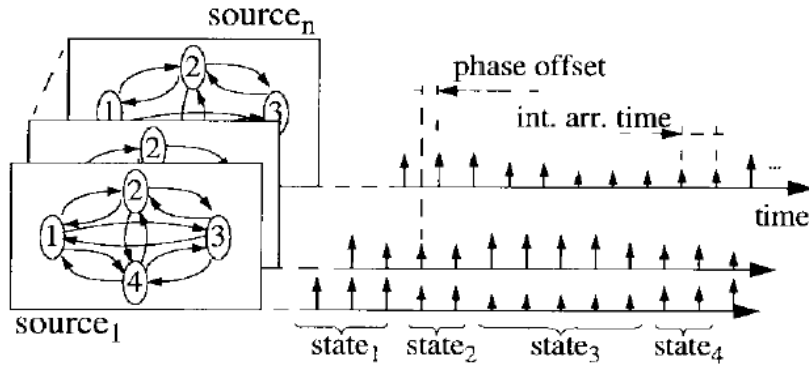


Figure C.1 - Voice Source Model (extracted from [VaRF99]).

In [VaRF99], it is also referenced that with the proper selection of  $\lambda_k$  and  $\beta_k$  parameters, this distribution function is a more accurate model of packet based encoded voice, than exponential burst length approximations.

The voice calls generation process should follow a Poisson process [Yaco93]. For the total call duration distribution, the exponential is used.

## C.2 Video traffic Model

In [ChRe98], a source model for Variable Bit Rate (VBR) video traffic model is presented. It is based on a finite-state Markov chain, being demonstrated that it accurately models a one- and two layers video. This model assumes two types of video frames generation, the *I* and *P* frames. *I* frame is driven by scene changes, depends on the video source, and as such can be considered independent of the encoder dynamics. However, in the time period characterisation by a sequence of *P* frames, one may expect that there are no significant changes in the information in successive frames. Therefore, the bitrates characterisation of successive *P* frames can be expected, to be correlated, or more generally clustered around an average value. This fact allows a technique that uses correlation between successive frame bitrates to identify both *I* and *P* frames in the data. The frame rate ranges from 24 to 30 frames per second.

The *I* frame statistic, is modelled by a Gaussian distribution function, which average and variance is adjusted as a function of measured data. *P* frames may be quite different, because they depend of video changes. In order to model these frames, a mechanism of  $k$  states was created, each state with their own average and variance.

The corresponding  $k$  state group to frame *P*, together with the only state that characterises frame

$I$ , typify the  $K+1$  Markov states that are represented by a probabilistic transitions matrix  $P$ . In this matrix, 90 % of the total of probabilistic transitions from one state to another are concentrated in  $\{P_{i-1}, P_{i0}, P_{i+1}\} \forall I=1, \dots, k$ . Considering  $i = n$  any state in the Markov chain and  $j = n-1$  state. The transmission speed of a  $i$  frame is given by [RaMe01], [ChRe98]:

$$\begin{cases} R_i(n) = m_i(1 - \alpha_i) + \alpha_i R_j(n-1) + g_i(n) & i, j = 1, \dots, k (P - \text{frames}) \\ R_{k+1}(n) = m_k + g_{k+1}(n) & (I - \text{frames}) \end{cases} \quad (\text{C.3})$$

where  $m_i$  is the estimated average value of transmission speed ( $i$  state),  $\alpha_i$  is a coefficient value that model the autoregressive process, which value is adjusted empirically (based on measurements over  $i$  state in  $P$  frame),  $g_i(n)$  is a Gaussian random variable, different for each state (average 0 and variance given by measurement data in  $i$  state).

### C.3 General WWW Traffic Model

In order to model the WWW browsing sessions, one may start by modelling a typical WWW browsing session, which consists of a sequence of packet calls [ETSI98], Figure C.2.

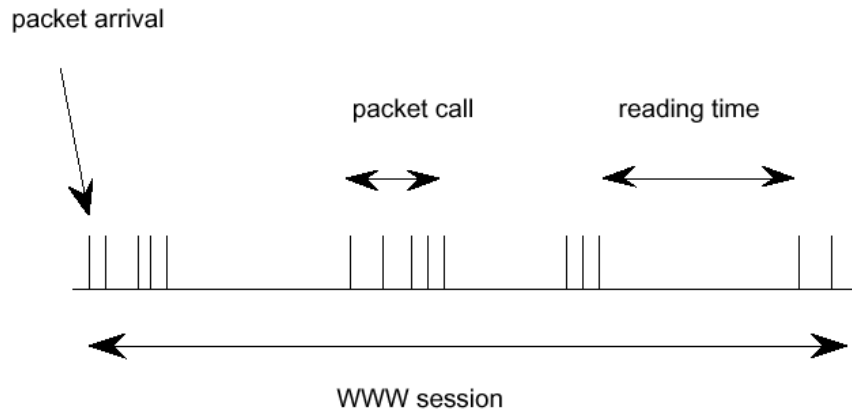


Figure C.2 - Typical WWW session (adapted from [ETSI98]).

Typically services are classified as Long Constrained Delay (LCD) services, because most of WWW based services are tolerant to delay. The session is unidirectional, i.e., in downlink. In a WWW session, a packet call corresponds to the downloading of a WWW document (e.g., web page with images, text, applets, etc.). After the document is downloaded, a reading time is also modelled. During a packet call, several packets may be generated; a packet service session contains one or several packet calls, depending on the application.

After the document is entirely retrieved to the terminal, the user is consuming a certain amount of time for studying the information, this time interval being called the reading time. It is also possible that the session contains only one packet call, in fact this is the case for a FTP. Hence, the following parameters must be modelled in order to catch the typical behaviour described in Figure C.2. Note that the number of events during the session models the session length implicitly.

The geometrical distribution is used (discrete representation of the exponential distribution), since simulations use discrete time scale.

