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INSTITUTO SUPERIOR TÉCNICO

Optimisation of Base Station Location in UMTS-FDD for Realistic Traffic Distributions

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Dissertação para obtenção do Grau de Mestre

em Engenharia Electrotécnica e de Computadores

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Março 2006

To all my friends…

Acknowledgements

First of all, I would like to thank Prof. Luis Correia for the zealous help and clear-sighted supervision of this work, giving a great contribution for its development. The weekly talk I had with him, discussing ideas and sharing with me his wide experience in mobile communications, gave me a constant motivation to put all my efforts in this project. He also introduced me to an interesting group of people that joins frequently to discuss their work in the wireless communications area. I have to thank them for having treated me like one of their own, giving me once more the opportunity to share experiences and learn much more about other areas besides my own work.

To Vodafone, especially to Carlos Caseiro, Pedro Lourenço and Marco Serrazina, for giving all the support to this thesis. They have given their business vision about the problem I had in hands, and have shared some useful information, which helped me in the algorithm conception and development.

To *Instituto de Telecomunicações*, I would like to add recognition for providing me the working space and all the conditions for the accomplishment of this work. There I met amazing people that I can consider today my friends and that have helped me, within their possibilities, whenever I needed. Thus, I have to give a special thanks to Daniel Sebastião, Gonçalo Carpinteiro, Carla Oliveira, Lúcio Ferreira and Martijn Kuipers, among others.

At last, but not the least, I am very grateful to all my family and my friends for having always shown me their patience and understanding; moreover, they have encouraged me to do my best and never give up.

Thank you all: without you this work would not be completed.

Abstract

The goal of this work was to develop an algorithm that places new base stations in a UMTS FDD network in order to improve its coverage and performance, adding them in an automatic and non-uniform way, considering a non-uniform multi-service traffic distribution in the service area. For that, the algorithm uses a different heuristic for different types of uncovered surfaces.

The algorithm was implemented over an already existing simulator, which was improved in this thesis. The simulator runs mainly over *MapInfo*, taking advantage of Geographic Information System tools. The other part of the software is developed in *C++* in order to decrease the runtime of the simulations. The entire simulator is composed of 4 blocks: the User Generation, the Network Creation, the Performance Analysis and the Base Station Placement.

For the simulations, 8 services were considered: speech-telephony, video-telephony, streaming multimedia, e-mail, location based service, MMS, file download and web browsing. Simulations were made for Lisbon with and without an initial network, a co-located GSM network being considered for the latter. In both cases, parameters like the reference service bearer and the user scenario were varied.

One can see that the algorithm places new base stations in areas with more traffic, decreasing the uncovered area and the non-served traffic: for the 128 kbps vehicular scenario, 15 base stations are placed over the initial network, each new sector processing 210 MB/h that were not covered yet by the initial network, when the initial sectors cover on average 543 MB/h.

The developed base station placement algorithm is more efficient that a previous one, since each new sector covers more traffic that was not covered yet by the initial network (210 MB/h instead of 92 MB/h for the 128 kbps – vehicular scenario).

Keywords

UMTS FDD, Base Station Placement, Multi-service Traffic, Optimisation, Simulation.

Resumo

O objectivo desta tese consistiu no desenvolvimento de um algoritmo para colocação de estações de base numa rede UMTS FDD, de forma a melhorar a sua cobertura e desempenho, colocando-as de uma forma automática e não uniforme, e considerando uma distribuição não uniforme de tráfego multi-serviço. Para tal, o algoritmo utiliza diferentes heurísticas para diferentes tipos de superfícies não cobertas.

O algoritmo foi implementado sobre um simulador já existente. O simulador funciona, de uma maneira geral, em *MapInfo*, aproveitando as ferramentas existentes nos Sistemas de Informação Geográfica. A outra parte do programa é desenvolvido em *C++*, por forma a reduzir a duração das simulações. O simulador é composto por 4 blocos: a geração dos utilizadores, a criação da rede, a análise do desempenho, e a colocação de estações de base.

Nas simulações, foram considerados 8 serviços: voz, vídeo telefonia, *multimedia streaming*, *e-mail*, serviços de localização, MMS, descarregamento de ficheiros, e navegação na Internet. Simulações foram feitas para a cidade de Lisboa, com e sem uma rede inicial, considerando para esta última uma rede co-localizada com a rede GSM. Para ambos os casos, variaram-se parâmetros como os débito dos serviços e os cenários de utilização.

Verifica-se que o algoritmo coloca estações de base em zonas com mais tráfego, diminuindo a área não coberta e o tráfego não processado: para o caso 128 kbps veicular, o algoritmo coloca 15 estações de base na rede inicial, e cada novo sector cobre 210 MB/h de tráfego que não estava previamente coberto, quando, na rede inicial, cada sector cobre em média 543 MB/h.

O algoritmo de colocação de estações de base desenvolvido é mais eficiente que um já existente, visto que cada sector introduzido cobre mais tráfego que não estava inicialmente coberto (210 MB/h em vez dos 92 MB/h para o caso 128 kbps – veicular).

Palavras-chave

UMTS FDD, Colocação de Estações de Base, Tráfego Multiserviço, Optimização, Simulação.

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List of Acronyms

3GPP	3rd Generation Partnership Project
BHCA	Busy Hour Call Attempt
BS	Base Station
CBD	Central Business District
CN	Core Network
CS	Circuit Switching
DL	Downlink
DRET	Delayed Relative Effective Throughput
EIRP	Equivalent Isotropic Radiated Power
E-UMTS	Enhanced UMTS
FDD	Frequency Division Duplex
GGSN	Gateway GPRS Support Node
GIS	Geographic Information System
GMSC	Gateway MSC
GPRS	General Packet Radio Service
GRS-1980	Geodetic Reference System
GSM	Global System for Mobile Communications
HHO	Hard Handover
HIMM	High Interactive Multimedia
HLR	Home Location Register
IS	Interim Standard
LoS	Line of Sight
LS	Large Surfaces
LSCP	Location Set Covering Problem
ME	Mobile Equipment
MMS	Multimedia Messaging Service
MT	Mobile Terminal
MS	Medium Surfaces
MSC	Mobile Services Switching Centre

OVSF	Orthogonal Variable Spreading Factor
PDC	Personal Digital Cellular
PS	Packet Switching
QoS	Quality of Service
RET	Relative Effective Throughput
RNC	Radio Network Controller
RNS	Radio Network Sub-system
RRM	Radio Resource Management
SF	Spreading factor
SGSN	Serving GPRS Support Node
SHO	Soft Handover
SMS	Short Message Service
SNR	Signal-to-Noise Ratio
SOHO	Small Office/Home Office
SS	Small Surfaces
SSHO	Softer Handover
TDD	Time Division Duplex
TDMA	Time Division Multiple Access
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunication System
USIM	UMTS Subscriber Identity Module
UTM	Universal Transverse Mercator
UTRAN	UMTS Terrestrial Radio Access Network
VLR	Visitor Location Register
VoIP	Voice over IP
VSS	Very Small Surfaces
WCDMA	Wideband Code Division Multiple Access
WWW	World Wide Web

List of Symbols

α_j	Orthogonality factor for user j.
ε	BS efficiency.
η	Load factor.
$\overline{\eta}_{bearer}^{user}$	Average DL load factor for a user with a service bearer.
η_{DL}	Global load factor of a cell in DL.
η_{DL}^{equiv}	DL equivalent load factor.
$\eta_{\max}$	Maximum load factor.
η_{UL}	Global load factor of a cell in UL.
$\eta_{\sec}^{equiv}$	DL equivalent load factor inside a sector.
$\overline{\eta}_{serv}^{user}$	Average load factor per user and per service.
λ_{BHCA}	Average number of busy hour call attempts.
$\rho(x, y)$	Function representing the mass distribution.
$\overline{\tau}$	Mean service time of a call.
$\overline{\tau}_{delay}$	Average packet delay.
υ	Activity factor.
υ_j	Activity factor for user j.
ξ	Uncovered equivalent DL load factor traffic density.
ζ	DL load factor traffic density threshold normalised to the maximum DL load factor.
$\gamma_{hotspot}$	Hot spot threshold normalised to the maximum DL load factor.
Δf	Signal bandwidth.
Ψ	Street orientation angle.
A	Area under study.
A_{BS}^{n}	Area covered by n sectors.
$A_{BS}^{n}\%$	Area covered by n sectors in percentage.

A_{cell}	Area covered by a BS that has 3 sectors, considering the nominal coverage area;
A_{cov}	Area covered by the network.
A_{unc}	Uncovered area.
A_{unc}^{surf}	Area of the uncovered surface.
A_{sec}	Sector coverage area.
$A_{\mathrm{sec}}^{\mathrm{sup}}$	Superposition area of a sector.
C_{unc}^{BH}	Uncovered traffic in terms of information transmitted in the busy hour.
C_{serv}^{BH}	Information transmitted in the busy hour per service.
C_m^x	x coordinate of mass centre.
C_m^y	y coordinate of mass centre.
D	Effective coverage distance of a BS.
d	Distance between the MT and the BS.
d_{ij}	Shorter distance between the area i and the potential location site j.
$\dim_{pixel}$	Pixel width.
$\dim_x$	Horizontal width of the grid in number of pixels.
E_b	Bit energy.
F	Noise factor.
f	Frequency.
G	Antenna gain.
$G_{a\,div}$	Antenna gain with diversity.
G_t	Transmission antenna gain.
G_{div}	Diversity gain.
G_P	Processing gain.
G_r	Receiving antenna gain.
G_{SHO}	Soft/softer handover gain.
H_B	Buildings height.
h_b	BS height.
h_m	MT height.

i	Inter- to intra-cells interference ratio.
L_0	Attenuation in free space.
L_{cu}	Cable/user losses.
L_F	Indoor penetration attenuation.
L_P	Propagation attenuation.
$\overline{L}_{Pj}$	Average propagation attenuation for user j.
$L_{P\max}$	Maximum value for the propagation attenuation for which the user has 50 % coverage.
L_{Ptotal}	Propagation attenuation with the margins for fading and soft/softer handover.
L_{tm}	Attenuation from diffraction and reflections of the signal.
L_{tt}	Attenuation due to the existence of multi-knife edges.
M_i	Interference margin.
M_{FF}	Fast fading margin.
M_{SF}	Slow fading margin.
N	Noise power.
N_0	Noise power spectral density.
n_{pixel}	Number of the pixel that the user is associated to.
N_b	Number of blocked calls.
N_{BHCA}^{user}	Average number of calls attempts performed by a single user in the busy hour.
N_{BS}	Total number of possible BSs in the area under study.
N_C	Number of combinations.
N_{call}^{day}	Number of calls per day and per user.
N_{ch}	Number of occupied channels.
N_{ch}^{av}	Number of available channels.
N_{CS}	Total number of CS calls.
N_d	Number of delayed calls.
N_i	Set of BSs that cover area i.
N_j^{codes}	Number of SF codes occupied by user j.

N_{PS}	Total number of PS calls.
N_{unc}	Number of uncovered users in the network.
$N_{user}^{network}$	Number of users in the network.
N_{users}	Number of users in the cell.
$\overline{N}_{users}^{active}$	Average number of active users.
$N_{user128}$	Number of users that have a throughput of 128 kbps.
$N_{users128-64}$	Number of users which throughput was reduced from 128 to 64 kbps.
$N_{user384}$	Number of users that have a throughput of 384 kbps.
$N_{user384-64}$	Number of users which throughput was reduced from 384 to 64 kbps.
$N_{user384-128}$	Number of users which throughput was reduced from 384 to 128 kbps.
P_b	Blocking probability.
P_{bearer}^{user}	Percentage of users with a service bearer within a certain service.
P_{BHU}	Busy hour usage.
P_d	Drop call probability.
P_t	Transmission power.
P_{del}	Delay probability.
P_{hf}	Handover failure probability.
P_m	Upper percentage threshold for medium surfaces.
P_r	Received power.
$P_{r\min}$	Minimum received power.
P_s	Upper percentage threshold for small surfaces.
$P_{\sec}^{\sup}$	Superposition area percentage of a sector.
$P_{\sup}$	Superposition area percentage threshold.
P_{Tx}^{BS}	BS transmission power.
P_{unc}	Uncovered users percentage.
P_{vs}	Upper percentage threshold for very small surfaces.
R_b	Transmission throughput.
$\overline{R}_b$	Average transmission throughput for a certain service.

R_b^{bearer}	Transmission throughput of a service bearer.
$\overline{R}_b^{real}$	Average of the real throughput.
R_{bj}	Bit rate of user j.
R_C	Chip rate.
R_{cell}	Nominal cell coverage radius.
R_{global}	Global transfer rate in a cell.
$\overline{T}_{\sec}^{dens}$	Traffic density inside a sector.
T_{unc}	Traffic that is not covered by the network.
$\overline{T}_{unc}^{dens}$	Mean uncovered traffic density.
$\overline{V}$	Average DL session volume data.
x_1	Horizontal coordinate of the first pixel of the BHCA grid.
x_j	Decision variable of the LSCP that is related to the potential BS site j.
y_1	Vertical coordinate of the first pixel of the BHCA grid.
w_B	Distance between buildings.
w_s	Streets width.

Chapter 1

Introduction

This chapter gives a short overview of the work, showing the motivation and the current state-of-the-art. At the end of the chapter, the work structure is provided.

Since early times, Man, as a social being, always had the need to communicate with others, so, it is natural to see that he spends much time finding new ways to fulfil this need. By the end of the twentieth century, mobile communications systems appeared, giving him the possibility to speak with far away people, wherever he wants.

At first, systems were analogue, being called first generation ones, Figure 1.1; digital mobile communications systems appeared as the second generation, obtaining a huge success in the last years, since the number of subscribers has increased a lot. There are different second generation systems all over the world with different characteristics and using different technologies: **P**ersonal **D**igital **C**ellular (PDC), cdmaOne (**I**nterim **S**tandard 95 – IS-95), US-TDMA (IS-136), etc., [HoTo00]. The system implemented in Europe is the **G**lobal **S**ystem for **M**obile Communications (GSM), which uses the **T**ime **D**ivision **M**ultiple **A**ccess (TDMA) technology, [Corr03].

Nowadays, voice information is responsible for a quite important part of the existing traffic in mobile communications systems, but, as time goes by and technology improves, users tend to use other services more often, increasing the variety of offered services and decreasing the weight of voice in the service distribution. This brings new challenges into network design, since it must deal with mixed traffic, both in **P**acket **S**witching (PS) and **C**ircuit **S**witching (CS). Thus, one can foresee a gradual transition from the CS traffic to the PS one, where data traffic will start to overcome the voice one.

The initial GSM networks were able to offer to users both voice and data services with quite low throughputs. With the appearance of the **G**eneral **P**acket **R**adio **S**ervice (GPRS), the so-called 2.5 generation, networks can increase their link throughputs, becoming possible to offer a wider variety of services and applications to users (e.g., multimedia applications). Despite that, the available throughputs are still below the ones observed in the fixed network.

In the third generation, there was the attempt to unify mobile communications systems by assuring a quite high level of compatibility between the different networks; however, that was not possible, because, among other things, it has been shown that it is impossible to have the same available frequency spectrum in the whole world. Thus, several third generation systems appeared, **U**niversal **M**obile **T**elecommunication **S**ystem (UMTS) being the European one. It uses a technology that is completely different from GSM, since the multiple access mode is the **W**ideband **C**ode **D**ivision **M**ultiple **A**ccess (WCDMA), where codes are used to distinguish the different channels.

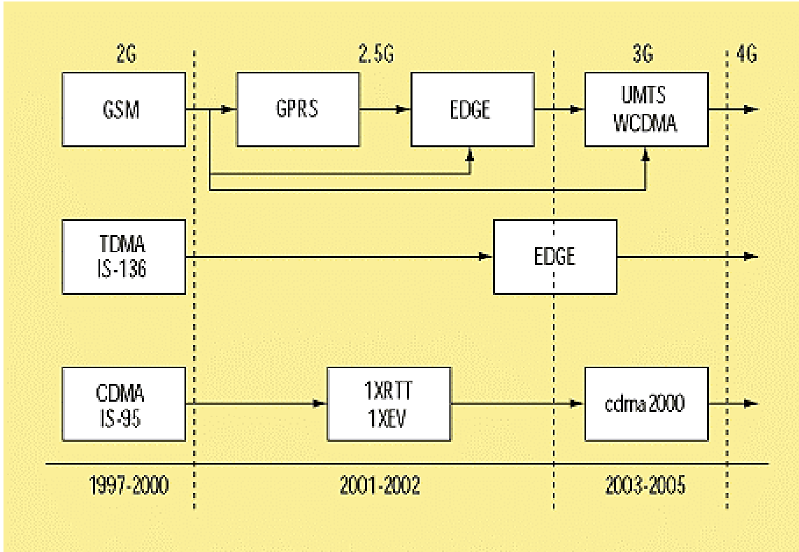


Figure 1.1 – The migration path from 2G to 4G mobile communication systems, [Fren01].

UMTS is designed for multimedia communications, providing higher throughputs and supporting a larger set of services and applications. These days, it is possible to have an enhanced person-to-person communication with high quality images and video, having access to information and services from public and private networks with higher bit rates.

The UMTS network dimensioning is different from the GSM one, being more complex. In contrast to GSM, in UMTS it is impossible to find *a priori* the number of available channels in a cell and, consequently, the number of users that can be connected to it. In fact, the number of channels is strongly dependent on the existing load on the cell and, consequently, on the characteristics of the users that are connected to it. Furthermore, it is difficult to analyse, in an analytic way, the performance of UMTS, since it supports both CS and PS traffics; therefore, one has to use simulators to observe the behaviour of the network for different scenarios.

Another parameter that is highly dependent on the load of the cell is the cell radius, and because of that the planning of a UMTS network is very difficult. Normally, the service area is covered by several **B**ase **S**tations (BSs), being important to plan correctly the position of each BS in order to obtain a good coverage. In mobile communications networks, it is usual to observe coverage gaps in the service area, which results from:

- the operator does not want coverage in some places, because there is not enough traffic in there;
- the network is dimensioned to a reference service bearer that does not correspond to the main traffic that exists in the area.

Despite a well designed network, at some point it becomes important to fill in some of the existing coverage gaps, because the traffic density shape is always changing: a network can a have a good coverage now and a bad one in the future. The more effective and easier solution to solve the coverage problem is to place extra BSs in uncovered areas. Then, it is important to have an algorithm that deals with this same problem by placing new BSs where the network has no coverage and traffic is significant.

The goal of this work was to develop a simulator that evaluates the performance parameters of a UMTS FDD network, like blocking and delay probabilities, for several scenarios. Then, when there are coverage gaps, the software must also be able to place new BSs in an automatic way, considering a non-uniform multi-service traffic distribution, in order to improve the network coverage.

There are already many developed BS placement algorithms, but they all deal with the problem in a discrete space, where there is a finite number of candidate sites, which are previously defined. Then, one needs to find the smaller sub-set of candidate sites that leads to the optimal coverage. This problem has a very complex resolution, since it has many variables and constraints, therefore, the usage of powerful optimisation algorithms is needed. However, none of these solutions can be used in the problem, because one wants to find the best places for the new BSs without having pre-defined possible locations.

The simulator is based on a previous one from [SeCa04] that makes a performance analysis of a UMTS network in the **F**requency **D**ivision **D**uplex (FDD) mode. One has improved it by adding features like:

- the frequency allocation takes into account the number of equivalent SF codes that are occupied by the users in a cell;
- the method for finding the covered users of a sector was improved, and users outside the nominal cell radius can be also covered;
- the number of sectors that a user can be connected to takes into account not only the active set but also the difference between the signal power strength: if a user connection in a cell has an attenuation that is a certain value above the one for best user connection, it is blocked.

The already existing simulator has also an automatic BS placement algorithm that finds the locations of the new BSs; however, they are spread in the uncovered areas in a uniform way and without taking into account the traffic distribution. Then, one has developed a new algorithm that uses a different heuristic to place new BSs for different kinds of uncovered surfaces: BSs are placed in a non-uniform way, adjusting in the best possible way to the area that is being handled. Moreover, BSs are only placed if the traffic in the area verifies certain specifications; this evaluation is made for each sector and, consequently, it is possible to have BSs with less than 3 sectors, in contrast to the existing BS placement algorithm that only adds BSs with 3 sectors.

Simulations were made by varying the BS placement algorithm input parameters and using different network scenarios. The algorithm was used in Lisbon for both with and without an initial network: in this work one uses the Vodafone's network, which is co-located with its GSM one. A comparison between the BS placement algorithm developed in this project and the one from [SeCa04] was also made. For the traffic distribution input data, one has used information provided by the MOMENTUM project, [MOME04].

The novelty of this thesis is the development of an algorithm that places, in an automatic way, new BSs into an initial network in order to improve its coverage, without having a pre-defined set of BS candidate sites. To accomplish this, it spreads through the uncovered areas the placing BSs in a non-uniform way, dealing with different kind of uncovered surfaces in different ways. Moreover, the BSs are placed taking into account the multi-service traffic distribution in the area.

In the second chapter of this thesis, one makes a brief introduction to the UMTS fundamental concepts, giving the basic tools to its comprehension. The network architecture is presented, as well as the way it works, the services and applications usually used, and their characteristics. In the following chapter, one shows and explains the models that are used in the thesis, describing the calculation of capacity and interference, traffic aspects, link budget, and the algorithm for the automatic placement of new BSs in the network. Chapter 4 describes thoroughly the implementation of the developed simulator, focusing on the several blocks that compose it. Furthermore, the input and output data is pointed out. In Chapter 5, the input data used for the simulations is shown as well as the several results obtained in this project, and their analysis. Conclusions and suggestions for future work are presented in the Chapter 6. At last, in the annexes, useful information is shown, like the method used for the calculation of the nominal cell radius, traffic distributions used in the simulator, fluxograms of the simulator, user's manual, and simulation results.

Chapter 2

UMTS Fundamental Concepts

An introduction to some UMTS technical issues is made in this Chapter: some network structure characteristics are explained, and the existing channels and codes are addressed. In a brief way, the services and application that are being offered by UMTS, and the network requirements to support them, are also introduced.

2.1 Network Architecture

The UMTS network architecture is composed of 3 main levels: the **U**ser **E**quipment (UE), the **U**MTS **T**errestrial **R**adio **A**ccess **N**etwork (UTRAN), and the **C**ore **N**etwork (CN), each one having its own well defined functionalities. The UE establishes the link between the user and the network, the UTRAN is responsible for the functionalities related to the radio system interface, and the CN deals with the information routing and the connection within the network itself and outside ones [HoTo00].

Each one of these levels is composed of several components, which are organised in the following way:

1. The UE consists of the **M**obile **E**quipment (ME) and the **U**MTS **S**ubscriber **I**dentity **M**odule (USIM). The first element, ME, i.e., the **M**obile **T**erminal (MT), enables the radio connection to the network, and the second one, USIM, is the electronic card where the user identification is saved, and where both authentication and encriptation information algorithms are processed.
2. The UTRAN is divided into sub-systems, designated by **R**adio **N**etwork **S**ub-systems (RNS), each one composed of a **R**adio **N**etwork **C**ontroller (RNC) and a Node B, at least. The Node B, i.e., the BS, converts the information streams that arrive from the UE so that they can be processed by the RNC, as well as the other way around. Besides this, it takes care of the **R**adio **R**esource **M**anagement (RRM) in a basic way. The other element, RNC, deals with the radio resource control, controlling the stream and congestion, and deciding on handover.
3. Finally, the CN has the following composition, which is very similar to the GSM one:
   - **H**ome **L**ocation **R**egister (HLR) – element where all the information related with each one of the operator clients is saved. As an example, the services that can be served to the user are listed there.
   - **V**isitor **L**ocation **R**egister (VLR) – component that has the information about all the network active users at a given moment. These users can belong to the network operator, or to another one using the roaming service.
   - **M**obile Services **S**witching **C**entre (MSC) – is responsible for the voice and data transport management in CS inside the network.

- **G**ateway **MSC** (GMSC) – like a gateway, it establishes a link between the CN and all outside CS networks.
- **S**erving **G**PRS **S**upport **N**ode (SGSN) – with a functionality similar to the MSC, it deals with PS information transport.
- **G**ateway **G**PRS **S**upport **N**ode (GGSN) – has a functionality similar to the GMSC, but it establishes a link with outside PS networks.

The layout of the several UMTS network components, and the way they are connected, is shown, in a simplified way, in Figure 2.1.

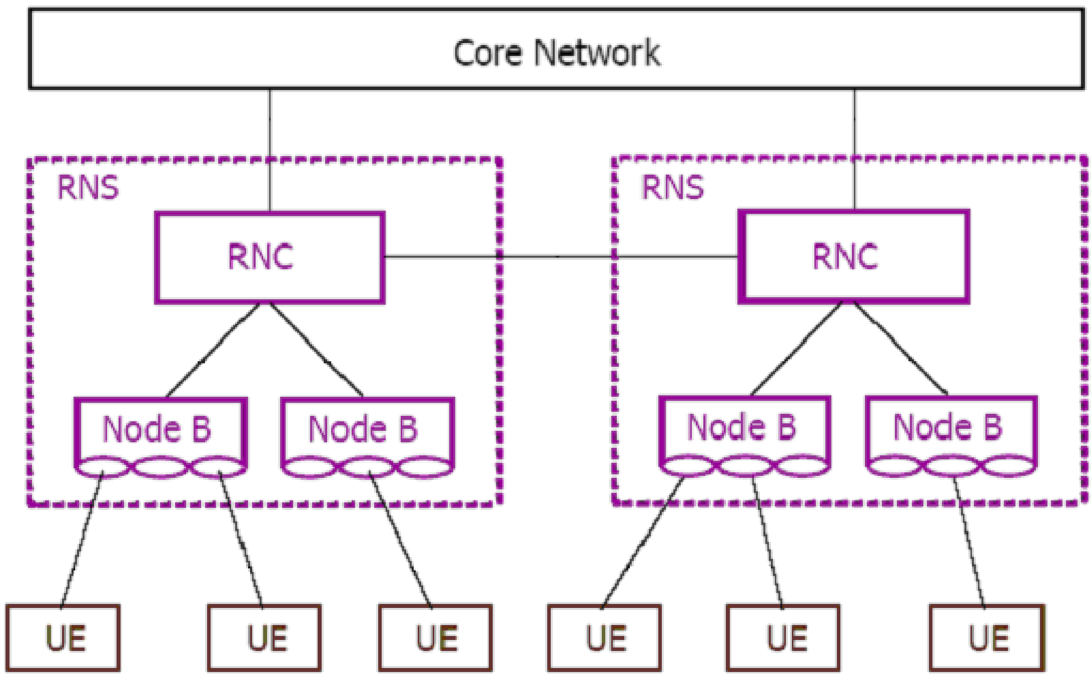


Figure 2.1 – UMTS network architecture, [Corr03].

One should note that the transition from GSM to UMTS is a lot easier at the CN level rather than at the UE and UTRAN ones. This results from the fact that the UMTS CN is an adaptation of the equivalent element in GSM, while the transition to a UE and a UTRAN implies the implementation of completely new protocols, as the multiple access is made by WCDMA and not by TDMA. Also, one should take into consideration that the UMTS network must be designed to serve both CS and PS traffics, which was not initially the case of GSM.

In contrast to GSM, which has only hard handover (HHO), UMTS has the 3 existing types of handover: hard, soft (SHO) and softer handover (SSHO). The difference between the soft/softer and hard handovers comes from the fact that in the latter a link is transferred from one cell to another without being connected simultaneously to both, while in the former the simultaneous connection exists. The soft handover is similar to the softer one, but in the former the link is transferred between 2 different cells, while in the latter the user is connected to 2 sectors of a cell. The existence of soft/softer handover has implications in the network, because when an MT is linked to several BSs/sectors, the drop probability of the connection is smaller. However, the system capacity decreases a lot, as the same user consumes resources from several BSs.

As already seen, the existence of SHO makes it possible for an MT to be linked to several BSs. The number of BSs to which an MT can be connected to is called the active set. The active set is an important parameter in the dimensioning of a UMTS network: a high value makes it possible for a certain user to be linked to more BSs, this way decreasing the outage probability. On the other hand, the system capacity is lower, because a user in SHO consumes resources from several BSs.

2.2 Services and Applications

Services can be defined by the capacity set that is provided by the network, enabling users to use applications. On the other hand, applications are tasks that allow the connection between two or more terminals, [FeSC02].

The main reason for the existence of UMTS relies on the large variety of services and applications that can be offered to the user, with higher throughputs and with **Q**uality of **S**ervice (QoS) guaranties. Moreover, it is a very flexible system, providing some QoS guaranties in the served services and applications, something that is not easy to accomplish. The whole system is based on connectivity to the Internet, which, currently, works on a best effort assumption and does not provide QoS guaranties. Thus, network mechanisms must be defined in order to, for instance, guarantying maximum delays. In fact, a user is not available to wait too long for a service, which in some cases becomes useless when the delays are too large.

Services can be distinguished in different ways. There are several proposed classifications, like, for instance, the one from the **3**rd **G**eneration **P**artnership **P**roject (3GPP) [3GPP03b]. As proposed by 3GPP, services can be classified into classes, according to the QoS that they can assure to the final user, [3GPP03a], [3GPP03b], Table 2.1.

Table 2.1 – Main characteristics of the service classes, [3GPP03a], [3GPP03b].

Class	Conversational	Streaming	Interactive	Background
Real-time	Yes	Yes	No	No
Symmetric	Yes	No	No	No
Switching	CS	CS	PS	PS
Assured throughput	Yes	Yes	No	No
Delay	Minimum and fixed	Minimum and variable	Moderate and variable	Large and variable
Example	Voice	Video-clip	WWW	SMS

In the conversational class, services have similar two-way traffic, in **D**own**l**ink (DL) as much as in **U**p**l**ink (UL) (symmetric or near-symmetric traffic). The most well known application in this class is the voice service in CS. However, other applications are also considered here. It is the case of **V**oice **o**ver **IP** (VoIP), video telephony, and some games, which, for their own characteristics, need very low delays. In this kind of services, it has been verified that, by imposition of human perception, the end-to-end delay must be small. As an example, it is considered that both video and audio conversation only seem fluent to the human when the delays are lower than 400 ms, [HoTo00].

Services in the streaming class are based in an information transfer technique called streaming, where the information is transported in a continuous stream, allowing its processing by the end user (e.g., visualisation) before the reception of the entire file is finished. Traffic is very asymmetric, DL being the most significant one. There is more delay tolerance compared to the conversational class. Examples of some applications for this class are audio streaming and video on demand.

In the interactive class, the user (a machine or a human being), can ask for different kinds of information from a certain remote server. Services are more tolerant to delays, generate an asymmetric traffic and, in contrast to the previously mentioned classes, use PS. However, on the other hand, there is no tolerance to errors in the received information; therefore, the error probability must be low to prevent too many retransmissions. As an example of an application in this class, one can mention the **W**orld **W**ide **W**eb (WWW) browsing.

The common aspect for applications considered in the background class relies on that the user does not have a limited time to receive the information. So, the system does not need to process the information immediately: the delay can be high. Therefore, the applications inserted in this class only use the network for the information transmission when the network resources are not being used by other services from other classes. Despite the delays, the information transmitted cannot have errors. Examples for the applications of this class are the e-mail and the **S**hort **M**essage **S**ervice (SMS).

However, not always applications have a direct relation to only one class. For instance, WWW is inserted in the interactive class, but an Internet site can have, for instance, a video, which implies requiring the streaming class or otherwise it might not have the desired quality. The opposite case is also possible: an application that does not need the QoS guaranties of a class can be downgraded, this way freeing network resources.

For the accomplishment of the QoS requisites, the network has to be well dimensioned, in order to offer a good coverage and to be able to support the offered services. On the other hand, several factors have to be taken into account, like, for instance, the potential users profile, their mobility, and the service prices. The GSM/GPRS network is used as a starting point of the network dimensioning, with the aim of foreseeing the use the available services. In [UMTS03], a study is made with the goal of trying to foresee and estimate the UMTS offered traffic, in terms of both UL and DL traffic requisites. It can be seen that the DL traffic volume is larger than the UL one (it is around 2.3 times higher).

One should note that, since UMTS became commercially available in a very short time, there is no data about the usage of some of the services mentioned before. Thus, when the network dimensioning is done, some estimation for the services usage must be assumed. In the future, when there is enough traffic data, real data can then be used to correct the estimations made in the initial network dimensioning.

2.3 Channels and Codes in UMTS

In mobile communication systems, and in UMTS in particular, there are different channel types, each one with its own characteristics and different use possibilities. This way, 4 types of channels can be distinguished and characterised in UMTS [HoTo00]:

1. Radio Channels: Each channel has a well defined bandwidth and channel separation, equal to 4.4 and 5 MHz respectively, Figure 2.2. There are pre-defined bands in UMTS. In the FDD mode, there is the $[1\,920, 1\,980]$MHz band for UL and the $[2\,110, 2\,170]$MHz one for DL. In the **T**ime **D**ivision **D**uplex (TDD) mode, one has the band $[1\,900, 1\,920] \cup [2\,010, 2\,025]$MHz, which can be used for both UL and DL. In the FDD mode, the separation between UL and DL is made by different frequency bands, while in the other mode the separation in made in the time domain, therefore, both UL and DL channels occupy the whole available bandwidth, but in different time-slots. The FDD mode is used in communications that have a symmetric volume of information, while the TDD one is used in asymmetric traffic. There are 12 and 7 channels in FDD and TDD, respectively.
2. Physical Channels: In UMTS, there is a large number of physical channels, which is not described here in detail. It should be noticed, however, that there is a channel separation between UL and DL, dedicated and common channels existing in both cases. These channels, on the other hand, can be used for either signalling/control or traffic. The common channels are shared by several users, and the dedicated ones connect a unique user to the UTRAN. User generated information can use several physical channels.
3. Logical channels: These channels can be associated to traffic (voice or data) or to different kinds of control/signalling functions. These channels can also be common or dedicated.
4. Transport channels: In UMTS, there are also transport channels, which are used to make the interface between the UE and the RNC.

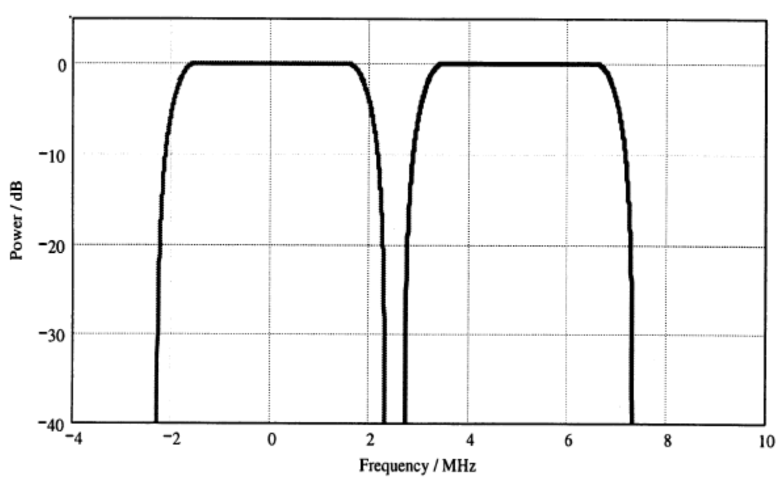


Figure 2.2 – Frequency spectrum, showing some radio channels in UMTS, [Corr03].

WCDMA being the multiple access technique used in UMTS, the information is spread onto a certain bandwidth by multiplying it with pseudo-random code symbols (spreading codes), the chips, the code throughput being equal to 3.84 Mcps. One of the goals is to separate the channels among themselves. WCDMA supports big variations in the binary throughput of the information. However, its transmission has a constant throughput in a frame, which has a duration of 10 ms.

The **S**preading **F**actor (SF) is a parameter that indicates the spreading level that is obtained by WCDMA, using a certain spreading code. It is given by the number of chips that exist in an information symbol period or, in another way, by the ratio between the bandwidths of the spread signal and of the original one, [HoTo00]. The spreading factor for UMTS depends on the network working in the TDD or FDD modes: in the TDD mode, its value can be between 1 and 16, while in the FDD one, it can be between 4 and 512.

In UMTS, the **O**rthogonal **V**ariable **S**preading **F**actor (OVSF) family code is used, Figure 2.3.

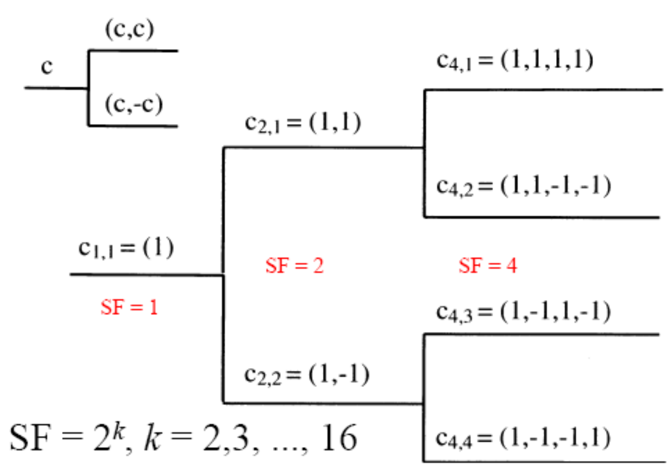


Figure 2.3 – OVSF code tree, [Corr03].

In each of the tree levels (level *n*), there are always 2^n orthogonal codes, each one with a length (and spreading factor) equal to 2^n. The codes from the OVSF family allow the existence of orthogonal codes with different length and, consequently, with different spreading factors. Thus, they are used in systems where the spreading factor varies, as it is the case of the UMTS. However, it has to be taken into account that there are some restrictions in the use of these codes. In fact, in order to be orthogonal among them, the used codes cannot be on the right side branch of the tree of another used code. Therefore, all the generated codes are orthogonal among them; so, a certain receiver gets the other codes as noise. In this way, in theory, there would be unlimited channels for each carrier, but when the number of codes is increased (and consequently the number of users), performance is badly degraded. Both interference and capacity depend on the number of users, this number being limited to a maximum of 256 or 512 available codes.