- Session arrival process: The arrival of session set-ups to the network is modelled as a Poisson process. For each service, there is a separate process. It is important to note that this process for each service only generates the time instants when service calls begin, and it has nothing to do with call termination.
- The number of packet call requests per session,  $N_{pc}$ : This is a geometrically distributed random variable with a mean  $\mu_{N_{pc}}$ .
- The reading time between two consecutive packet call requests in a session,  $D_{pc}$ : This is a geometrically distributed random variable with a mean  $\mu_{D_{pc}}$ . Note that the reading time starts when the last packet of the packet call is completely received by the user. The reading time ends when the user makes a request for the next packet call.
- The number of packets in a packet call,  $N_d$ : The traffic model should be able to catch the various characteristic features possible in the future UMTS traffic. For this reason, different statistical distributions can be used to generate the number of packets. For example,  $N_d$  can be a geometrically distributed random variable with a mean  $\mu_{N_d}$ . It must be possible to select the statistical distributions that describes best the traffic case under study. An extreme case would be that the packet call contains a single large packet.
- The time interval between two consecutive packets inside a packet call,  $D_d$ : This is a geometrically distributed random variable with a mean  $\mu_{D_d}$ . Naturally, if there is only one packet in a packet call, this is not needed.
- Packet size,  $S_d$ : The packet size distribution model is based on Pareto distribution that suits best for the traffic case under study; Pareto distribution with cut-off is used.

## C.4 Specific WWW Traffic Models

A user who runs NRT applications (e.g., HTTP, Napster, e-mail, etc.), follows a characteristic usage pattern [KLLo01]. A single user can run different applications that may be concurrently active, e.g., WWW browsing while downloading Napster music files.

Each application is completely described by its statistical properties. These statistical properties comprise of an alternating process of ON- and OFF-periods with some application specific length or data volume distribution, respectively. Moreover, within each ON-period the packet arrival process is completely captured by the packet interarrival-times and the corresponding packet sizes. As a consequence of adopting statistics through general distributions, this traffic model is not analytically tractable.

The single user traffic model characterises the traffic that an individual user generates [KLLo01]. In PS and CS networks, one has to distinguish between RT users and non NRT users. Considering just NRT users, the single user traffic model is employed on three different levels:

- Session-level: it describes the dial-in behaviour of the individual users, characterised by the session interarrival-time distribution and the session data-volume distribution.
- Connection-level: it describes for each individual application the corresponding distribution of connection interarrival-times and connection data volume, respectively.
- Packet-level: it characterises the packet interarrival-time distribution and the packet size distribution within the application specific connections.

Tables C.2 to C.6 show results presented in [KLLo01], where main WWW services are characterised individually at different bitrates.

Table C.2 – Distribution of Session arrival interarrival-times.

Distribution and parameters		Comments
Lognormal ( $\mu; \sigma^2$ )	0.6061; 7.5330	Similar to ISP [KLLo01]

Table C.3 - Distribution of Session Volume assumed in [KLLo01].

Distribution	64 kbps	144 kbps	384 kbps
UMTS users	50%	30%	20%
Lognormal( $\mu; \sigma^2$ )	5.1613;13.8210	5.2943;14.1839	5.4197;14.4979



Table C.4 - Parameters of packet interarrival-times.

Services	Distribution	64 kbps	144 kbps	384 kbps
HTTP	Lognormal( $\mu; \sigma^2$ )	-.7597;3.5448	-.2588;3.8720	-3.9599;4.3342
e-mail	Lognormal( $\mu; \sigma^2$ )	-.3678;2.4220	-3.7152;2.6410	-4.1058;2.8902
Napster	Lognormal( $\mu; \sigma^2$ )	-.1757;1.6076	-3.2357;1.3796	-3.2649;1.1853
FTP	Lognormal( $\mu; \sigma^2$ )	-.0691;3.8055	-3.2656;3.9347	-3.4160;4.0337
UDP	Lognormal( $\mu; \sigma^2$ )	-.9629;4.6606	-3.3120;4.7290	-3.6787;4.8532

Table C.5 - Statistical properties at connection level.

Services		Distribution	64 kbps	144 kbps	384 kbps
HTTP	Interarrival time	Lognormal( $\mu; \sigma^2$ )	-0.3278;4.4807	-0.6907;4.8483	-1.1997;5.3259
	Volume	Lognormal( $\mu; \sigma^2$ )	2.8651;12.6098	2.8072;13.0871	2.7888;13.4888
e-mail	Interarrival time	Pareto( $x_m; \alpha_p$ )	14.4360;2.1345	15.1334;2.1254	16.0229;2.1223
	Volume	Lognormal( $\mu; \sigma^2$ )	3.2677;13.2369	3.2799;13.5579	3.3084;13.8518
Napster	Interarrival time	Not available			
	Volume	Lognormal( $\mu; \sigma^2$ )	5.8875;14.3687	5.9213;14.4278	6.0113;14.5865
FTP	Interarrival time	Not available			
	Volume	Lognormal( $\mu; \sigma^2$ )	3.3433;13.9698	3.3020;14.7826	3.3435;15.3229

Table C.6 - Fractions of different packet sizes in overall traffic.

Services	Fractions of packets in overall traffic [%]			
	Packet size 40 byte	Packet size 576 byte	Packet size 1500 byte	Other packet sizes
HTTP	46.77	27.96	8,10	17.17
Napster	34.98	45.54	4.18	15.30
e-mail	38.25	25.98	9.51	26.26
FTP	40.43	18,08	9.33	32.16
UDP	Lognormal( $\mu; \sigma^2$ )		(1.8821; 5.4139)	

## C.5 Radio Interface Adaptation

The simulator works at the radio interface level, not performing any signal processing (channel coding, rate matching, interleaving, frame multiplexing, etc.) [3GPP00b]. This processing has a huge impact on radio interface bitrate, increasing this parameter. Thus, for each service, the important rate to be specified is the service bitrate at the radio interface after all signal processing procedures, and not simply after compression. This adaptation process includes the channel coding and channel matching adaptation, leading in most cases to a standard bitrate result.