The codes used in UMTS are called channelisation and scrambling, Table 2.2. Channelisation codes are used in UL to separate the channels (both traffic and control) from the same MT and in DL to separate the information from each one of the MTs. Scrambling codes separate the several MTs in UL and the sectors of the cell in DL.

Table 2.2 – Functions and attributes for the codes used in UMTS, [Corr03].

	Channelisation	***Scrambling***
Use	DL: MT separation UL: channel separation	DL: sector separation UL: MT separation
Duration	DL: 4 – 512 *chip* UL: 4 – 256 *chip*	38 400 *chip*
Number	Spreading factor	DL: 512 UL: < 1 000 000
Family	OVSF	Gold or S(2)
Spreading	Yes	No

One should note that only channelisation codes spread the signal. In fact, the multiplication of the signal by the scrambling code does not affect the bandwidth of the transmission, Figure 2.4.

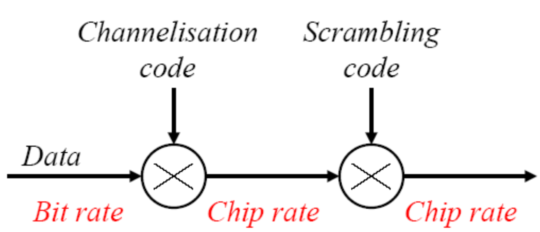


Figure 2.4 – Codification scheme for UMTS information, [Corr03].

Chapter 3

Models for Traffic and Capacity

In this chapter some characteristics that are more specific to UMTS are analysed, concerning a practical application in this work. Thus, issues like interference, capacity, coverage, traffic models, radio network optimisation, and performance parameters are addressed.

3.1 Capacity and Interference

In mobile communications systems, effects caused not only by the thermal noise coming from electronic components but also by the interference from several MTs and BSs need to be considered. In the case of UMTS, BSs may work all in the same frequency, hence, interference cannot be neglected. In order to guarantee a certain QoS, it is important to define the maximum number of users, so that interference does not exceed given thresholds.

The number of users that can be connected to a BS is limited by several parameters: global load factor, BS transmission power, and the number of available codes.

The global load factor of a cell indicates the load that is offered by a set of users, each one using a type of service. In the UL's case, the global load factor is given by, [HoTo00]:

$$\eta_{UL} = (1+i)\sum_{j=1}^{N_{users}} \frac{1}{1+\dfrac{R_C/R_{bj}}{(E_b/N_0)_j \cdot \upsilon_j}} \tag{3.1}$$

where:

- i is the inter- to intra-cells interference ratio;
- N_{users} is the number of users in the cell;
- R_C is the chip rate (equal to 3.84 Mcps);
- E_b is the bit energy;
- N_0 is the value of the noise power spectral density;
- R_{bj} is the binary throughput of user j;
- υ_j is the activity factor for user j.

For the DL's case, the expression is a little bit different:

$$\eta_{DL} = \sum_{j=1}^{N_{users}} \upsilon_j \frac{(E_b/N_0)_j}{R_C/R_{bj}} \cdot \left[(1-\alpha_j)+i_j\right] \tag{3.2}$$

where:

- α_j is the orthogonality factor for the codes in DL.

In contrast to UL, in DL there are no scrambling codes to identify the several users of a certain cell sector, this function being performed by the channelisation codes. However, as a consequence of multi-path propagation, the codes will be out of phase among them, so, they are not perfectly orthogonal. The orthogonality factor appears in the expression for the load factor in DL, in order to take into account the effect of a certain loss of orthogonality of the codes: it varies from value 0 to 1, being higher when the considered codes are more orthogonal. Furthermore, in DL the parameter i depends of the MT position, being different from one user to another. Therefore, the inter- to intra-cells interference ratio is no longer constant, becoming a parameter that depends of the user, i_j.

The interference effect can be taken into account by defining the interference margin:

$$M_{i[\text{dB}]} = -10\log(1-\eta) \tag{3.3}$$

The interference margin increases with the load factor, η (which is equal to η_{DL} or η_{UL}, depending on the case), Figure 3.1: when the latter is equal to 1, the former becomes infinite and, consequently, the system cannot work; so, η must be always lower than 1. It is usual to consider that a cell has a maximum capacity for η as the ones presented in Table 3.1. As it can be seen from (3.1) and (3.2), η increases when N_{users} is higher, which puts a direct limitation on the number of users for a UMTS network cell. Despite that, the maximum number of users is not constant: the variation of η depends also on other parameters like, for instance, the inter- to intra-cells interference ratio, the throughput, the activity factor of each user and, in the DL's case, the orthogonality factor for the codes. Thus, a good knowledge of these parameters is needed for a correct estimation of the maximum number of users that a cell can support.

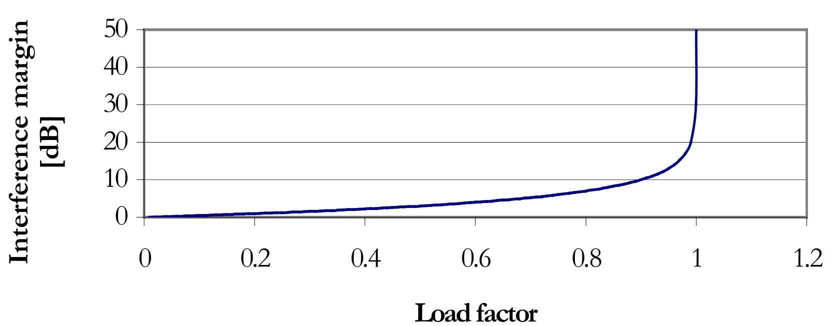


Figure 3.1 – Variation of the interference margin with the load factor.

Table 3.1 – Typical maximum values for the load factor and the interference margin.

	UL	DL
Maximum load factor ($\eta_{\max}$)	0.50	0.70
Maximum interference margin (M_i) [dB]	3.0	5.2

There are others factors to be considered when a UMTS network is dimensioned. One of them is the BS transmission power:

$$P_{Tx}^{BS} = \frac{N_0 \cdot R_C \cdot \sum_{j=1}^{N_{users}} \upsilon_j \cdot \overline{L}_{Pj} \cdot \frac{\left(E_b/N_0\right)_j}{R_C/R_{bj}}}{1-\eta_{DL}} \tag{3.4}$$

where:

- $\overline{L}_{Pj}$ is the average propagation attenuation of user j.

The maximum BS transmission power is usually 43 dBm, this power being used for both traffic and control channels. One can easily verify from (3.4) that the maximum number of users is also limited by the BS transmission power.

The number of available codes needs also to be considered. For each user in the cell, a different code is given, so, at each moment, the number of users must be equal or below the number of existing codes. In general, the number of available codes is not relevant for the network dimensioning, as the other two factors (interference and BS transmission power) are more restricting. However, this last factor cannot be neglected.

As previously mentioned, in UL, the separation of the MTs is made by the scrambling codes, while in DL it is made by the channelisation ones, Table 2.2. Therefore, the number of available codes is much higher in UL than in DL: there are 2^{24} scrambling codes in the former case and only 512 channelisation codes (OVSF codes) in the latter one, thus, only the latter can impose restrictions. In the system, the usage of a code with a 512 SF implies a very low service bearer throughput offered to the user, therefore, the transmitted information having an extreme high overhead. Thus, in DL, the maximum SF is equal to 256 for the used codes.

The use of a code with a different SF depends on the bit rate of service: the higher the service throughput is the smaller the SF of the code will be, Table 3.2. Usually there are 2 codes with 256

SF that are used in common channels; therefore, there are only 254 codes available for the users. The usage of a code with a certain SF by a user can be seen as an occupation of several 256 SF codes. This number of occupied codes increases with the service bearer throughput, Table 3.2. Then, the number of possible users within a cell is given by the following condition:

$$\sum_{j=1}^{N_{users}} N_j^{codes} \leq 254 \tag{3.5}$$

where:

- N_j^{codes} is the equivalent number of 256 SF codes occupied by the user j.

Table 3.2 – SF and the number of equivalent SF codes occupied for a certain service bearer.

Service bearer [kbps]	**SF**	**Equivalent 256 SF codes occupied**
12.2	32	8
64	16	16
128	8	32
384	2	128

If one of these restricting conditions is not fulfilled for a set of users, with their own characteristics, then, they cannot be all linked to the cell. There are two ways to deal with this problem: either some users are blocked/delayed, or their throughputs are decreased.

3.2 Traffic Aspects

In order to obtain a good traffic estimation, one needs to use models that represent the network behaviour. There are traffic models that allow an analytical study of the network, based on certain parameters, like the number of available channels, the incoming calls rate, or the mean service time.

In the most common models, it is usual to use Poisson distributions for the shaping of the call generation, [Corr03] and [Virt02]. Some traffic models are used, like Erlang-B for CS traffic or Pollaczeck-Khinchin for PS traffic, to obtain estimations of block/delay in the network.

However, these models are far from being a good approximation for a mobile network, especially for UMTS. In fact, in a mobile network there are some aspects that influence the network dimensioning, like user mobility, the variation of the population or handover strategies. There is also a relatively recent problem: the existence of mixed traffic, that is, the existence of CS and PS traffic in the same network.

UMTS has more specific problems, like the variation of the number of traffic channels during the operation, and the difficulty in estimating this number, since it depends on the interference, which depends on the number and characteristics of the users.

Simulation must be used to obtain the data needed for a correct network dimensioning. Models for incoming calls and for the duration of the service must be used for the selected applications. Moreover, in order to shape the behaviour of each different application, models must use, for instance, the dependence of the occupied channels on the throughputs.

Each application has different requirements in terms of throughput, packets generation or channel occupation. For voice, for instance, one usually uses a model that takes into account not only its ON/OFF behaviour, but also the effect of the voice compressor and coder. In [SeFC03] a review of some models that can be used in UMTS is presented.

Generally, for this kind of simulators, and for the one used in this work, which uses the advantages of the GIS graphical tools, one needs information about the spatial traffic distribution. This can be obtained, for example, from the MOMENTUM project [MOME04], where data is presented in a set of pixel grids, each one for a different service, and with the value of the correspondent traffic of each location. This is very useful in cases like, for instance, users generation. The data was created based on available information from operators, and using 3 key elements: the user profile, providing a description on how calls are generated by each type of subscriber; the operational environment; and the spatial distribution of subscribers, Figure 3.2.

One of the first things that must be done is to define the set of services that are offered by the network under study, because different services have different characteristics and different spatial traffic distributions. In MOMENTUM, this issue was analysed and, as a result, 8 services are defined, representing the foreseen UMTS services and the 4 service classes defined by 3GPP, [3GPP03a], [3GPP03b]:

- Speech-telephony – traditional speech-telephony.

- Video-telephony – communication for the transfer of voice and video between two locations.
- Streaming Multimedia – service that allows the visualisation of multimedia documents on the streaming basis, e.g., video, music, or slide show.
- Web Browsing – interactive exchange of data between a user and a web server. It allows the access to web pages. This information may contain text, extensive graphics, video and audio sequences.
- Location Based Service – interactive service that enables users to find location-based information, such as the location of the nearest gas stations, hotels, restaurants, and so on.
- **M**ultimedia **M**essaging **S**ervice (MMS) – a messaging service that allows the transfer of text, image and video.
- E-mail – a process of sending messages in electronic form. These messages are usually in text form, but can also include images and video clips.
- File Download – download of a file from a database.

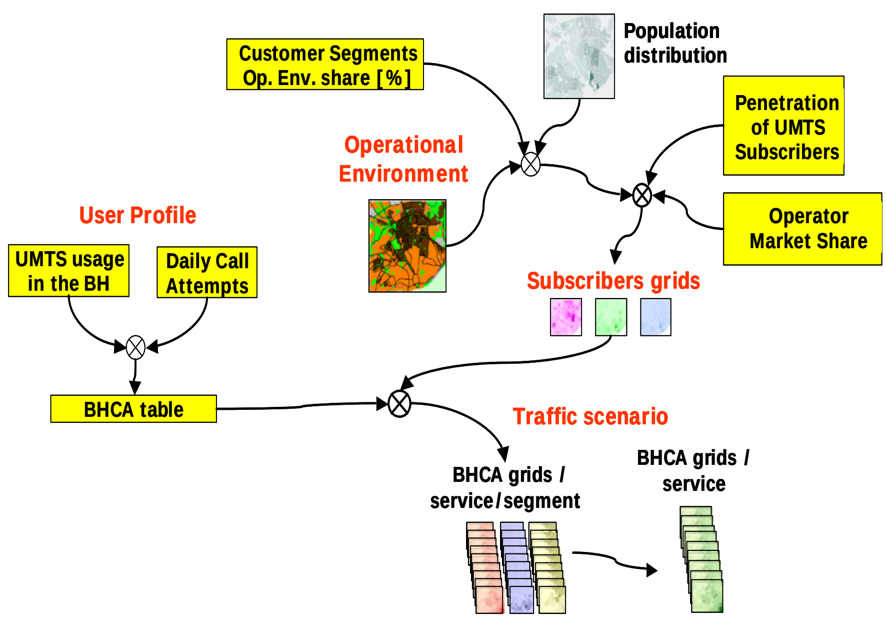


Figure 3.2 – General process for the construction of a traffic scenario, [FCXV03].

In [FeVe04], a different set of services that can be offered by **E**nhanced **UMTS** (E-UMTS) is presented:

- Sound;
- **H**igh **I**nteractive **M**ulti**m**edia (HIMM);

- Narrowband;
- Wideband;
- Broadband.

The services that are used in this work are the former ones, proposed by MOMENTUM, because, as one has already mentioned, these ones represent the 4 service classes, and because they cover a wide range of information volume and bit rate, Figure 3.3. The different services have their own different characteristics like, for instance, the symmetry of the connection, the switching mode used, and the source bit rate, Table 3.3.

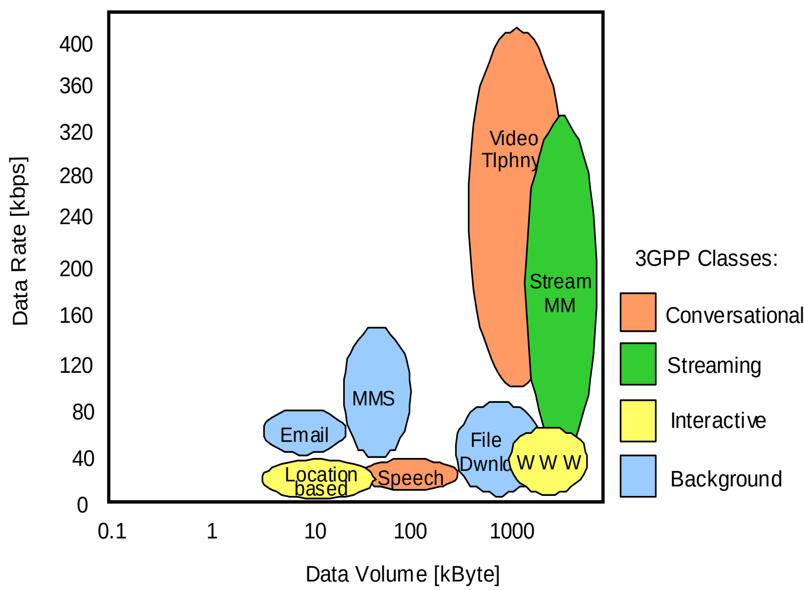


Figure 3.3 – Service set bit rate range and DL session volume, [FCXV03].

Table 3.3 – Service characteristics, [FCXV03].

Service class	Service	Symmetry	Switching mode	Source bit rate range [kbps]
Conversational	Speech-telephony	Sym	CS	4 – 25
	Video-telephony	Sym	CS	32 – 384
Streaming	Streaming Multimedia	Asym	PS	32 – 384
Interactive	Web Browsing	Asym	PS	< 2000
	Location Based Service	Asym	PS	< 64
Background	MMS	Asym	PS	< 128
	E-mail	Asym	PS	< 128
	File Download	Asym	PS	64 – 400

The starting point of the process is to define a user profile. It is clear that not every costumer has the same type of usage customers, being divided in three segments, each one with different characteristics, [FCXV03]:

- Business user – early adapters, with intensive and almost entirely professional use, primarily during office hours.
- **S**mall **O**ffice/**H**ome **O**ffice user (SOHO) – followers, with both professional and private use, during the day and in the evening.
- Mass-Market user – with low use, with flat traffic levels.

The information of the user profile is organised in tables, each one corresponding to one of the 8 considered services that contain, for each customer segment, the **B**usy **H**our **C**all **A**ttempt (BHCA) per user, which is the mean number of calls that are performed by a user in the busy hour. These BCHA tables are built based on marketing data and, therefore, depend on factors such as the area under study and the strategy of the operator concerning UMTS usage. The number of calls per day and per user, N_{call}^{day}, and the busy hour usage, P_{BHU}, are estimated for each customer segment. One should note that busy hour usage, which is the percentage of traffic per day taking place in the busy hour, is usually larger for business users and smaller for mass-market ones, because business costumers use UMTS on more specific times of the day, while mass-market users have a more spread usage. The BHCA tables are then obtained using the following expression:

$$N_{BHCA}^{user} = P_{BHU} \cdot N_{call}^{day} \tag{3.6}$$

The second step is to identify the operational environmental. Using raster land user data and vector data, it is possible to create a grid, each pixel having the information of the type of terrain (operational environment classes) for the corresponding zone of the area under study. In MOMENTUM, 11 different operational environment classes are considered.

The population distribution is obtained by using available information on the resident population and on the population pendulum movement (due to workers displacement) for several zones, typically districts, for the period of the day under study. These values are weighted according to the operational environment class of the area, this way, being possible to create a population distribution. In some cases, the population needs to be independently estimated. In fact, it is difficult, using the mentioned approach, to estimate the population in the following situations:

- Highway, highway with jam, road and street pixels without population.

- All highway and road pixels crossing rural or open areas.
- All railways pixels.

Therefore, in these cases, the number of persons by pixel is calculated separately, considering, among other things, that a car contains in average 1.5 persons and that cars are evenly distributed. The distance between consecutive cars depends on the type of environment. There are other cases, like exhibition areas or train stations, where the population is estimated extrapolating from GSM speech traffic data, [FCXV03].

The last step is to estimate the number of subscribers of a certain customer segment for each pixel of the grid (subscriber distribution), Figure 3.4. For that, the following information is used:

- Operational environment share between customer segments – percentage of persons that belongs to a certain customer segment. This value depends on the operational environment.
- UMTS subscriber penetration – the percentage of subscribers in the population of a certain customer segment. Typically, business users have the largest subscriber penetration and the mass-market the smallest one.
- Operator market share.
- The population distribution.

a) Business. b) SOHO. c) Mass Market.

Figure 3.4 – Lisbon UMTS subscribers per customer segment, [FCXV03].

The spatial traffic distribution, associated to a GIS tool, is obtained by multiplying the values of each pixel from the subscriber distribution with the user profile of the corresponding customer segment and service. The result is a set of 24 grids with information about the BHCAs for each one of the 3 customer segments and the 8 services. Then, to obtain the spatial traffic distribution for the several services, one just needs to add the 3 customer segment grids for each considered service.

3.3 Link Budget and Cell Radius

The study of both capacity and coverage is fundamental in order to achieve a good radio network dimensioning. The link budget takes into account, for each scenario, the effects of the terrain morphology, the type of service, the mobility of users, and the handover, among others. With a well defined link budget, it is possible to find the maximum cell radius for each service using a certain propagation model, and, finally, to do the network dimensioning in terms of coverage.

As a starting point, the area where the network is implemented is characterised in terms of both building and user densities. One must also consider the mobility of users and their location: users can be pedestrian, or move using some kind of vehicle, and can do it inside or outside a building. Their locations cause a change, mainly, in the signal's attenuation associated to the path between the BS and the MT. Mobility, on the other hand, changes the fading effects. It is also important to consider the effects of the QoS, hence, services with different QoS requirements have different sensitivities.

Therefore, one needs to calculate the link attenuation. It is known that the propagation attenuation is given by, [Corr03]:

$$L_{P[\mathrm{dB}]} = EIRP_{[\mathrm{dBm}]} - P_{r[\mathrm{dBm}]} + G_{r[\mathrm{dBi}]} \tag{3.7}$$

where:

- P_r is the received power;
- G_r is the receiving antenna gain;
- $EIRP$ is the effective isotropic radiated power.

The $EIRP$ value is given by:

$$EIRP_{[\mathrm{dBm}]} = P_{t[\mathrm{dBm}]} + G_{t[\mathrm{dBi}]} - L_{cu[\mathrm{dBm}]} \tag{3.8}$$

where:

- P_t is the transmission power;
- G_t is the transmission antenna gain;
- L_{cu} represents existing losses. In DL, it represents the loss in the cable that connects the transmitter to the antenna, while in UL it results from the presence of the user near the

antenna, having values in the [3;10] dB interval for the voice and in the [0;3] dB one for the data.

The usual values of the $EIRP$ for different types of BSs and MTs are presented in Table 3.4.

Table 3.4 – $EIRP$ values for the different kinds of TMs and BSs, [Corr03].

***EIRP* [dBm]**			
Base Station			**Mobile Terminal**
Macro Cell	**Micro Cell**	**Pico Cell**	
[40;43]	[30;33]	[20;23]	[10;33]

The propagation attenuation model depends on parameters like slow and fast fading margins, M_{SF} and M_{FF}, indoor penetration attenuation, L_F, and the gain associated to soft and softer handovers, G_{SHO}. Soft and softer handovers decrease the fading effect, because simultaneous connections to several BSs allow the existence of several paths between the BS and the MT, each one being affected in a different and independent way by fading. Power control also contributes to the decrease of the fading effect. Expressions (3.9) and (3.10) take into account the effects presented before, [HoTo00], [Corr03] and [3GPP03c]. The typical value for G_{SHO} is usually somewhere between 1 and 3 dB, for M_{FF} between 2 and 5 dB, and equal to 5 for M_{SF}. The value of L_F can reach 20 dB in some cases.

$$M_{[\mathrm{dB}]} = M_{SF[\mathrm{dB}]} + M_{FF[\mathrm{dB}]} + L_{F[\mathrm{dB}]} - G_{SHO[\mathrm{dB}]} \tag{3.9}$$

$$L_{P\,total\,[\mathrm{dB}]} = L_{P\,[\mathrm{dB}]} + M_{[\mathrm{dB}]} \tag{3.10}$$

Another issue that must be considered is the minimum value for the received power, also called sensitivity. This value must be assured to guarantee a certain **S**ignal-to-**N**oise **R**atio (SNR) in the connection, which is approximated by E_b/N_0. The minimum SNR varies with the service bearer, Table 3.5. For each service bearer, the values also vary with the direction of the communication and the mobility of the user.

In order to study the minimum received power of the connection, it is important to know the noise power at the receiver input. The noise value depends of the signal bandwidth, Δf, which is considered to be equal to the chip rate ($\Delta f = R_C = 3.84$ Mcps), on the noise factor, F , and the interference margin, M_i , which depends of the system load.

Table 3.5 – The E_b/N_0 for each UMTS service, [Corr03].

Service	Service bearer [kbps]	E_b/N_0 [dB]
Voice	12.2	$[4.8\ ;\ 8.8]$
Data	64	$[1.1\ ;\ 3.8]$
	128	$[0.9\ ;\ 3.5]$
	384	$[0.4\ ;\ 3.2]$

The noise power value is then given by:

$$N_{[\text{dBm}]} = -174 + 10\log\left(\Delta f_{[\text{Hz}]}\right) + F_{[\text{dB}]} + M_{i[\text{dB}]} \tag{3.11}$$

Another parameter that affects the minimum received power is the processing gain, which is given by (3.12), where R_b is the transmission throughput. For voice at 12.2 kbps, the processing gain is 25 dB, and for data at 384 kbps it is equal to 10 dB.

$$G_{P[\text{dB}]} = 10\log\left(R_C/R_b\right) \tag{3.12}$$

The minimum received power is defined by the following expression:

$$P_{r\,\min[\text{dBm}]} = N_{[\text{dBm}]} - G_{P[\text{dB}]} + E_b/N_{0\,[\text{dB}]} \tag{3.13}$$

By using a propagation model and the link budget, the maximum coverage radius of a certain cell can be determined. The propagation model is a function for the median of the propagation attenuation that depends, among other things, on the distance between the BS and the MT, d . Therefore, the radius of a cell is given by d , where the function of the propagation model, $L_P\left(d\right)$, is equal to the maximum possible value for the propagation attenuation, $L_{P\max}$, which is obtained from (3.7), considering P_r as $P_{r\min}$.

The propagation models usually used for outdoor environments are the COST 231 – Okumura-Hata and the COST 231 – Walfisch-Ikegami ones, [Corr03], [DaCo99] and [Pars92]. The COST

231 – Okumura-Hata model is based on an extensive campaign of measurements in the city of Tokyo, which led to some mathematical expressions. The model takes into account factors like frequency, distance, antenna's height and type of environment, their values having a validity limit. Applying some correction factors, some adaptations to several different environments can be made. The COST 231 – Walfisch-Ikegami model estimates the attenuation by studying the fields that are reflected by streets and buildings surrounding the MT, and the diffraction caused by the set of buildings that penetrate the first Fresnel ellipsoid.

There are validity domains for the values of the several parameters. Both models are recommended for an urban environment. The COST 231 – Okumura-Hata model is usually used for distances greater than 5 km, while the COST 231 – Walfisch-Ikegami one is used for smaller distances. The propagation model that was chosen for this thesis is the COST 231 – Walfisch-Ikegami one, since the simulations are made in a city, and the cell radius is normally below 1 km, Annex A.

The determination of the cell radius is described in detail in Annex B. The cell radius can change, decreasing when the cell is loaded, since M_i increases. For the nominal cell radius calculation, the method used is the same, M_i being fixed.

The BS antennas can be omni-directional or sectorised, the antenna radiation pattern, as well as the coverage area, being completely different for the two cases.

3.4 Network Coverage Optimisation

This work aims at simulating a network, verifying coverage gaps and placing extra BSs in the best locations, in order to optimise the system. A network can have a good coverage in the service area when considering the nominal cell coverage area; however, when the cells are loaded, these cell coverage areas become smaller and coverage gaps can appear. Moreover, the change of the spatial traffic distribution can lead to the appearance of uncovered areas with a high traffic level. For these situations, it is important to fill in the uncovered area with new BSs. In order to do this, an efficient algorithm must be defined: one that places BSs in an automatic way, taking into account the traffic distribution.

The problem that one has in hands is typically a **L**ocation **S**et **C**overing **P**roblem (LSCP), developed by Toregas et al., [ToSR71], which aims at finding the minimum number of BSs as well as their location, to obtain a certain coverage, [MuKe02]. The LSCP can be applied to discrete or continuous spaces. In the former, there is a finite number of BS candidate locations, spread on the area that is supposed to be covered. The goal is to discover which sub-set of these points is the best. In the latter, one may locate a BS anywhere in the studied area, or, in other words, there is an infinite number of BS candidate locations. This latter case has a much more complex resolution. The LSCP for a discrete space can be formulated in the following way:

Minimise

$$\sum_{j} x_j \tag{3.14}$$

Subject to

$$\sum_{j \in N_i} x_j \geq 1 \qquad ,\forall i \tag{3.15}$$

$$x_j = \{0,1\} \qquad ,\forall j \tag{3.16}$$

where:

- j is the index of the potential BS locations;
- x_j is the decision variable related to the potential BS location j, which is equal to 1 when the BS site is selected and equal to 0 otherwise;
- i is the index of locations that must be served;
- N_i is the set of BSs that cover area i:

  $$N_i = \{ j | d_{ij} \leq D \}$$

  D being the effective coverage distance of a BS, and d_{ij} the shortest distance between area i and the potential location site j.

Equation (3.14) aims at minimising the number of potential BS sites selected in the final solution, while constraints (3.15) specify that each location i must be covered by at least one BS. Constraints (3.16) assure that the decision variables are only equal to 0 or 1, being limited and discrete. As one can easily see, the number of decision variables is equal to the number of potential BS sites, and the number of constraints of the LSCP is equal to the sum of the latter one with the number of locations to be covered. Therefore, the complexity of the resolution of this problem is too high. There are, however, some algorithms that try to solve this problem in an efficient way.

A literature survey was made concerning this subject and some works were found. In all of them, an assumption is made: there is a set of candidate sites where the BSs can be installed, i.e., the operator already knows a limited set of places where a BS can be placed (discrete space). This set depends on an existing negotiation with the terrain owners and other entities. Besides, the set can be limited due to authority constraints on new BS installation and on electromagnetic pollution in urban areas. Then, an algorithm to optimise the sub-set of the BS locations is used.

A brief explanation of some of the optimisation algorithms can be found in [MoAT99]. In all of these algorithms, a set of control nodes that represents the surface to be covered is used, as described in the LSCP. The goal is to find the smallest sub-set of possible BSs that provides coverage to all the control nodes. The reason to find the smallest possible sub-set is obvious. Less installed BSs leads, in a first approach, to less interference in the system and costs less to the operator. The *Greedy Algorithm* is the simplest algorithm. At first, it selects the BS that covers most of the control nodes, both being removed from the studied area; these steps are repeated, over and over again, until the coverage of all control nodes. In general, the runtime of this algorithm is smaller than the other ones. The *Genetic Algorithm*, [Darr03], is a popular optimisation method, which is inspired by the evolution. The first step is to generate an initial population of possible solutions that are normally chosen in a random way. Then, for each population element (also called by chromosomes), an evaluation is made and a value for the reproductive opportunity is attributed. Thus, chromosomes that represent a better solution to the target solution will get a greater change to *reproduce* than the ones that correspond to poorer solutions. Selection, recombination and mutation are applied to each population generating a *next population*. This procedure is repeated until a good solution is reached. The *Combination Algorithm for Total Optimisation* is a method that follows a combinatorial approach. The principle is simple: the algorithm tries all the possible BSs combinations and selects the best one. The number of combinations is given by the following equation:

$$N_C = \sum_{k=1}^{k=N_{BS}} \frac{N_{BS}!}{k!(N_{BS}-k)!} \tag{3.17}$$

where:

- N_{BS} is the total number of possible BSs in the area under study.

So, one can see that the number of combinations increases a lot with the number of candidate sites, Figure 3.5. Therefore, limitations regarding runtime must be seriously taken into account. One way to implement this algorithm is to split the total number of possible BSs into smaller groups that are randomly selected. As the number of elements in each group is smaller the processing time is also smaller. Then, the optimal solution for each group is found, and a unique group of these best solutions is made. The process is repeated until the number of solutions cannot be further reduced.

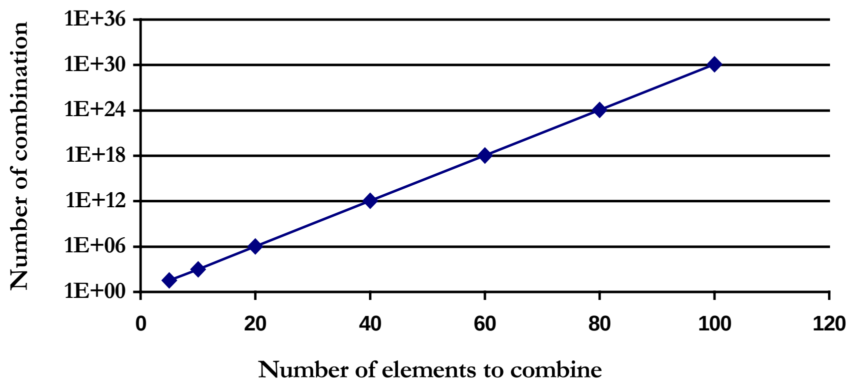


Figure 3.5 – The increase of combinations with the number of candidates sites for placing BSs.

Examples of works that deal with the placement of BSs on uncovered areas are [KoFN02] and [Hurl00], where optimisation is achieved using the *Simulated Annealing* algorithm. In [HPCP01] and [PaYP02], genetic algorithms are used, and in [AmCM03] 3 optimisation algorithms are tested: *Randomized Greedy*, *Reverse Procedures* and *Tabu Search*.

There is another algorithm used by [Huan01] that uses a layer method for the BS position optimisation, reducing the computational complexity. It begins to divide the whole study area in pixels with a very low resolution, all of them being possible BSs sites. Then, the algorithm chooses the best sites for placing new BSs, basing the choice in some criteria like transmission power, interference or user coverage. Afterwards, the resolution is increased in the chosen pixels by dividing them into several smaller ones. Now, the new possible BS sites are these new pixels. This method is repeated until the wanted grid resolution is reached. It can be seen that, with this algorithm, the complexity of the BS location optimisation is much lower, achieving, nevertheless, good results.

As one has already mentioned, all these algorithms deal the problem in discrete spaces, where BSs can only be in a finite set of possible locations, and the complexity of the problem is high. In this thesis one wants to work in a continuous space, without no restrictions concerning BS location; therefore, a new algorithm was developed: one that places BSs in the best location without having pre-defined possible locations, using different heuristics for different kind of uncovered areas. Besides, it takes into account not only the uncovered surfaces, but also the existing multi-service traffic distribution in the area.

3.5 Performance Parameters

In every network dimensioning, it is important to have some network parameters, the so-called performance parameters, that show the network performance for certain configurations; therefore, it is possible to compare configurations and choose the best one, which leads to the best set of performance parameters.

In a CS connection, one of the performance parameters that must be considered is the blocking probability, P_b, [Rapp92]. A call is blocked when it is initiated at a moment when all the physical channels are unavailable. The blocking probability is given by:

$$P_b = \frac{N_b}{N_{CS}} \tag{3.18}$$

where:

- N_b is the number of blocked call in the system;
- N_{CS} is the total number of CS calls.

The blocking of a call is always undesirable, so, the blocking probability must be small in any good communications network. Normally, systems have a blocking probability below 2 %, around 1%.

In a PS connection, a call is never blocked, because there are no channels dedicated to a single user. In fact, several users share the same channel, therefore, the transmission of a packet is delayed for a certain amount of time. In a way similar to the blocking probability, the delay probability, P_{del}, is given by:

$$P_{del} = \frac{N_d}{N_{PS}} \tag{3.19}$$

where:

- N_d is the number of delayed call in the system;
- N_{PS} is the total number of PS calls.

This probability has also to be small, although a delayed packet is less undesirable than a blocked call.

There is also the uncovered users percentage, given by:

$$P_{unc} = \frac{N_{unc}}{N_{user}^{network}} \tag{3.20}$$

where:

- N_{unc} is the number of uncovered users in the network;
- $N_{user}^{network}$ is the total number of users in the network.

The mean packet delay, $\overline{\tau}_{delay}$, and the average of the real throughput that is served to the user, $\overline{R}_b^{real}$, which is lower than the theoretical one due to packet delays, are performance parameters that are usually used in systems with PS traffic. In this work, the simulation is static; therefore, it does not analyse the temporal evolution of the network. These parameters cannot be calculated, hence, they are not considered. Other parameters used in mobile communications networks are the drop call probability, P_d, and the handover failure probability, P_{hf}. This work does not take into account the mobility of the users, therefore, these parameters are not considered as well.

In this work, as the users throughput can be decreased before his/her blocking in the cell, one uses the **R**elative **E**ffective **T**hroughput (RET) and the **D**elayed **R**elative **E**ffective **T**hroughput (DRET), [FaDi03]. RET gives a notion on how much the user throughput is decreased in the network, while DRET indicates the average value of the throughput for users which throughput was reduced. Since the lowest data throughput is 64 kbps, these parameters can be calculated for users that have a throughput equal to 128 or 384kbps, their values being given by:

$$RET_{384} = 1 - \frac{\left(1-\frac{128}{384}\right)\cdot N_{user384-128} + \left(1-\frac{64}{384}\right)\cdot N_{user384-64}}{N_{user384}} \tag{3.21}$$

$$DRET_{384} = 1 - \frac{\left(1 - \frac{128}{384}\right) \cdot N_{user384-128} + \left(1 - \frac{64}{384}\right) \cdot N_{user384-64}}{\left(N_{user384-128} + N_{user384-64}\right)} \tag{3.22}$$

$$RET_{128} = 1 - \frac{\left(1 - \frac{64}{128}\right) \cdot N_{user128-64}}{N_{user128}} \tag{3.23}$$

$$DRET_{128} = 1 - \left(1 - \frac{64}{128}\right) = 0,5 \tag{3.24}$$

where:

- $N_{user384}$ is the number of users that have a throughput of 384kbps;
- $N_{user384-128}$ is the number of users which throughput is reduced from 384 to 128 kbps;
- $N_{user384-64}$ is the number of users which throughput is reduced from 384 to 64 kbps;
- $N_{user128}$ is the number of users that have a throughput of 128 kbps;
- $N_{user128-64}$ is the number of users which throughput is reduced from 128 to 64 kbps.

These parameters can vary from 0 to 1, being equal to 1 when none of the user throughput is decreased and becomes lower with the decreasing of the users throughput. Besides, a greater user throughput decrease leads to a greater RET and DRET decrease. As the 128 kbps users can only be reduced to 64 kbps, then, the $DRET_{128}$ value is always equal to 0.5, as it has been already shown.

Other useful parameters are the η_{DL}, η_{UL} and P_{Tx}^{BS} for all network cells. These parameters, which are presented in Section 3.1, are important, because they show what is the cause for either the reduction of the user throughput or the user blocking/delay.

The global transfer rate, R_{global}, is given by:

$$R_{global} = \sum_{j=1}^{N_{users}} R_{bj} \tag{3.25}$$

and shows the total information throughput that is being handled by the cell.

There are other parameters that help on the evaluation of network performance in terms of the placement of BSs and their coverage. One is the mean uncovered traffic density given by:

$$\overline{T}_{unc}^{dens}[km^{-2}] = \frac{T_{unc}}{A_{unc}[km^{2}]} \quad (3.26)$$

where:

- T_{unc} is the traffic that is not covered by the network;
- A_{unc} is the uncovered area.