However in MBNs, it is allowed a dynamic bitrate adaptation according to signal to interference ratio.

# **Annex D**

## **Models Validation**

The present annex presents some validation processes taken for some models used in the thesis. In Section D.1, traffic source models assessment is presented. In Section D.2, the CF validation is shown. Finally, in Section D.3, the MIMO implementation model is also validated.

## D.1 Traffic Source Models Validation

Examples of traffic source models validation can be found in this section, results of several samples of the inverted exponential CDF function, presenting some error levels compared with the theoretical one. These errors tend to zero if the number of samples increases or/and if the histogram bar interval decreases, leading to a more linear approximation.

The following figures (D.1 to D.8) present the services traffic source models behaviour. These results were already extracted from the traffic vectors (RRM traffic inputs) used to generate the voice service. One may conclude that services duration, session initial time histograms and packet oriented arrival time follow the expected behaviour describe in traffic source models.

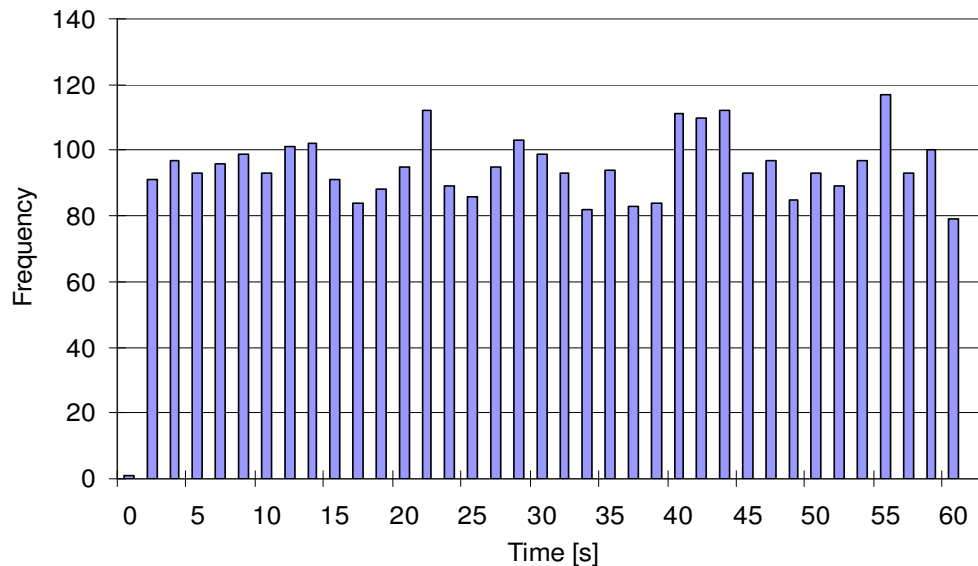


Figure D.1 - Voice calls initial time histogram.

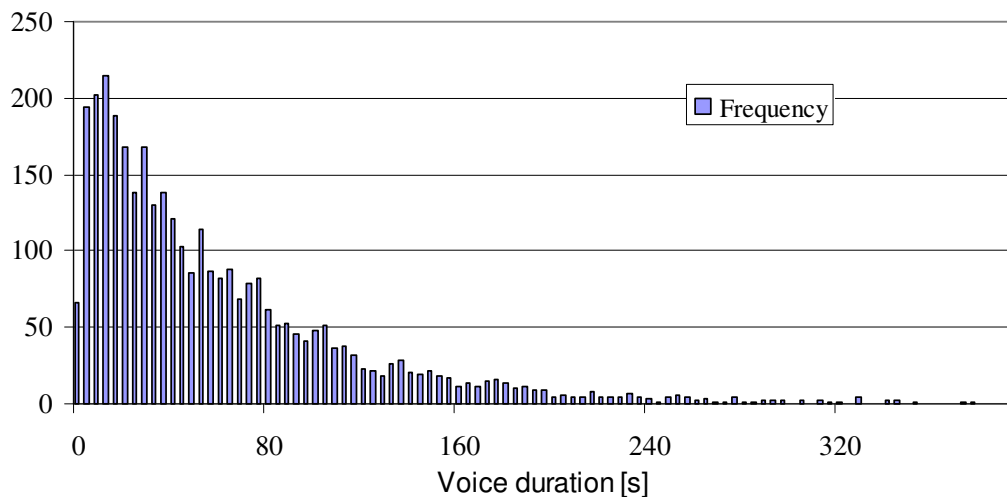


Figure D.2 - Voice calls duration time histogram.

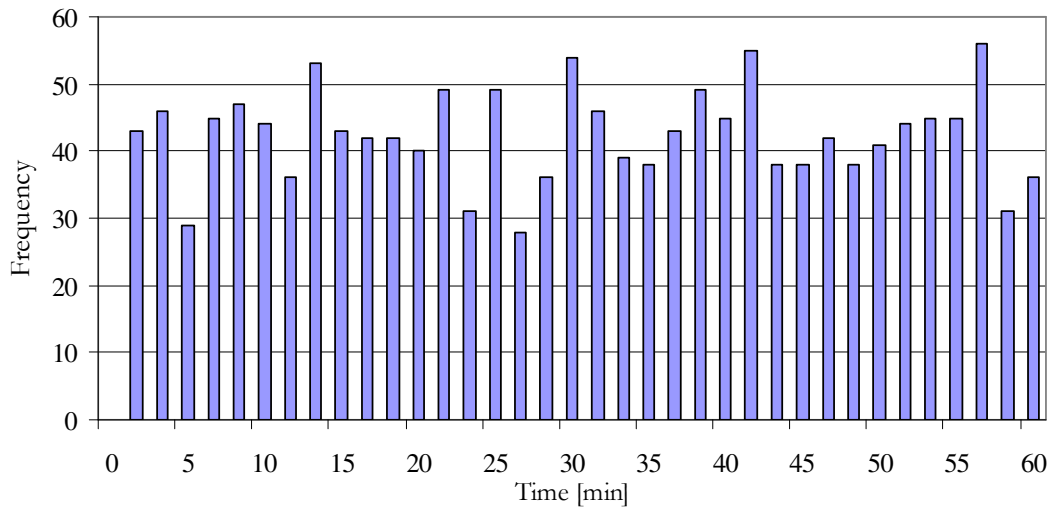


Figure D.3 – Video-telephony calls initial time histogram.