A_{unc} is given by:

$$A_{unc} = A - A_{\text{cov}} \quad (3.27)$$

where:

- A is the whole service area;
- A_{cov} is the area covered by the BSs, being calculated without considering the superposition of several sectors.

There is also the percentage of the area that is covered by a certain number of sectors; for a number greater than one, this area corresponds to a SHO area. This parameter is defined by:

$$A_{BS}^{n}\% = \frac{A_{BS}^{n}}{A} \quad (3.28)$$

where:

- A_{BS}^{n} is the area covered by n sectors. Although this area belongs to several sectors, it is considered only once in the parameter calculation.

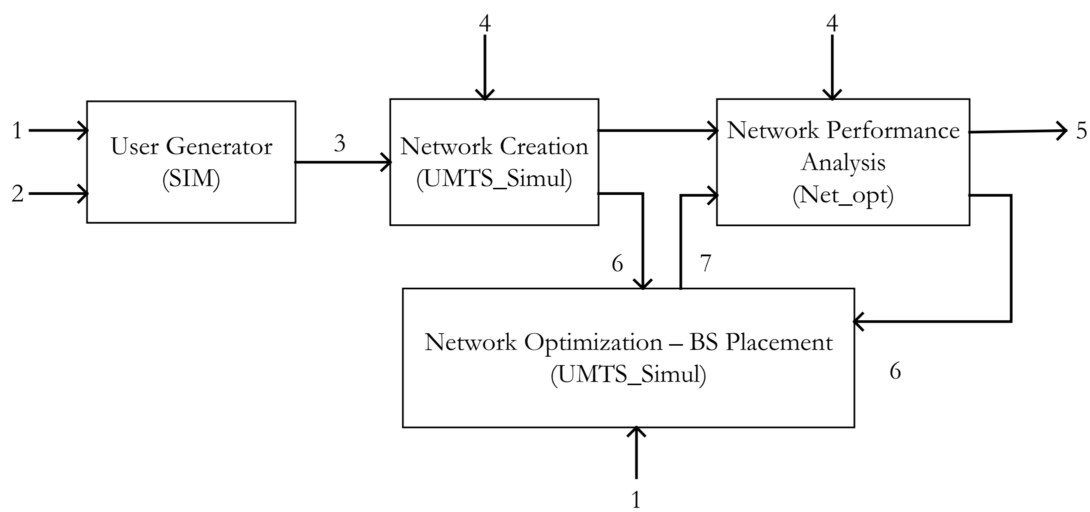
Chapter 4

Model and Simulator Development

This chapter describes the models that are used by the algorithm that places new BSs in an initial network regarding the improvement of its coverage. One also shows the implementation of the algorithm in a simulator, which also makes the performance analysis of a network.

4.1 Simulator Overview

The simulator developed in this work is based on [SeCa04], some problems having been fixed and new features having been added. It deals with many different things that are related with the network; therefore, it is divided into four main blocks: User Generator, Network Creation, Network Performance Analysis, and New BS Placement, Figure 4.1.



1 – Traffic distribution.
2 – User characteristics and operational environment.
3 – Information regarding generated users.
4 – Network characteristics.
5 – Network performance parameters.
6 – Network coverage information.
7 – Information about the new BSs on the network.

Figure 4.1 – Simulator scheme.

For User Generator, Network Creation, and Network Performance Analysis blocks, one has used the routines already developed in [SeCa04], some improvements being made in the last two blocks. However, the existing BS Placement algorithm was replaced completely by a new one, which was developed in this thesis, because the old one spreads new BSs in a uniform way and without taking into account the traffic distribution.

The User Generator block is responsible for the generation of all active users that request a service from the network. Each user has associated information that is needed for the Network

Performance Analysis block. In order to do this, the simulator receives as input data the traffic distribution for all services that can be provided by the network, the operational environment, and user characteristics.

The next step in the simulation is the creation of the network, which is performed by the second block, Network Creation. Information about the network BSs is loaded, BSs being placed in the area. The nominal cell radius is calculated using a propagation model, and the nominal coverage area and the active users are represented in the network. By knowing the network characteristics, like the maximum BS transmission power, and the users that are covered by each sector, it is possible to perform the network analysis.

The Network Performance Analysis block loads all the sectors with the corresponding users, each one with its own services, calculates the performance parameters, and updates the network coverage using the new radius for each cell.

The BS Placement block is responsible for the placement of new BSs in the network in order to improve its coverage. The insertion of a BS considers not only the uncovered area but also the existing traffic in those same areas, therefore, a spatial traffic distribution is needed as input. This block can run after the Network Creation block or after the Network Performance Analysis one, using the nominal coverage area or the real coverage area, respectively.

4.2 User Generator

The User Generator used in this work is the same from [SeCa04], which was developed in *C++*. It loads information on the spatial traffic distribution and operational environment, like the ones provided by Vodafone and obtained from the MOMENTUM project [MOME04]. As a result, one has a realistic generation, where users are spread in the area according to the traffic distribution, and have their own characteristics, like the service, the penetration attenuation (L_F) and mobility.

4.2.1 Input and Output Data

The generator needs 3 types of input data: the operational environment, the spatial traffic distribution, and the percentage and the penetration attenuation values for the several user scenarios.

The information on the operational environment is organised in a grid of pixels, each one with a value that represents the type of terrain, Table 4.1. The characteristics of the grid have to be previously defined: the generator has to know what is the dimension of the grid, the area that is covered by each pixel, and the geographic coordinates of the first pixel (**U**niversal **T**ransverse **M**ercator (UTM) Cartesian projection system, based on the **G**eodetic **R**eference **S**ystem 1980 (GRS – 1980) spheroid).

Table 4.1 – MOMENTUM operational classes, [FCXV03].

Pixel value	Class	Description
1	Water	Sea and inland water (lakes, rivers).
2	Railway	Railway.
3	Highway	Highway.
4	Highway with traffic jam	Traffic jam in a highway, corresponding to a lot of cars stopped, or moving at a very low speed.
5	Road	Main road of relatively high-speed users, typically inserted in suburban and rural areas.
6	Street	Street of low-speed users, typically inserted in an urban area.
7	Rural	Rural area with few buildings, much vegetation and a low population density.
8	Sub-urban	Sub-urban area with medium building, vegetation and population densities.
9	Open	Small pedestrian land area surrounded by mean urban, dense urban, or residential areas.
10	Urban	Areas with both high building and population densities, and few vegetation.
11	Central Business District (CBD)	Area with very high building density, with almost no vegetation. The population density is very high, and it has much tertiary sector population.

The spatial traffic distributions are organised in grids that are similar to the operational environment ones. However, there is one grid for each network service, each pixel having the value of the number of BHCA, λ_{BHCA}, (BHCA grids).

As previously mentioned, the generator associates different characteristics (penetration attenuation and mobility) to each user. In order to do that, the software user needs to define the percentages for the several user scenarios, outdoor, urban indoor, sub-urban indoor, and rural indoor, where different penetration attenuations are used. The mobility type that is considered in each operational class must be also defined. All these values can be modified in a specific window of the generator, Figure C.5.

At the end of the generation, the software saves into an output file the information on all generated users: identification, geographic coordinates of its location in UTM Cartesian projection system based in the GRS – 1980 spheroid, service, penetration attenuation and mobility.

4.2.2 Algorithm

Initially, the user generation algorithm finds the number of users that have a certain service, Figure D.1. This can be made by considering the number of users in each pixel as a result of a Poisson process with an average of λ_{BHCA}, which is obtained from the BHCA grids information for the corresponding pixel and service. In this case, the location of the user is the same as the pixel that generates him. However, one can easily see that, for small pixels, the λ_{BHCA} values are very small in the majority of the cases; therefore, it is difficult to generate users pixel by pixel and achieve the wanted user distribution.

Thus, another approach is taken: the idea is to calculate the total number of users by using a Poisson process with an average that is equal to the sum of λ_{BHCA} from all pixels of the BHCA grid of a certain service. Now, the location of each user must be found in a different way, because there is no correspondence between the users and the pixels: a pixel must be allocated to each user in a way that the user distribution is the wanted one. This is done by the following method, Figure 4.2:

1. The probability for a user to be in the pixel is associated to every pixel, being considered to be equal to the corresponding λ_{BHCA};

2. A vector with the cumulative probabilities of all pixels is built;
3. For each user, the variable X with a Uniform distribution between 0 and 1 is generated;
4. The value Y is obtained by multiplying the X value by the cumulative probability of the last pixel;
5. The pixel allocated to the user is the one that has a cumulative probability equal or higher than Y.

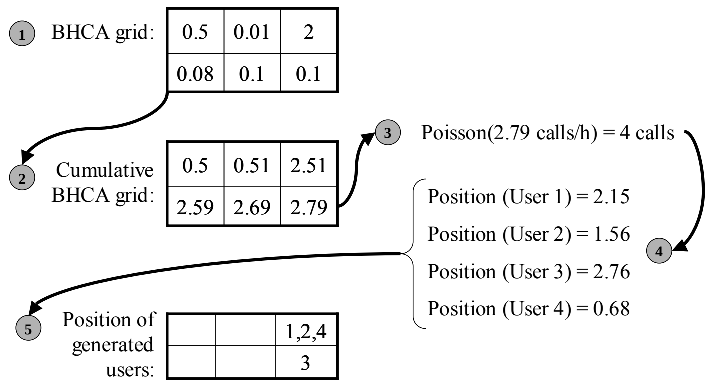


Figure 4.2 – User generation algorithm, [FCXV03].

By knowing the pixel that is allocated to each user, it is now possible to define the location of the users:

$$x_{[\mathrm{m}]} = \left\lfloor \left(n_{pixel} \,\%\, dim_x\right) \cdot dim_{pixel\,[\mathrm{m}]} \right\rfloor + x_{1[\mathrm{m}]} \tag{4.1}$$

$$y_{[\mathrm{m}]} = y_{1[\mathrm{m}]} - \left(\frac{n_{pixel}}{dim_x}\right) \cdot dim_{pixel\,[\mathrm{m}]} \tag{4.2}$$

where:

- x and y parameters are the horizontal and vertical geographic coordinates location of the user in UTM Cartesian projection system based in the GRS – 1980 spheroid, respectively;
- n_{pixel} is the number of the pixel that the user is associated to;
- dim_x is the horizontal width of the grid in number of pixels;
- dim_{pixel} is the width of the pixel in metres;
- $\left(n_{pixel} \% dim_x\right)$ is the remain of the entire division of n_{pixel} by dim_x;
- x_1 and y_1 are the coordinates of the first pixel of the BHCA grid.

Using the operational environment grid, it is possible to know the operational class where the user is; then, the corresponding user scenario can be generated using the respective percentages. Finally, the penetration attenuation and the mobility of the user are found by using the correspondence between the last two parameters and the user scenario or the operational class, respectively. The service of the user is known, since the user generation is performed service by service.

When the user generation is complete for a certain service, the algorithm repeats all steps described before for the new service. In the end, the software saves all the information into an output file.

4.3 Network Creation

The Network Creation block is developed in *MapInfo* [MAPI04] in order to take advantage of the existing **G**eographic **I**nformation **S**ystem (GIS) tools. It loads the information about the network and displays it in the area under study.

4.3.1 Input and Output Data

The information that is needed by the software block can be classified into 3 groups of data related with users, with the network, and about the service area.

The data about the network users created in the user generation is loaded. It is a file where the users and all the important characteristics are represented: identification, location, service, penetration attenuation and mobility. Then, the users are displayed in the area.

The information regarding the network is distributed by the following files, which are loaded by the simulator:

- *Network.dat* – file with the location of all the network BSs. The location is represented in longitude/latitude coordinates.
- *R_pattern.dat* – table with the transmission antenna gain of the network BSs for all the horizontal arrival angles (assumed to be equal for all BSs).

- *Eb_No.dat* – table with the values of the ratio between the bit energy and the noise power spectral density for the several service bearers in UL and DL.

Other information, like the maximum BS transmission power, maximum UL/DL load factors, number of carriers, reference service bearer, and user scenario, can be modified in a related window of the program.

For the definition of the area under study, the simulator user can modify some parameters that are used in the propagation model: building height, street width, width between buildings' centres, etc. Moreover, there is more information saved in other files:

- *Dados.dat* – file with some information about the district borders of the area under study, and statistical information in each district like the number of person for each age range.
- *Zonas.dat* – file with information about the characterisation of each area, and the location of streets, avenues and bridges.

At the end, the block provides two output files:

- *Definitions.dat* – file with all values of the several defined network parameters, like the parameters used in the propagation model, the maximum DL/UL load factors, the interference margins in UL/DL, the nominal cell radius, the active set, the services offered by the network and the number of available carriers.
- *Data.dat* – file with the information of the covered users.

4.3.2 Algorithm

The software starts by asking its user the location of the *Dados.dat* and *Zonas.dat* files on the hard disk, displaying a map of the service area like, for instance, the one shown in Figure 4.3. Then, the network users are loaded, being saved into a table; the simulator checks for users located outside the service area and erases them. The users that are located inside the service area are placed in the map, being represented by multicolour flags, each colour corresponding to a different service, Figure 4.4. The services that are offered to the network can be defined in an adequate window. When the name of one of the services that are defined in the window does not correspond to the one saved in the user generation output file, the simulator does not recognise that service and does not load the corresponding generated users into its internal table. The maximum number of services that can be defined is 8.

All BSs are placed in the area and the nominal cell radius, which is equal for all the BSs, is found by using the radiation pattern of the BS antenna and the method described in Annex B, where the COST 231 – Walfisch-Ikegami propagation model is used, Annex A. The simulator finds the coverage cell radius considering a pre-defined reference service bearer and a reference user scenario for both UL and DL, the nominal cell radius being the more restricting one. Then, using the radiation pattern of the BS antenna, the nominal coverage area of each sector is drawn and displayed in the map, where all BSs have 3 sectors, Figure 4.5, and one can see the total coverage of the network for a certain reference scenario, Figure 4.6. One should note that a sector only has three possible orientations: 0 º, 120 º and 240 º from the North direction. Moreover, there is always a SHO area that is intersected by more than one sector. It is also possible to load the network coverage area from files obtained from previous simulations.

Figure 4.3 – Map of Lisbon.

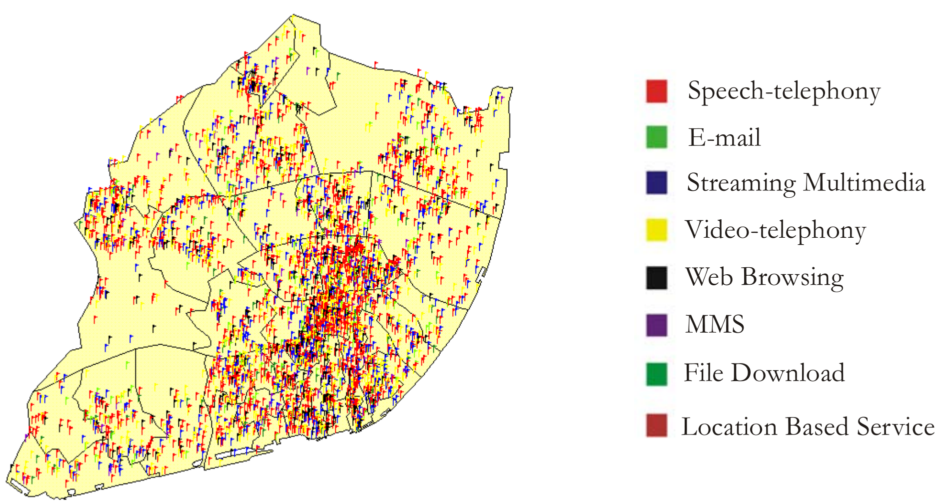


Figure 4.4 – Map of Lisbon with 5000 generated users.

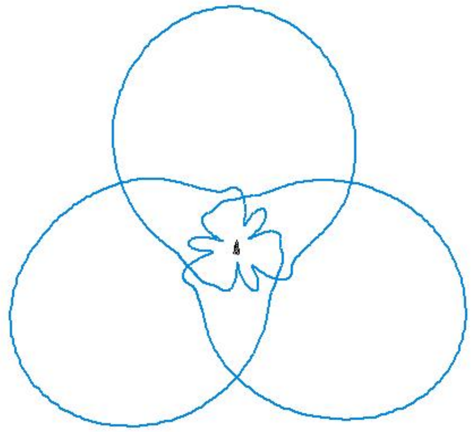


Figure 4.5 – Nominal coverage area for the three sectors of a BS.

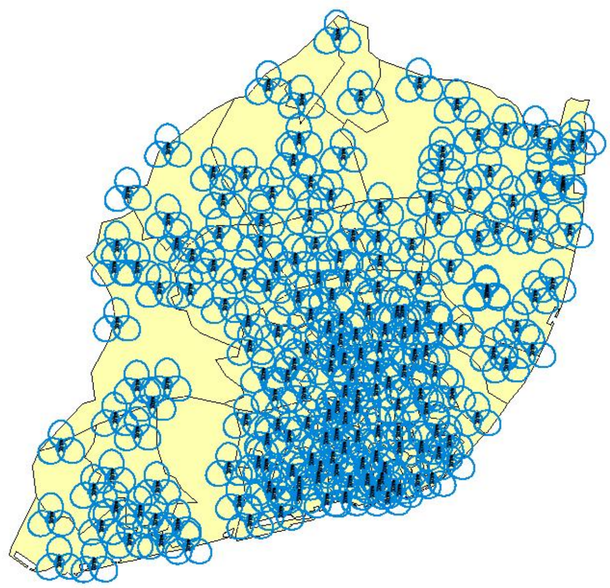


Figure 4.6 – Lisbon's network coverage for a 128 kbps (PS) reference service bearer and a vehicular reference user scenario.

Finally, the Network Creation block finds the users that are covered by each sector of the network in order to provide this information to the Network Performance Analysis block. One simple way to achieve this, which is performed in [SeCa04], is to find the users that are inside the nominal coverage area of a certain sector, which can be easily done by using the *MapInfo* tools. However, there can be other users that, being outside the nominal coverage area, are covered by the sector because they have less restrictive service bearers. One has seen that the error in finding the users that are covered by a certain sector can be equal to 64,7 % in the worst case.

In this work, this problem is fixed by temporarily change the nominal cell coverage radius. In fact, the simulator calculates a new nominal cell coverage radius by considering the less restricted service bearer for both M_i and L_F equal to zero, the nominal coverage area of the sectors being updated. This way, it is assured that all users outside this new area are not covered by the corresponding sector, so the software block only has to select the inside users and save them to an output file. There are inside users that will be not covered by the sector, because they have a more restrictive service bearer than the reference one or/and have a high L_F; however, they will be treated in the Network Performance Analysis block. Finally, the former nominal coverage area is drawn.

4.4 Network Performance Analysis

The Network Performance Analysis block receives information about the network (BS parameters, coverage) and the active users created by the User Generator, and finds the performance parameters for a certain scenario. It was developed mainly in *C++*, which is a faster programming language than the *MapBasic* one, in order to decrease the runtime of each simulation.

4.4.1 Input and Output Data

The input data of this block is composed of 2 files that have information about the network, and the covered users, both provided by the Network Creation block (*Definitions.dat* and *Data.dat*, respectively).

At the end of the analysis, some parameters related with the network are calculated, being saved into output files:

- *Users.out* – file where all the information about the users is stored, like the number of blocked, delayed and uncovered users, the number of PS and CS users, and also the list of served users with information about the service bearer requested to the network and the one that is offered by it.
- *Data.out* – file with the data about the network sectors, like the number of used carriers, the UL/DL load factors, the radius, and the number of served users.

4.4.2 Algorithm

The Network Performance Analysis block starts to load the users that are covered by each sector from the file provided by the Network Creation block (*Data.dat*), placing them in a specific data structure to be used by the software, Figure D.3. Basically, this structure is composed of a simple list of BSs, each object having the BS's identification, a pointer to the next object and a three-element vector, containing pointers for objects that represent the BS's sectors. Each sector has information about itself and pointers to structures that represent the users that are connected to it, being composed of lists containing information about the user: identification, location, service, penetration attenuation, etc. There is a list for the served users, another for the blocked or delayed ones, and still another for the users in hard handover.

One has already seen that there are users that are provided by the Network Creation block for a certain sector and are not covered by the latter one, so, the simulator has to clear these users from the created structure. For every user, the software calculates the coverage distance for the characteristics of the considering user (service bearer, user scenario and penetration attenuation). If d is higher than the calculated one, the user is deleted from the BS object, because it is not covered by it. The number of uncovered users is written in an output file.

The structure is updated, considering the active set, therefore, a certain user is connected to a number of sectors that is always below the active set value, giving priority to the sectors with lower link attenuation. Moreover, a new feature is added into the original simulator: the active set threshold. Now, a user is only connected to a sector if the active set is not surpassed, and if the link attenuation is not a certain value (active set threshold) above the lowest one; the value of the parameter is taken as 5 dB. Although the value of the active set is normally equal to 3, it can be defined in the adequate simulator window.

Next, the simulator starts to run a cycle where it goes through all sectors, allocating a certain carrier to each one of the covered users, Figure D.4. This allocation is made by a method that assures that the sector load is equally spread through all available frequencies, Figure D.5. The maximum number of available carriers in the network is equal to 4, which is the number of available carriers for each Portuguese operator. The algorithm provides the first carrier to all users, testing the UL/DL load factors, the BS transmission power and the number of equivalent occupied codes. If one of these tests fails, the number of available frequencies is incremented and the process is repeated again until the success of all tests. If one of the tests fails and the maximum number of available frequencies has already been reached, the simulator blocks, one by one, the users that are outside the sector nominal coverage area, starting with the farthest one. At the end, when all outside users are blocked and the requirements are not fulfilled yet, the simulator decreases the service bearer rate of the users until the reference service bearer is reached, starting with those that have the highest throughput. For users near the coverage area bound, the throughput can be decreased to a level below the reference service bearer one. Finally, if none of this works, the cell radius is decreased by 5 %, all users being outside the new sector coverage area blocked; the steps described above are repeated again. In every frequency allocation, the algorithm analyses if any user is in hard handover, that is, if it is connected to another sector by a different carrier. If so, it is placed in the hard handover list of the sector.

When a user is blocked in the end of the frequency allocation algorithm, he/she is placed in the blocked or delayed users list. If the user is in hard handover in other sectors, these latter ones will try to serve him/her: he/she is placed again in the lists of connected users of those sectors, and the algorithm is repeated for those same sectors.

Another cycle is ran to find users that are in soft handover, being connected to different sectors by links with different throughputs, which is not allowed. In these cases, 2 different methods can be applied to the user. In the first one, all connection rates of the user are decreased to the lowest one; in the other, which is used by default, the user is blocked in the sector where he/she has not the higher throughput, therefore, the soft handover gain is decreased but the user gets a higher service bearer bit rate.

The number of blocked or delayed users is calculated by verifying if each user in the blocked/delayed users lists is connected to another sector. If not, the user is considered to be blocked or delayed, considering CS or PS, respectively.

Finally, all this information is provided to the *MapInfo* developed part, where the new sector coverage areas are represented, Figure 4.7, and the performance parameters are shown and saved into the *output.dat* file. The simulator also finds the maximum, the minimum and the average of some performance parameters along the several sectors, and writes them into a proper file: *max_tab.tab*, *min_tab.tab* and the *avg_tab.tab*, respectively.

4.5 New Base Station Placement

Sometimes, the original network is not sufficient to cover the whole service area when considering the nominal coverage area or the real one, obtained from the Network Performance Analysis block. Then, it is important to place new BSs where there is no good network coverage, which is exactly what the New BS Placement block does. In [SeCa04], an automatic way of placing new BS was developed; however, it is done through a uniform BS spreading, and it does not take the traffic in the area under study into account. So, it is not a good algorithm, because it treats equally different kinds of uncovered areas, and it places BSs where there is no significant traffic. Thus, a new algorithm is developed in this work.

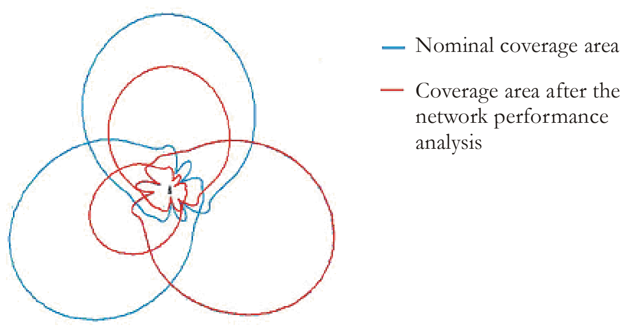


Figure 4.7 – The difference between the nominal coverage area and the one obtained after the network performance analysis for a certain BS.

4.5.1 Models

The simulator developed in this work uses GIS graphical tools, therefore, needs information about the global spatial traffic distribution: one grid with information about all the 8 services traffic. In order to obtain this, an algorithm was developed. A very simple approach is to simply add the 8 grids for the several services. However, this is not a very realistic model in the sense that a user with a higher bit rate introduces a higher load to the network. The model used in this work finds the equivalent DL load factor for each pixel from the BHCA grids.

The information transmitted per hour within a single pixel is found for each service using the following expressions:

$$C^{BH}_{serv[\text{kb}]} = \lambda_{BHCA} \cdot \overline{V}_{[\text{kb}]} \qquad (4.3)$$

$$C^{BH}_{serv[\text{kb}]} = \lambda_{BHCA} \cdot \overline{R}_{b[\text{kbps}]} \cdot \overline{\tau}_{[\text{s}]} \cdot \upsilon \tag{4.4}$$

where:

- C^{BH}_{serv} is the information transmitted in the busy hour per service;
- λ_{BHCA} is the number of BHCA;
- $\overline{R}_b$ is the mean throughput;
- $\overline{V}$ is the average DL session volume data;
- $\overline{\tau}$ is the mean service time of a call.
- υ is the activity factor.

Expression (4.3) is used for PS services, while (4.4) is used for CS ones. A service can have different service bearers, each one with different bit rates; therefore, the previous expression must consider the mean transmission throughput for each service:

$$\overline{R}_{b[\text{kbps}]} = \sum_{bearer} P^{user}_{bearer} R^{bearer}_{b}{}_{[\text{kbps}]} \tag{4.5}$$

where:

- P^{user}_{bearer} is the percentage of users with a service bearer within a certain service
- R^{bearer}_{b} is the transmission throughput of the service bearer.

The mean number of active users, $\overline{N}^{active}_{users}$, is calculated by:

$$\overline{N}^{active}_{users} = \frac{C^{BH}_{serv[\text{kb}]}}{3600 \cdot \overline{R}_{b[\text{kbps}]} \cdot \upsilon} \tag{4.6}$$

This means that the number of active users at any moment within the busy hour is, on average, equal to $\overline{N}^{active}_{users}$.

The average DL load factor per user and per service, $\overline{\eta}^{user}_{serv}$, is defined by:

$$\overline{\eta}^{user}_{bearer} = \upsilon \frac{E_b / N_0}{R_C / R_b} \left[(1-\alpha) + i \right] \tag{4.7}$$

$$\overline{\eta}_{serv}^{user} = \sum_{bearer} P_{bearer}^{user} \overline{\eta}_{bearer}^{user} \tag{4.8}$$

where:

- $\overline{\eta}_{bearer}^{user}$ is the average load factor for a user with a specific service bearer.

One should note that E_b/N_0, and α depend on the user scenario. Consequently, the result of (4.7) and (4.8) is different from one user scenario to another: it is important to know which is the user scenario that must be considered in each pixel of the grid. This decision is based on the operational environment: each type of environment has a specific associated user scenario.

Finally, the total DL equivalent load factor for a single pixel, considering all services offered by the network, is obtained by the following expression:

$$\eta_{DL}^{equiv} = \sum_{service} \overline{N}_{users}^{active} \cdot \overline{\eta}_{serv}^{user} \tag{4.9}$$

In this work, the BS Placement block has to find, automatically, a possible location of BSs for a good coverage in a continuous space, considering the traffic in the service area. Many heuristics can be used to achieve this objective and it is a good approach to use different heuristics for different situations. In fact, the best algorithm for a certain case can be the worst for another. Thus, it is important to analyse all the uncovered surface cases that can appear in a mobile communications network.

The possible situations can be divided into four main groups, depending on the relation of their area with the BS coverage area:

- **V**ery **S**mall **S**urfaces (VSSs).
- **S**mall **S**urfaces (SSs).
- **M**edium **S**urfaces (MSs).
- **L**arge **S**urfaces (LSs).

An uncovered area is considered to be a VSS if its area is below a given low percentage of the BS coverage area, when considering the reference service bearer. There is no significant impact in the network in placing any BS, so, the best heuristic is the simplest one: to put no BS.

In a first approach, if the surface is small compared with the BS coverage area (SS case), the best thing to do is to put no BS, because, like in the later case, there is no significant coverage improvement on the network in doing it. However, if the traffic in the area is high, above a given hot spot threshold, $\gamma_{hotspot}$, one can consider that the area is a hot spot; therefore, there is an advantage in placing a BS there. The best place for adding the BS is the geometric centre of the uncovered surface: the algorithm places the BS with all the sectors and draws the corresponding coverage areas. In Figure 4.8, the placement of a tri-sector BS, like the ones used in this work, in a hot spot area, as well as the coverage area is shown.

The geometric centre can be found using the mathematic expression for the mass centre, [Apos96]:

$$C_m^x = \frac{\int_{A_{unc}} x\rho(x,y)ds}{\int_{A_{unc}} \rho(x,y)ds} \tag{4.10}$$

$$C_m^y = \frac{\int_{A_{unc}} y\rho(x,y)ds}{\int_{A_{unc}} \rho(x,y)ds} \tag{4.11}$$

where:

- C_m^x is the x coordinate of the mass centre;
- C_m^y is the y coordinate of the mass centre;
- $\rho(x,y)$ is the function representing the mass distribution along the surface;
- A_{unc} is the uncovered surface.

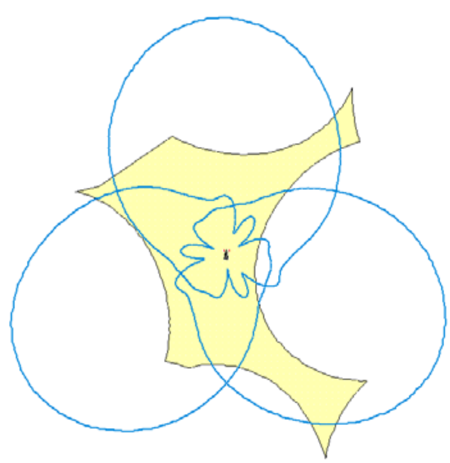


Figure 4.8 – Placement of a BS in the geometric centre of an SS that is considered to be a hot spot.

In this case, the $\rho(x,y)$ function can be associated to the traffic distribution, the point obtained by (4.10) and (4.11) being closer to the higher mass of traffic. Although, this is not the approach taken here, since the point one is looking for is the one that leads to the maximum coverage of the uncovered area, which corresponds to the geometric centre of it. This is obtained by making $\rho(x,y)$ constant:

$$C_m^x = \frac{\int_{A_{unc}} x ds}{\int_{A_{unc}} ds} \quad (4.12)$$

$$C_m^y = \frac{\int_{A_{unc}} y ds}{\int_{A_{unc}} ds} \quad (4.13)$$

The geometric centre is always closer to the main amount of area, and many times it does not correspond to the middle of the surface or/and it may be outside, Figure 4.9.

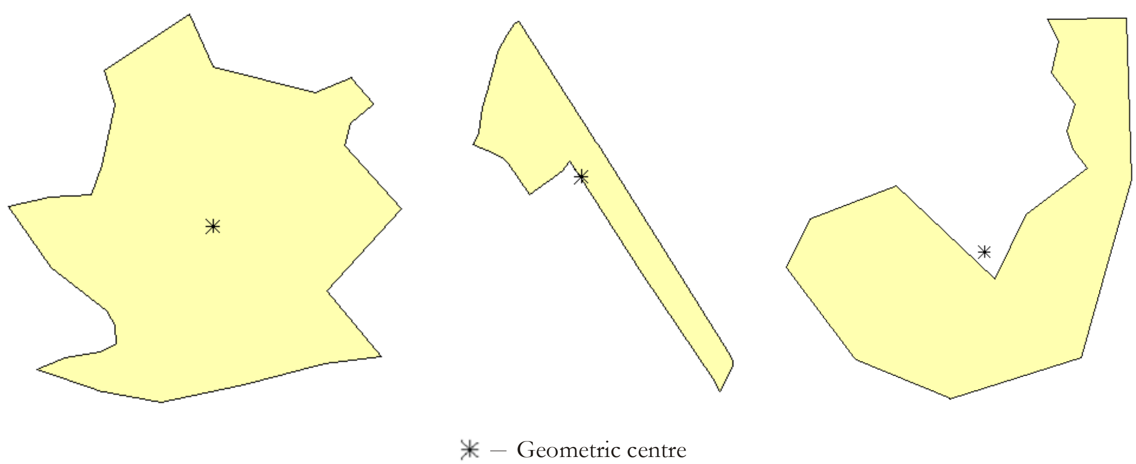


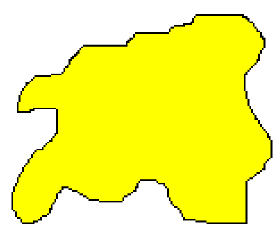
Figure 4.9 – Geometric centre for several surfaces.

Expressions (4.12) and (4.13), by having a surface integration, are not easy to implement in computer programs using a GIS approach. One can easily notice that the only problem is to calculate $\int_{A_{unc}} x ds$ or $\int_{A_{unc}} y ds$: the other integration, $\int_{A_{unc}} ds$, is equal to the area of the surface, A_{unc}, which is very simple to determine using GIS tools. The algorithm for integration divides the surface into several stripes, vertical or horizontal ones according to the x or y coordinate of the geometric centre, respectively. Each stripe i has its own area, A_i, and a coordinate that represents its centre, x_m^i or y_m^i, Figure 4.10, the integrations being obtained by:

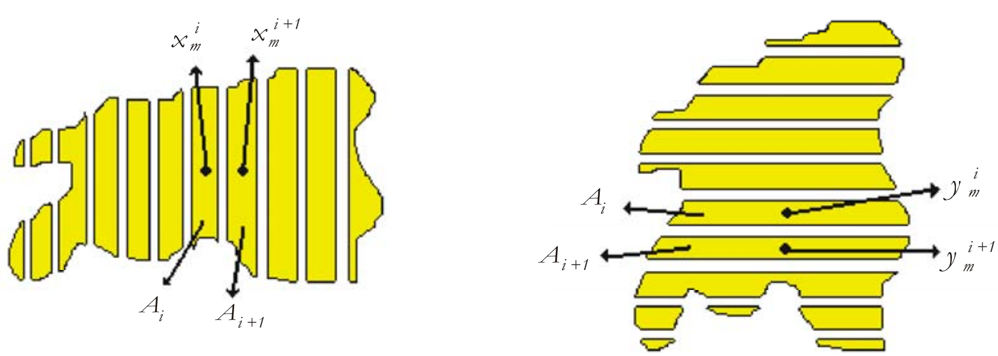
$$\int_{A_{unc}} xds = \sum_i x_m^i A_i \tag{4.14}$$

$$\int_{A_{unc}} yds = \sum_i y_m^i A_i \tag{4.15}$$

When the uncovered area is similar to the BS coverage one, then, it is called a MS. In these situations, it is a good idea to consider the placement of a BS, the best location being, in a first approach, the geometric centre of the surface. However, in some occasions the insertion of an extra BS is not enough to cover successfully an area of this kind, Figure 4.11. If the placed BS only covers a small amount of the uncovered surface, it has to be removed and another placing method must be used: one that spreads several BSs through the surface. In both cases, the placement of an extra BS is only done if the traffic density in the corresponding area is above the traffic density threshold, ζ : in that case, its coverage area must be erased from the uncovered surface and the remaining one must be treated again, using the corresponding heuristic.



(a) Uncovered surface



(a) $\int_{A_{unc}} xds$. (b) $\int_{A_{unc}} yds$.

Figure 4.10 – Algorithm for the calculation of the geometric centre.

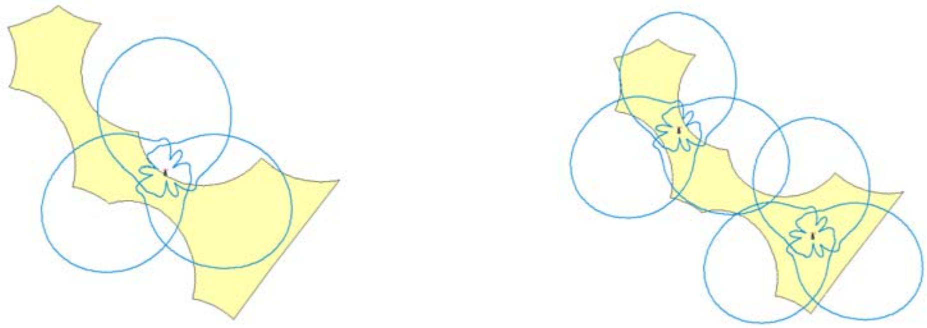


Figure 4.11 – Different approaches in the placing of BSs for MS.

In the last case, LS, the surface is large and several BSs must be placed in order to have a good coverage of the surface. There are many heuristics that can be used to spread BSs throughout the surface. The one used in this work is the following: BSs are placed along a line that is equidistant to the bounds of the uncovered surface, Figure 4.12 (the distance is closer to the nominal cell radius). Furthermore, the distance between two consecutive BSs is always the same and it must be closer to the double of the cell radius. In every BS placement, its coverage area is erased from the surface, and, at the end of the spreading BS algorithm, the remaining area is classified into one of the four groups already described and treated by the corresponding method. Again, a BS is only placed if there is enough traffic.

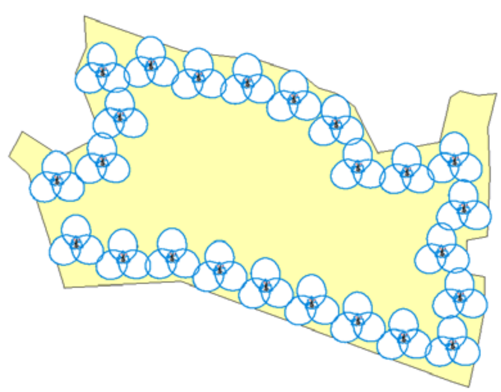


Figure 4.12 – BS spreading through an LS.