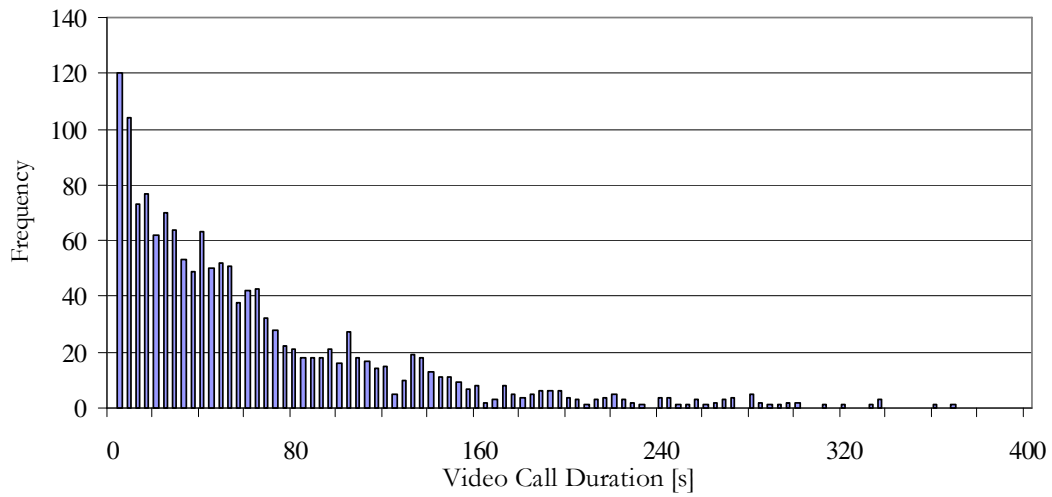


Figure D.4 - Video-telephony calls duration time histogram.

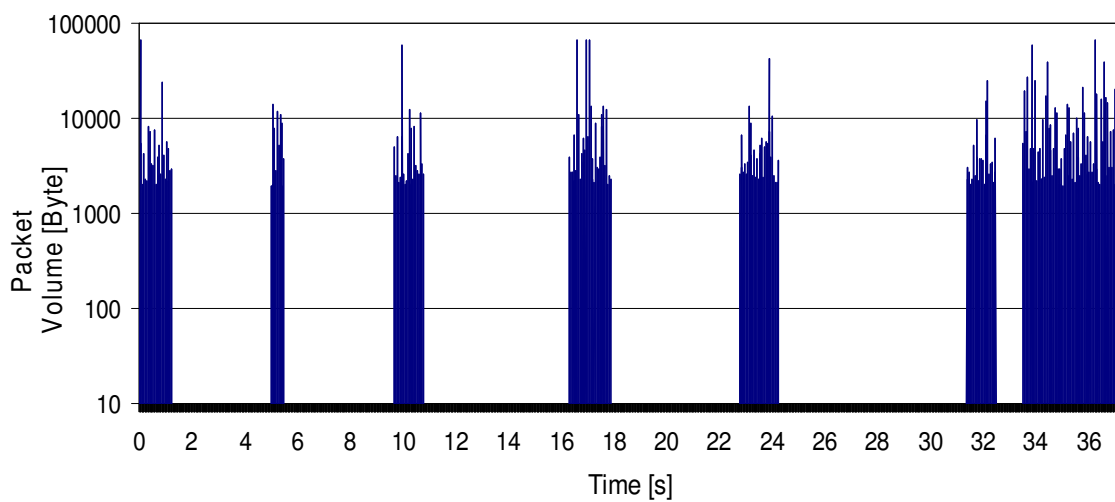


Figure D.5 - Example of a WWW Session.

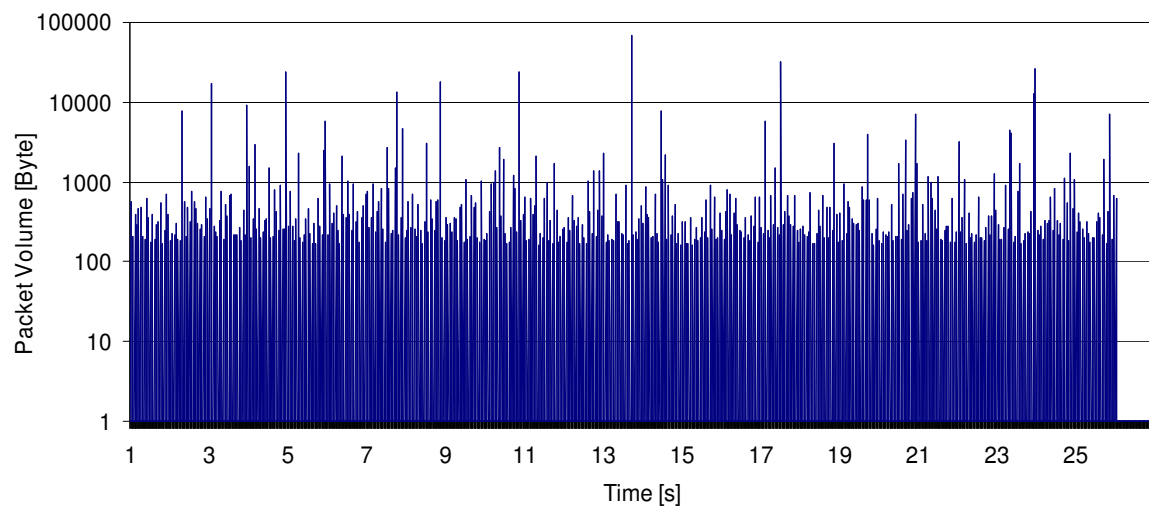


Figure D.6 - Example of a Streaming session.