For ζ , one can consider the traffic as the offered load of the users, the number of calls in one hour, the volume data transmitted in one hour, etc. In this work, one uses the first option, because is the parameter that represents the load in a better way, and consequently the efficiency, that a BS, placed there, is going to have.

The ζ parameter is expressed in terms of load factor density normalised to the maximum DL load factor. There are many ways to define this parameter: for instance, one can choose a value that leads, in UMTS, to the equivalent efficiency of a GSM BS when it has the minimum traffic considered by the operator for placing a BS. The efficiency in the GSM network is given by:

$$\varepsilon = \frac{N_{ch}}{N_{ch}^{av}} \tag{4.16}$$

where:

- N_{ch} is the number of occupied channels;
- N_{ch}^{av} is the number of available channels.

For having the same efficiency in UMTS, the traffic inside a sector must be:

$$\eta_{thresh}^{\sec} = \varepsilon \cdot \eta_{\max} \tag{4.17}$$

where:

- $\eta_{\max}$ is the maximum load factor.

So, the traffic density threshold normalised to the maximum DL load factor is obtained by the following expression:

$$\zeta_{[\mathrm{km}^{-2}]} = \frac{\eta_{thresh}^{\sec}}{\eta_{\max} \cdot A_{\sec[\mathrm{km}^2]}} = \frac{\varepsilon}{A_{\sec[\mathrm{km}^2]}} \tag{4.18}$$

where:

- $A_{\sec}$ is the sector coverage area.

The $\gamma_{hotspot}$ parameter is expressed in terms of the load factor normalised to the maximum DL load factor. In the hot spot area, the simulator places always a BS with 3 sectors; therefore, the traffic in the area must be the triple of $\eta_{thresh}^{\sec}$. So, the hot spot threshold normalised to the maximum DL load factor is given by:

$$\gamma_{hotspot} = \frac{3 \cdot \eta_{thresh}^{\sec}}{\eta_{\max}} = 3 \cdot \varepsilon \tag{4.19}$$

Besides the performance parameters presented in Section 3.5, one can consider the uncovered equivalent DL load factor traffic density, ξ, and the uncovered traffic in terms of information transmitted in the busy hour, C_{unc}^{BH}. ξ is calculated from a expression based on (3.26):

$$\xi_{[km^{-2}]} = \frac{T_{unc}}{A_{unc[km^2]}} \tag{4.20}$$

where:

- T_{unc} is equal to the uncovered η_{DL}^{equiv} for the uncovered areas, considering only MS and LS.

C_{unc}^{BH} is determined by:

$$C_{unc\,[\text{MB/h}]}^{BH} = \sum_{serv} C_{serv\,[\text{MB/h}]}^{BH} \tag{4.21}$$

where:

- C_{serv}^{BH} is obtained from (4.3) and (4.4), considering λ_{BHCA} for the uncovered areas and for the corresponding service.

4.5.2 Input Data

As mentioned before, the New BS Placement block takes traffic into account; so, the software needs to receive some kind of information about it as an input. The simulator considers the existence of several services, each one with a different spatial traffic distribution, represented by the BHCA grids used in the user generation. Therefore, the input data has to join all this information in order to get a spatial multi-service traffic distribution: the η_{DL}^{equiv} distribution. This information is organised in a grid of pixels similar to the BHCA ones.

As the spatial η_{DL}^{equiv} distribution depends on the service bearer distribution, (4.5) (4.8), a generator was developed to create the New BS Placement input data every time the distribution is changed (called *traffic*).

The BS Placement block provides a file with information about several performance parameters as output data: it has, among other things, the number of BSs, number of sectors with each orientation, uncovered area, uncovered traffic, uncovered equivalent DL load factor traffic density, etc.

4.5.3 The Algorithm

The algorithm starts by obtaining all the uncovered area by erasing the covered one from the service area. Then, the software individualises all the disjoined areas, treating them one by one. By classifying the area that is being handled, a different heuristic is used in order to cover that same area, Figure 4.13. The classification is made through a comparison between the area of the uncovered surface and the area of the nominal BS coverage one:

- VSS.

$$\frac{A_{unc}^{surf}}{A_{cell}} < P_{vs} \tag{4.22}$$

- SS.

$$P_{vs} \leq \frac{A_{unc}^{surf}}{A_{cell}} < P_{s} \tag{4.23}$$

- MS.

$$P_{s} \leq \frac{A_{unc}^{surf}}{A_{cell}} < P_{m} \tag{4.24}$$

- LS.

$$P_{m} \leq \frac{A_{unc}^{surf}}{A_{cell}} \tag{4.25}$$

where:

- A_{unc}^{surf} is the area of the uncovered surface;
- A_{cell} is the area covered by a BS that has 3 sectors, considering the nominal coverage area;
- P_{vs} is the upper percentage threshold for VSS;
- P_{s} is the upper percentage threshold for SS;
- P_{m} is the upper percentage threshold for MS.

For VSSs, the algorithm does not put a BS and the surface is erased.

When the uncovered area is considered to be an SS, the simulator calculates the traffic inside it by adding the values of the corresponding pixels of the η_{DL}^{equiv} grid. If it is above $\gamma_{hotspot}$, this area is considered to be a hot spot; therefore, it places a BS with 3 sectors in its geometric centre, erases the BS coverage area from the surface and adds its remaining parts to the disjoined area list. If not, the surface is erased from the uncovered areas and no BS is placed. The $\gamma_{hotspot}$ parameter can be defined by the simulator user through an adequate window as a value normalised to the maximum DL load factor.

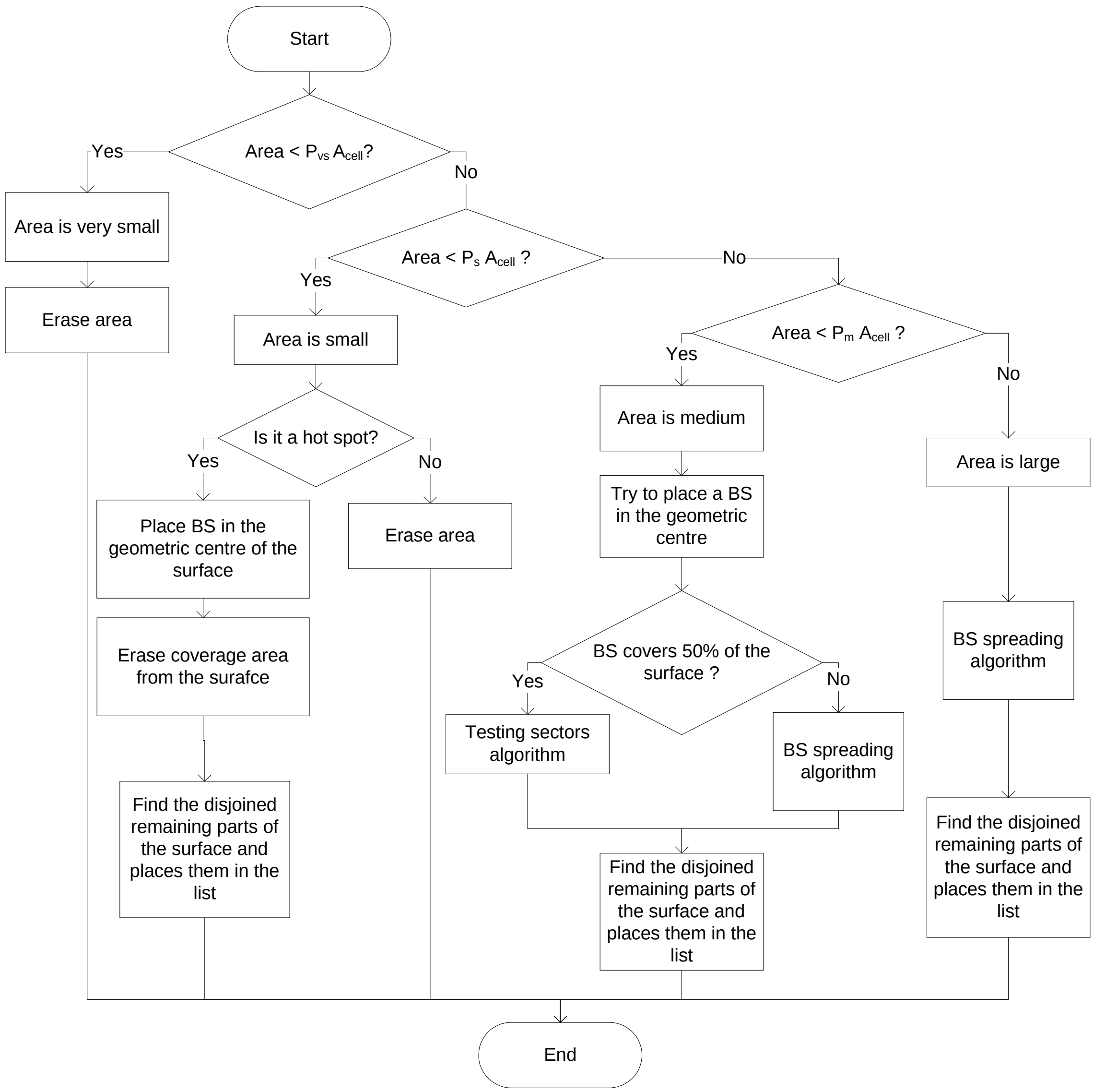


Figure 4.13 – Area analysis for BS placement fluxogram.

In the MS case, one or more BSs can be placed, depending on the shape of the area. The algorithm starts to test the addition of a single BS in the geometric centre: it draws the coverage of the 3 sectors and evaluates the percentage of it that is occupied by the surface. If the percentage is higher than 50 % then the BS is placed there. On the opposite situation, the simulator spreads several BSs along the surface using a surface spreading heuristic. In both cases, the traffic density inside each sector is calculated by:

$$\overline{T}_{\sec}^{dens}\left[\mathrm{km}^{-2}\right] = \frac{\eta_{\sec}^{equiv}}{A_{\sec\left[\mathrm{km}^{2}\right]}} \tag{4.26}$$

where:

- $\eta_{\sec}^{equiv}$ is the η_{DL}^{equiv} inside the sector, being obtained by summing all the pixels from the η_{DL}^{equiv} grid that are inside the sector coverage area.

Furthermore, it finds the intersection of the coverage area with the ones from the other sectors, $A_{\sec}^{\sup}$, and, consequently, the superposition area percentage through:

$$P_{\sec}^{\sup} = \frac{A_{\sec}^{\sup}}{A_{\sec}} \tag{4.27}$$

The tested sector is only added to the network if its $\overline{T}_{\sec}^{dens}$ is higher than ζ and $P_{\sec}^{\sup}$ is lower than the superposition area percentage threshold, $P_{\sup}$, Figure 4.14. These 2 parameters can be modified by the simulator user, the former one being normalised to the maximum DL load factor. One can see that each BS can have less than 3 sectors; in an extreme situation, the BS can have no sectors, in which case, the corresponding BS is removed from the network. The new BS coverage area is erased from the surface and the remaining parts are added to the disjoined area list.

For the last category, where one has an LS, the software calls the BSs spreading algorithm, placing several BSs along the surface. For each one of these insertions, the tests for the covered traffic density and the superposition area are done for each of the 3 sectors as described for MS in the last paragraph. The new BSs coverage area is erased from the surface and the remaining parts, which are not covered yet, are placed in the disjoined area list.

The BSs spreading algorithm used in this simulator is quite simple: it tries to put the BSs near the bound of the uncovered area, Figure 4.15. It starts by finding a line that is always at an equal distance from the surface bound, which has the same value as the nominal cell radius. There can be cases where the area is tight and is not possible to get an equidistant line for that distance; therefore, the latter parameter is decreased and the step is repeated again. After finding the equidistant line, the software tries to put the first BS in a point of the line that is obtained by using 2 functions of *MapBasic* (*ObjectNodeX()* and *ObjectNodeY()*), testing always the traffic density and the superposition area for all sectors. Then, the algorithm finds all the line points that are at a distance from the BS that is equal to the double of the nominal cell radius, which are the new BS candidate sites. One by one, the points are tested and when a new BS is added, the other candidate points are erased from the list; the latter steps are repeated in order to find the new candidates points, which are equidistant to the new BS. This cycle is repeated over and over again, until it is not possible to place a BS in any of the candidate points.

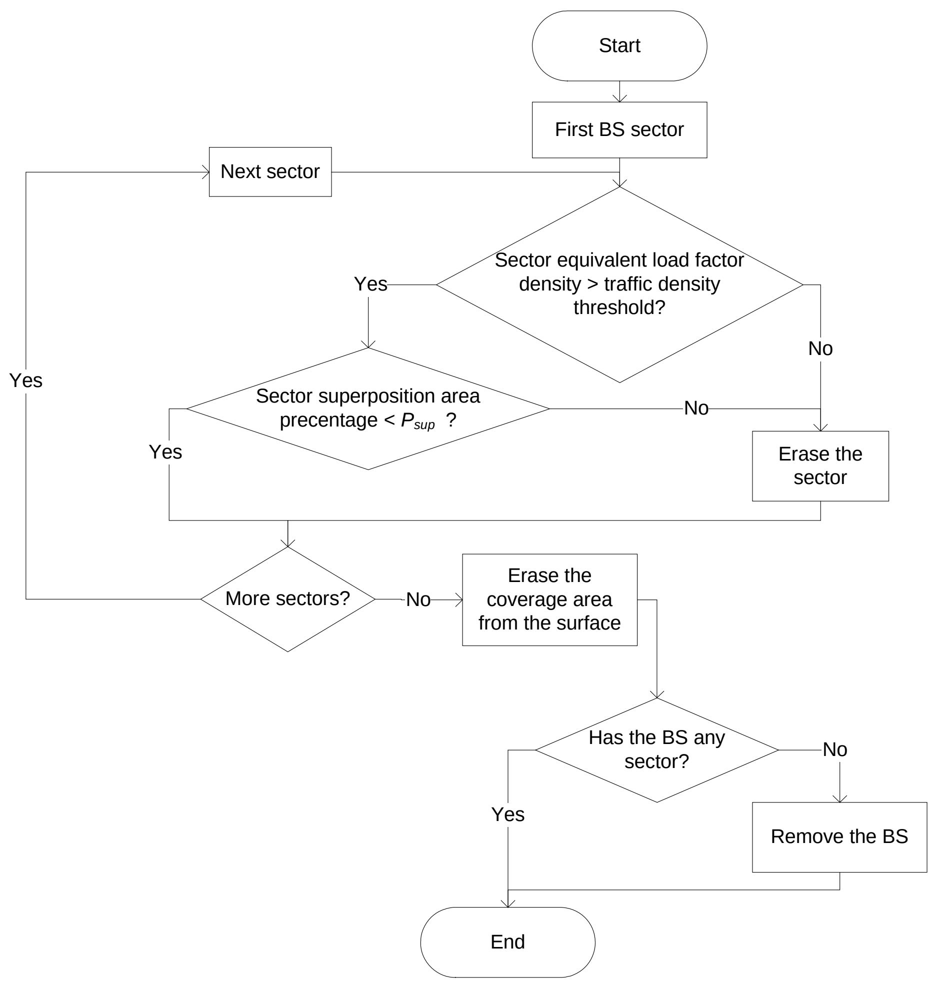


Figure 4.14 – Testing sectors fluxogram.

At the end of each surface analysis, the simulator evaluates if there are more disjoined areas in the list, and if so, it repeats all the steps described above for the next area. On the opposite case, the algorithm stops, and the software evaluates the performance parameters related to network coverage, like the number of BSs and sectors, the uncovered area, the uncovered equivalent DL load factor traffic density, and the area covered by one, two or more sectors.

As the VSS should be quite small compared with the BS coverage area, one considers a very low P_{vs} value, equal to 10 %. For P_s and P_m, one has considered 50 and 125 %, respectively, which leads to an MS with an area that is around the BS coverage area.

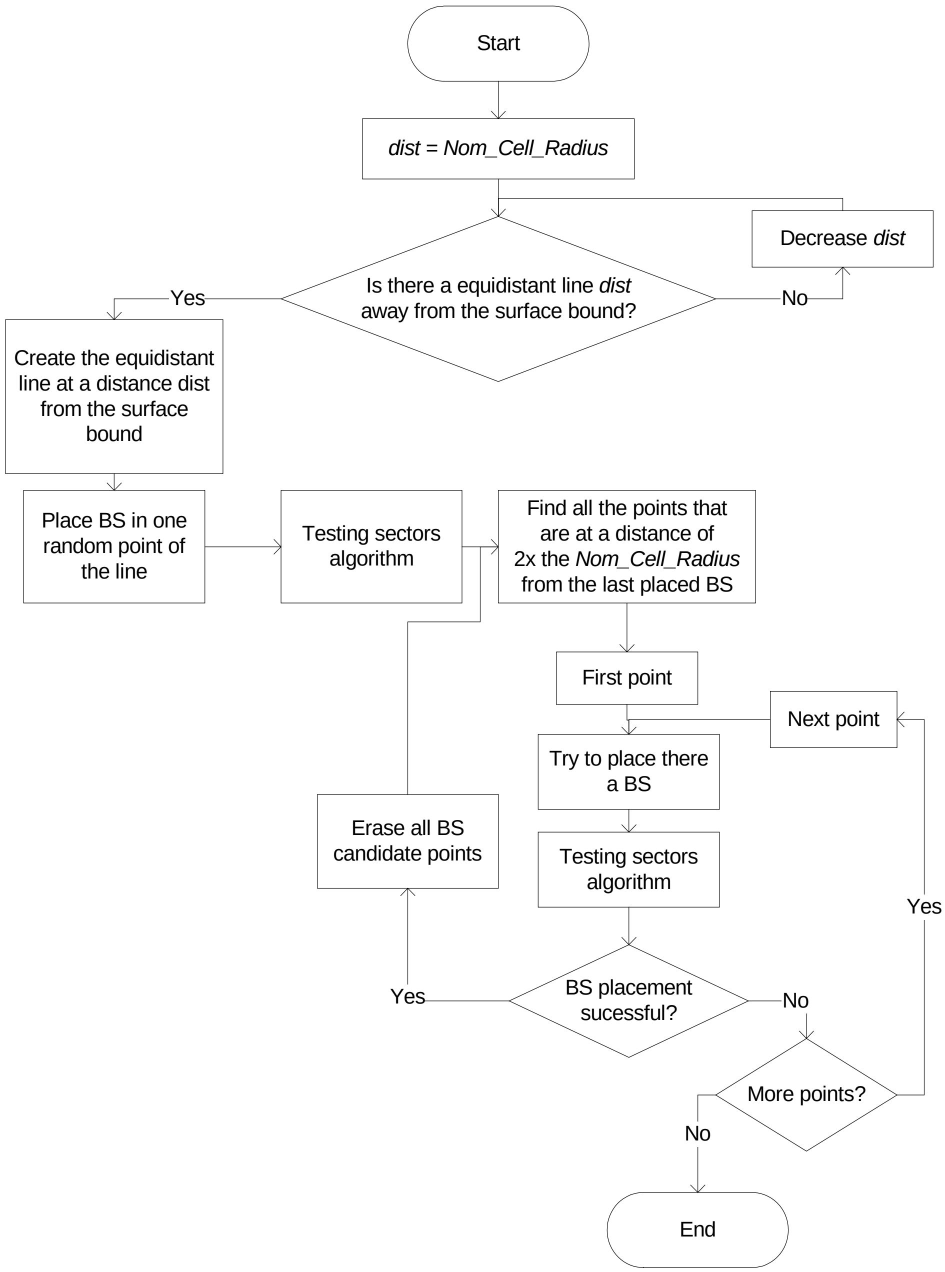


Figure 4.15 – BS spreading fluxogram.