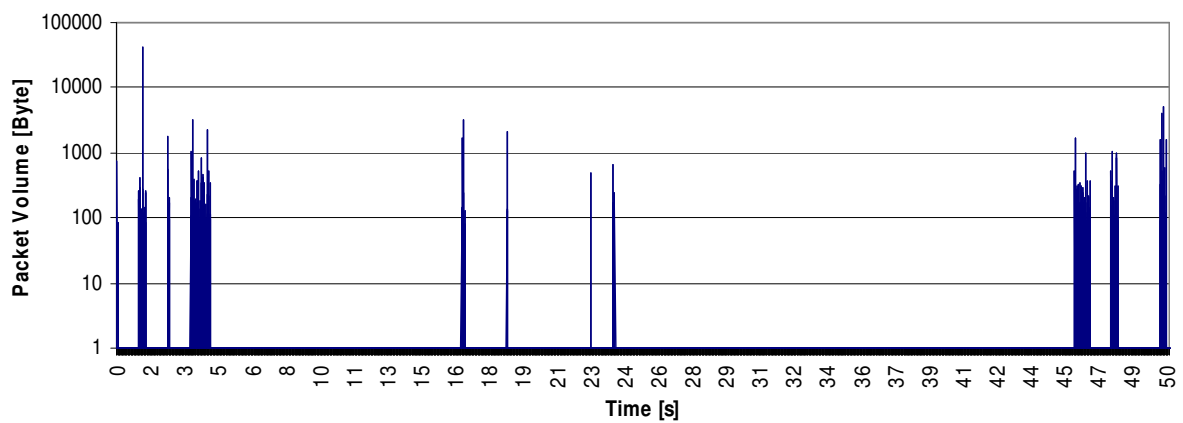


Figure D.7 - Example of a FTP session in time.

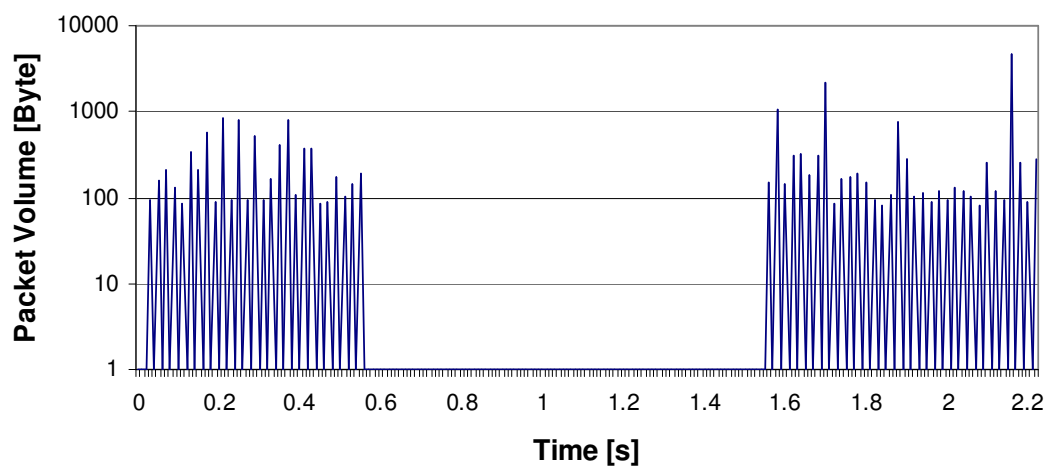


Figure D.8 - Example packets volume for an e-mail session in time.

## D.2 Cost Function Validation

A final example of the simulator assessment process is presented in Figure D.9, where a high level system parameter behaviour can be used to analyse the simulator overall stability and convergence. This parameter represents the network total cost per second, which is based on the complete CF formula. This parameter virtually depends on all relevant parameters under simulation, therefore, being very useful to detect any divergent parameter. Other important observed characteristic is (as expected) the initial instability, natural to all dynamic system and time based simulators, which in this case is less than 12 min. After this period, the convergence is obtained, since it depends on other average and stable indicators, one may conclude that also these sub indicators-parameters are stable and under valid values.

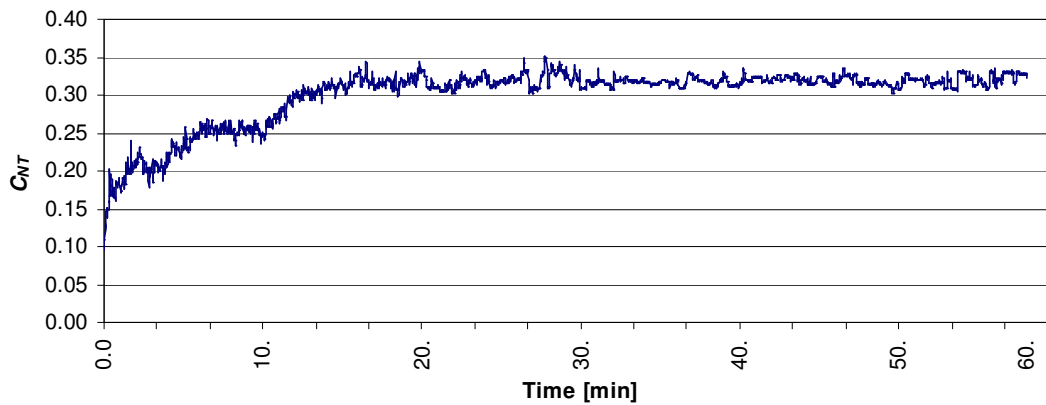


Figure D.9 – Example of simulation convergence (e.g. network total cost).

## D.3 MIMO Relative Gain Validation

The relative MIMO gain implementation validation procedure in the JRRM Simulator was performed using the reverse engineering procedure, which means that simulated results were compared with the “theoretical” or expected ones. The results for the MIMO 4×4 are presented in Figure D.10, here the matching is very clear. The same process was adopted in the 4×2 MIMO case, Figure D.11, in this case the differences seems high. However, if one looks carefully at the error scale/differences, one can conclude that the absolute error is negligible.

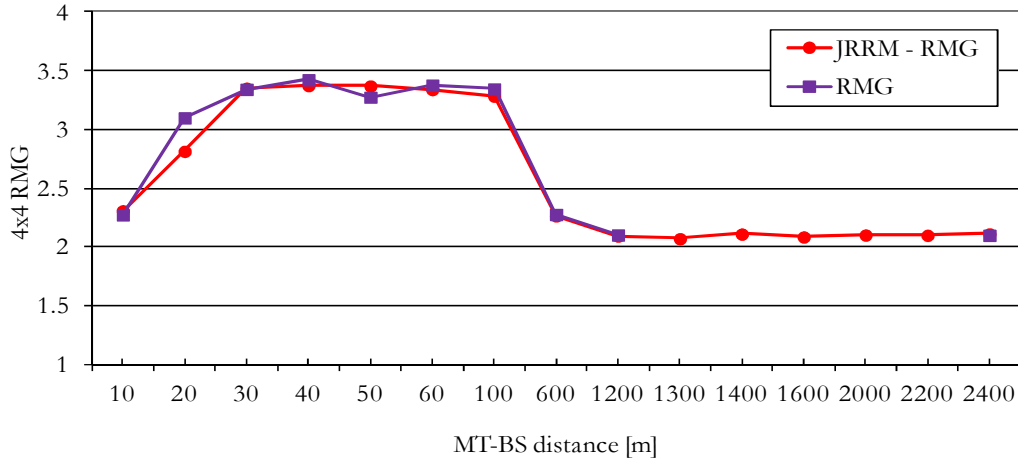


Figure D.10 - Comparison between the “theoretical” RMG and the JRRM simulator for 4×4 antennas.

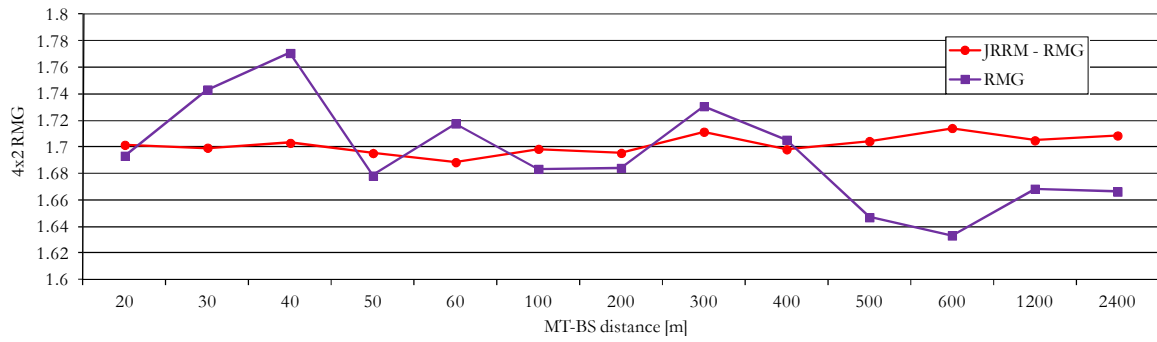


Figure D.11 - Comparison between the “theoretical” RMG and the JRRM simulator for 4×2 antennas.

All simulations results were obtained for a 1 hour observation of the network, after achieving a convergence status, i.e., the first initial 10 minutes of simulation are discarded, which is required to skip the natural initial ripple of time base simulations.



# **Annex E**

## **Fittingness Factor**

### **Results**

This annex presents further results generated by the FF algorithm.

The following figures (from Figure E.1 to Figure E.6) present in the time domain the number of active MTs per each simulated service as a function of a given KPIs used by the CF and processed by the FF algorithm. All results were based on the reference scenario, therefore, all of them reflect the service set distribution percentage.

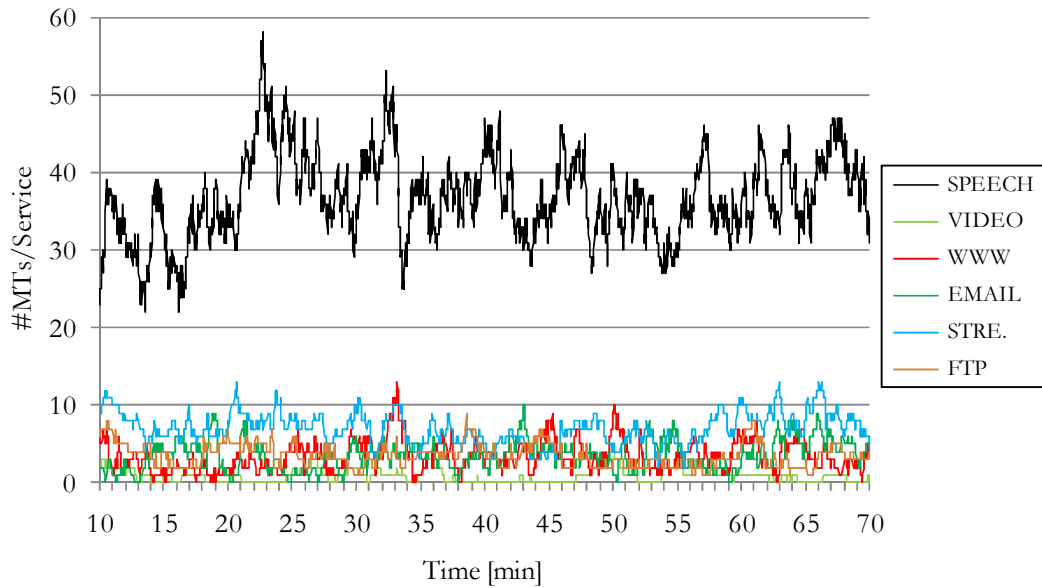


Figure E.1 – The number of active MTs per service for FF CF-Channels (viewed in time).

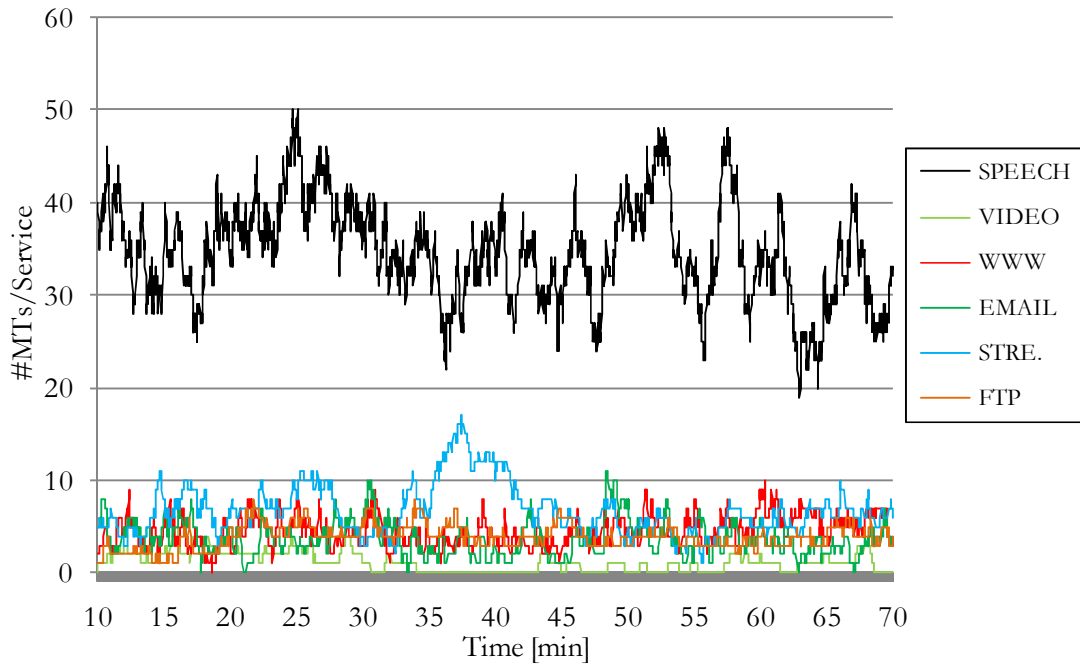


Figure E.2 – The number of active MTs per service for FF CF-Cost (viewed in time).

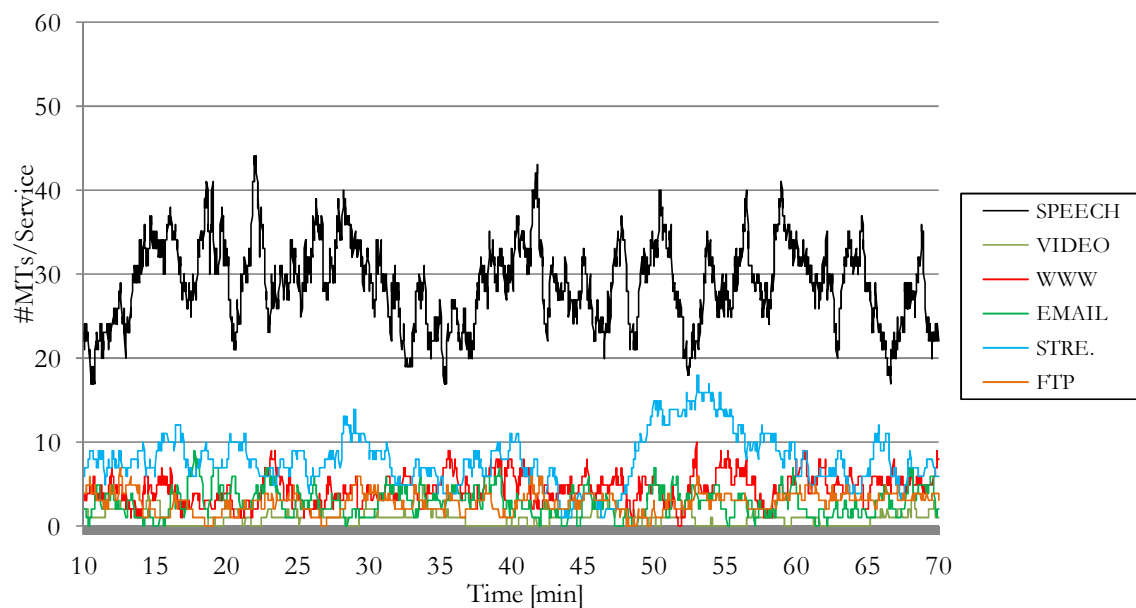


Figure E.3 – The number of active MTs per service for FF CF-Blocking (viewed in time).

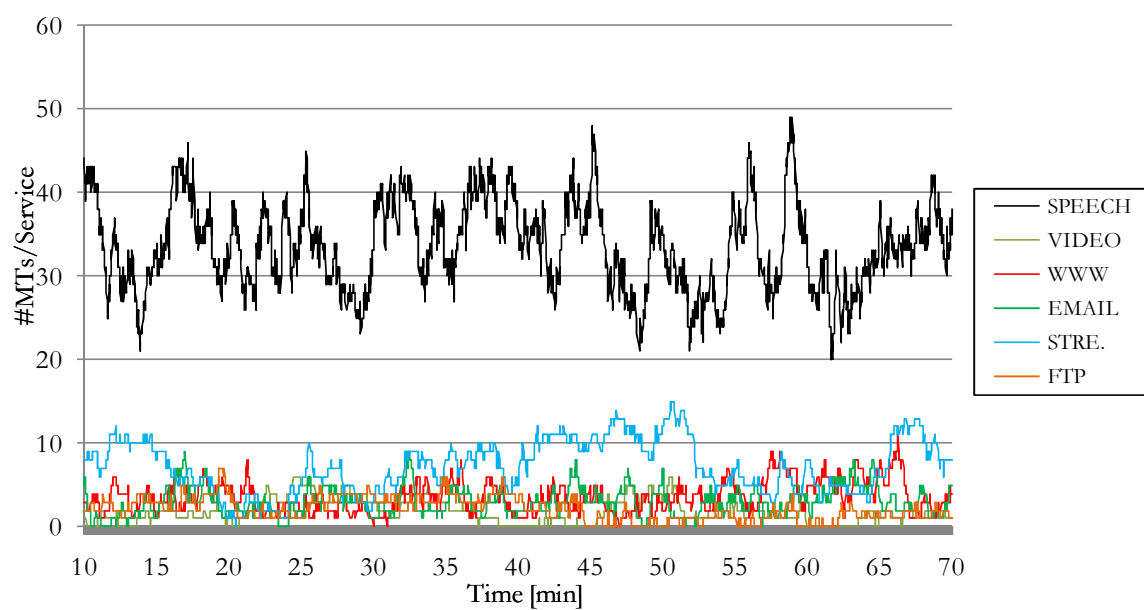


Figure E.4 – The number of active MTs per service for FF CF-Delay (viewed in time).

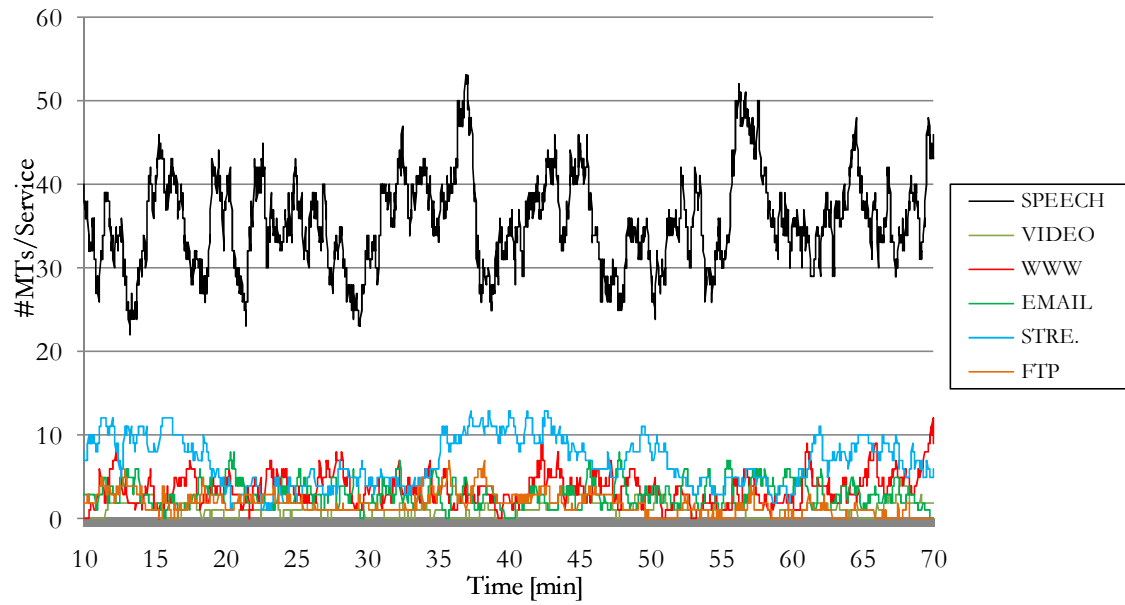


Figure E.5 – The number of active MTs per service for FF CF-Load (viewed in time).

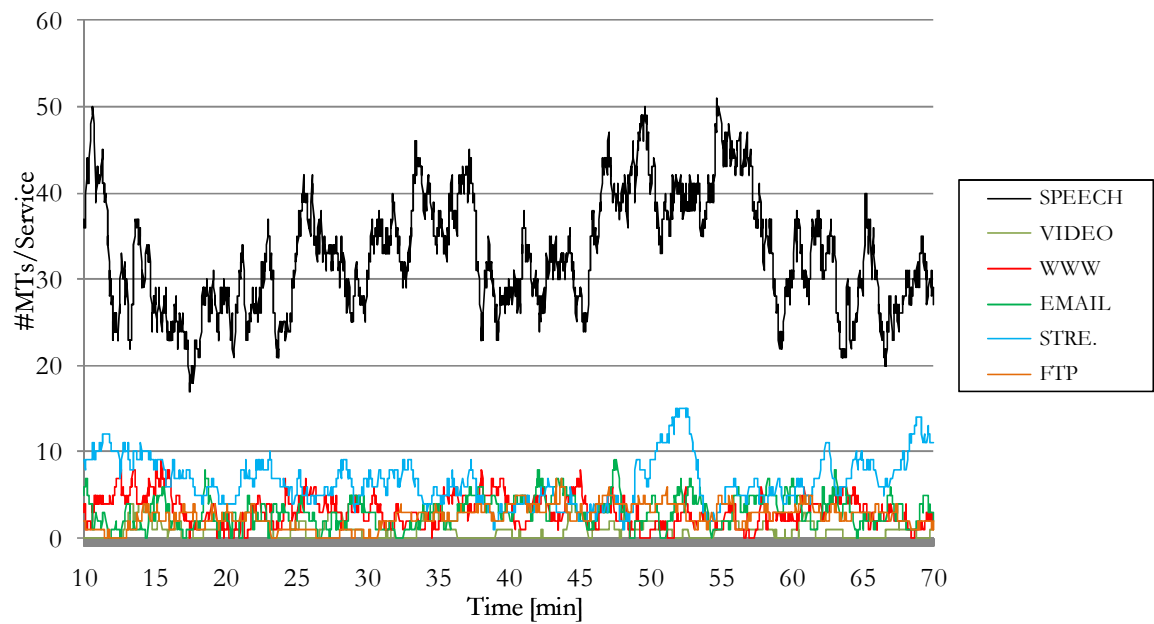


Figure E.6 – The number of active MTs per service without the FF (viewed in time).

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