4.6 Simulator Validation

One important step in a simulator development is its validation, only then one can assure that the simulator is working properly and can trust in their results.

The User Generator, Network Creation and Network Performance Analysis blocks were developed in [SeCa04], and all tests have already been done; therefore, one assumes the good performance of the simulator, and no more tests were done in this work. The BS Placement block was completely developed in this thesis, and needs to be tested.

Several tests were also made for the New BS Placement algorithm, using different areas. The idea was to run the algorithm over a set of surfaces that represents the 4 types of uncovered surfaces (VSS, SS, MS and LS), and verify if the heuristic used is the correct one as described in Section 4.5.3. Furthermore, one observed if all uncovered areas are well covered concerning the surface shape and the traffic distribution. One has verified that the algorithm places BSs using the correct heuristic and that the solution seems to be a good one, since it almost covers the whole uncovered area. For example, in Figure 4.16 one has a LS, and one sees that the algorithm spreads new BSs along the area, covering almost the whole surface. In areas with low traffic, the algorithm did not place any BS.

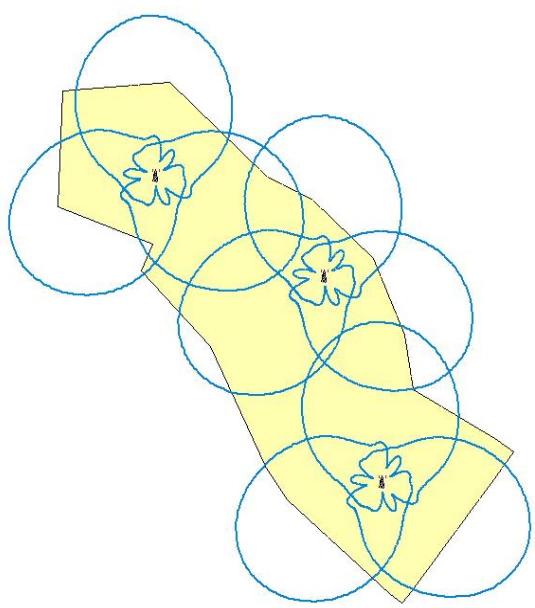


Figure 4.16 – Validation of the BS placement algorithm for LS.

Then, one has varied, one by one, some BS placement input parameters (ζ and $\gamma_{hotspot}$), using always the same uncovered area, Figure 4.17, in order to observe how the algorithm reacts to these variations and if the performance parameter values were as expected. The algorithm was always able to fill in the areas with more traffic with BSs, leaving the low traffic areas without coverage, Figure 4.18. Moreover, the performance parameters related with the placement were the expected ones: for instance, the number of placed BSs increased with the decreasing of ζ (the number of placed BSs is 70 and 71 for ζ of 50 and 10 km^{-2}, respectively), Table 4.2, and the superposition area increases with the decreasing of $\gamma_{hotspot}$ (the superposition area is 38.0 and 50.9 % for $\gamma_{hotspot}$ of 100 and 30 %, respectively), Table 4.3.

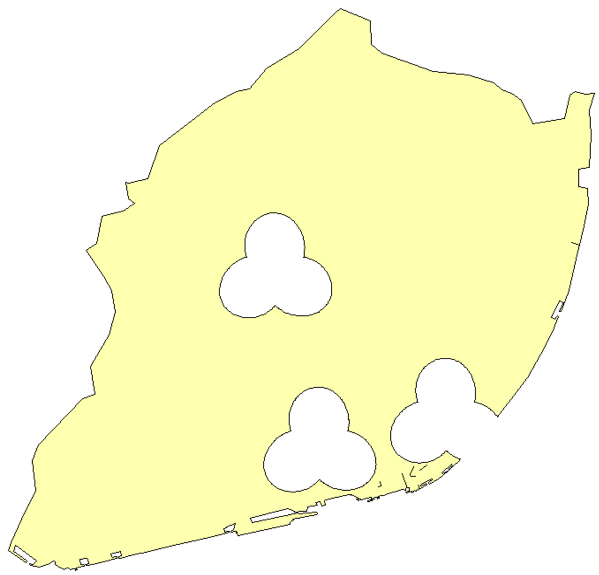


Figure 4.17 – Uncovered area used in the New BS Placement algorithm validation.

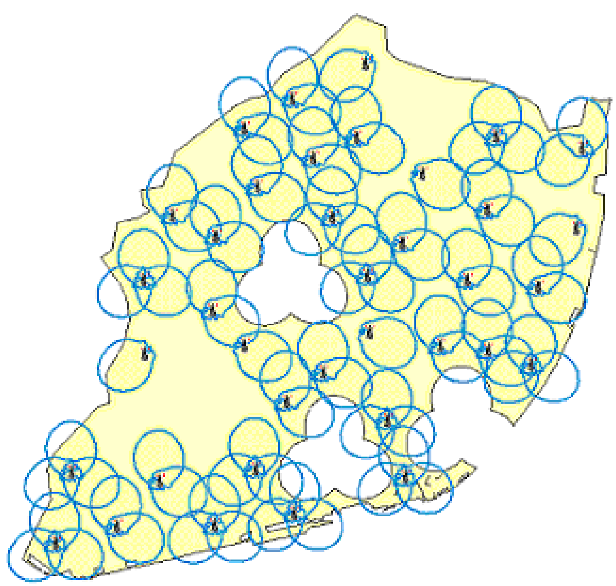


Figure 4.18 – New BS Placement algorithm result for the validation area.

Table 4.2 – Results for the testing area for a P_{sup} of 100 % and a ζ of 50 km^{-2}.

	$\gamma_{hotspot}$ [%]	
	30	100
Number of placed BSs	70	58
Uncovered area [%]	14.7	21.2
ξ **[km^{-2}]**	0.26	0.43
Superposition area [%]	50.9	38.0

Table 4.3 – Results for the testing area for a P_{sup} of 100 % and a $\gamma_{hotspot}$ of 30 %.

	ζ [km^{-2}]	
	10	50
Number of placed BSs	71	70
Uncovered area [%]	8.1	14.7
ξ **[km^{-2}]**	0.00	0.26
Superposition area [%]	56.9	50.9

Chapter 5

Analysis of Results

In this chapter, one analyses the results for several scenarios in two different approaches: in the first one, the BS placement algorithm is used in an area without any network, and in the second one, the algorithm is used over a network co-located with a GSM one. A comparison between the BS placement from this simulator and another one, [SeCa04], is also presented. The input data and the reference scenario are defined as well.

5.1 The Reference Geographical Scenario

In this work, all simulations are made for Lisbon. Some of them are made for an already existing UMTS FDD network, the initial network, which was provided by Vodafone, being co-located with the GSM one, Figure 5.1. The network has more BSs in areas with more traffic, like downtown and *Avenidas Novas*, which are areas with a high-density of business users, while in areas like *Monsanto* Park, where the traffic is low, and the airport, where there is no traffic in the runway, there is a lower density of BSs.

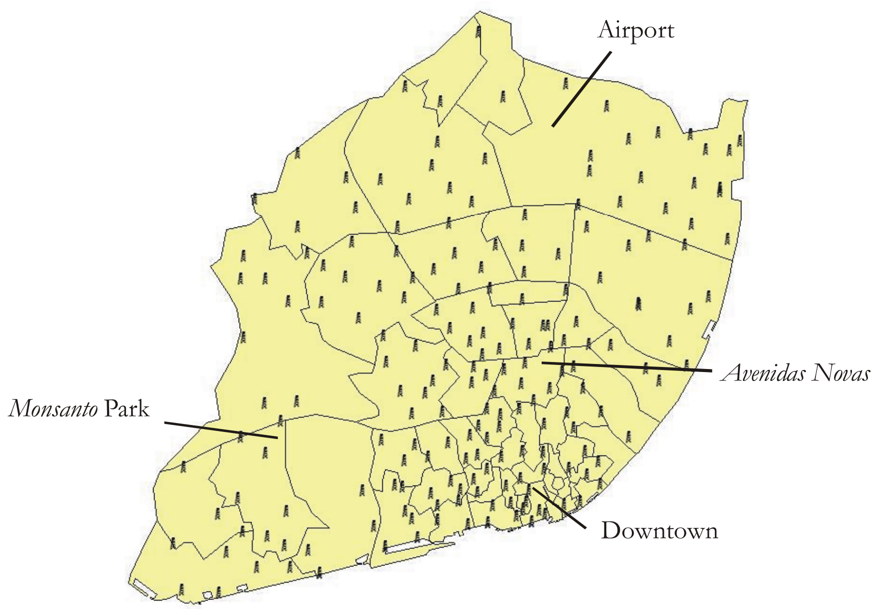


Figure 5.1 – Initial network co-located with a GSM one.

For the user generator, the operational environment grid has 700×565 pixels of 20×20 m^2 area each, obtained from the MOMENTUM project, [MOME04]: as these grids do not cover the whole city of Lisbon, they had to be adjusted, cloning information in about 2 % of the service area in order to have information covering all the area, Figure 5.2. One can see that the downtown of the city is mainly an urban environment, and that *Avenidas Novas*, where there is a large concentration of offices, is a CBD environment. The *Monsanto* Park and the airport are considered to be sub-urban and rural environments, respectively.

The distribution of user scenarios per operational environment is defined according to [Voda05], Table 5.1, where all considered operational environment are already described in, Table 4.1. One has considered that in both water and open environment areas there are no users inside buildings or vehicles, all being outdoor ones. For the railway, highway and highway with traffic jam environments, all users are classified as indoor, because they are inside a vehicle, and the type of indoor scenario is chosen considering the most realistic attenuation: the first one has a higher L_F and its users are classified as urban indoor ones, while the other two have medium L_F and are equivalent to sub-urban users. For all other operational environments, one has considered that part of the users is inside a building or a vehicle, and the other is outdoor. Once more, the type of indoor scenario is chosen taking into account the most realistic L_F for the considered environment. One should note that for urban and CBD operational environments, the majority of the users are in an urban indoor scenario, since they are inside big buildings.

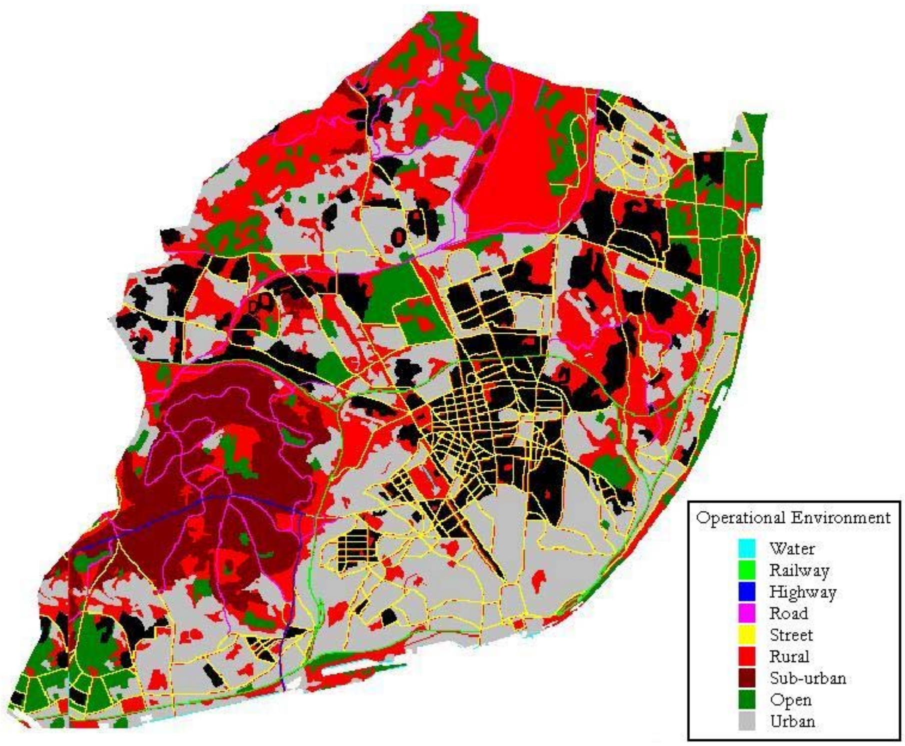


Figure 5.2 – Operational environment grid.

Each one of these considered scenarios has a pre-defined correspondence with a certain L_F, Table 5.2. These values try to show a realistic view in terms of L_F for the different scenarios in Lisbon, [Voda05]. Only indoor users have some L_F, since they are inside buildings or vehicles: the urban users, which are in areas with high buildings, have a higher L_F, while the rural ones, with a low-density of buildings, have the lowest one.

Table 5.1 – Distribution of user scenarios per operational environment.

Operational class	User distribution				
	Outdoor	Indoor			
			Urban	Sub-urban	Rural
	[%]	[%]	[%]	[%]	[%]
Water	100	0	-	-	-
Open	100	0	-	-	-
Railway	0	100	100	0	0
Highway	0	100	0	100	0
Highway with traffic jam	0	100	0	100	0
Road	20	80	0	100	0
Street	50	50	0	100	0
Rural	60	40	0	0	100
Sub-urban	50	50	0	100	0
Urban	30	70	100	0	0
CBD	10	90	100	0	0

Table 5.2 – L_F values for the different user scenarios.

	Outdoor	Indoor		
		Urban	Sub-urban	Rural
L_F **[dB]**	0	20	12	6

There is a correspondence between the operation environment and the user scenario, Table 5.3, thus, it is possible to classify a user that is generated in a pixel with a certain operational environment in terms of mobility (pedestrian, vehicular, indoor). Users that are in railway, highway, highway with traffic jam and roads environments are mainly inside vehicles, being classified as vehicular. Users in streets are considered to be walking or inside low-velocity vehicles, being at a pedestrian scenario. On the rural, sub-urban, urban and CBD environments, users have an indoor scenario because they are mainly inside buildings; in the other cases, users cannot be inside buildings or vehicles, being considered to be in pedestrian scenarios.

Table 5.3 – Correspondence between the operational environment and the user scenario.

Operational environment	User scenario
Water	Pedestrian
Open	Pedestrian
Railway	Vehicular
Highway	Vehicular
Highway with traffic jam	Vehicular
Roads	Vehicular
Streets	Pedestrian
Rural	Indoor
Sub-urban	Indoor
Urban	Indoor
CBD	Indoor

For the Network Creation block, one uses the information about the initial network, like the location of each BS and the horizontal radiation pattern of the tri-sectors BS antennas, Figure 5.3, which corresponds to the Kathrein – 742265 model, [Kath05].

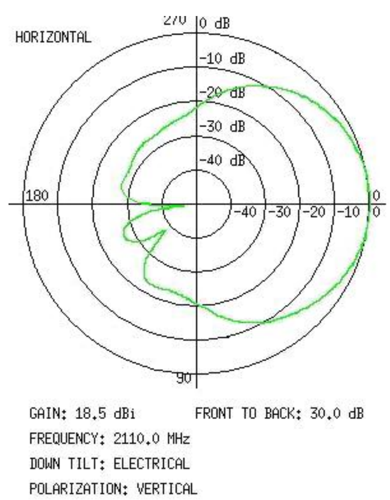


Figure 5.3 – Horizontal radiation pattern for the BS antenna.

The parameter $\overline{\eta}_{bearer}^{user}$ increases with the service bearer rate, Figure 5.4, Table 5.4, and varies with the user scenarios, since a different user scenario corresponds to a different E_b/N_0 value, Table B.3; therefore the former parameter is smaller for indoor users and higher for vehicular ones.

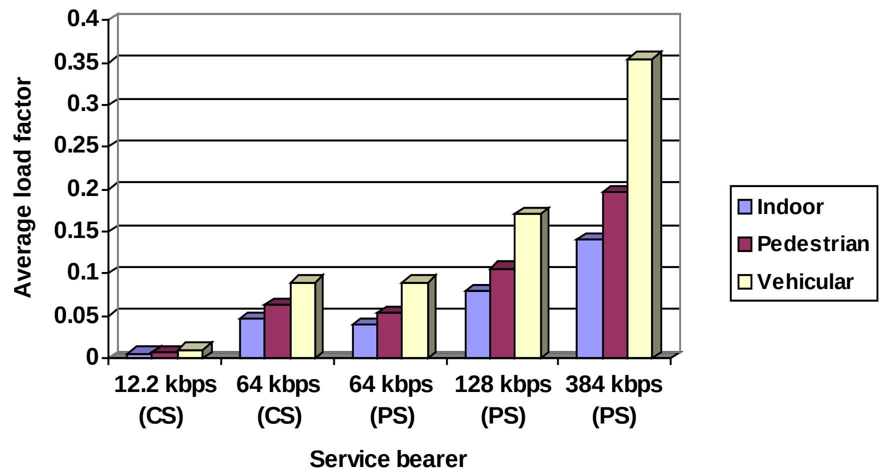


Figure 5.4 – $\overline{\eta}_{bearer}^{user}$ for several service bearers and user scenarios.

Table 5.4 – $\overline{\eta}_{bearer}^{user}$ values for several service bearers and user scenarios.

Service bearer	User scenario	DL load factor per user
12.2 kbps (CS)	Indoor	0.0054
	Pedestrian	0.0071
	Vehicular	0.0103
64 kbps (CS)	Indoor	0.0468
	Pedestrian	0.0624
	Vehicular	0.0895
64 kbps (PS)	Indoor	0.0398
	Pedestrian	0.0531
	Vehicular	0.0895
128 kbps (PS)	Indoor	0.0796
	Pedestrian	0.1062
	Vehicular	0.1710
384 kbps (PS)	Indoor	0.1407
	Pedestrian	0.1964
	Vehicular	0.3548

The nominal cell radius is calculated by using the link budget described in Annex B, with the information about the E_b/N_0 of each service bearer/user scenario, Table B.3, and the pre-defined values for the radio parameters, which were discussed with Vodafone, [Voda05], Table B.4, Table B.5. Obviously, L_F is higher for indoor scenarios, since users are inside buildings, and it is lower for the vehicular one, since they are inside vehicles. The parameter G_{SHO} is considered to be equal for all the 3 user scenarios. Furthermore, N is considered to be equal to 5 and 9 dB in UL and DL, respectively, [Voda05]. One can see that for this scenario the nominal cell radius tends to decrease with the service bearer bit rate, being higher in pedestrian scenarios and lower in indoor ones, Figure 5.5.

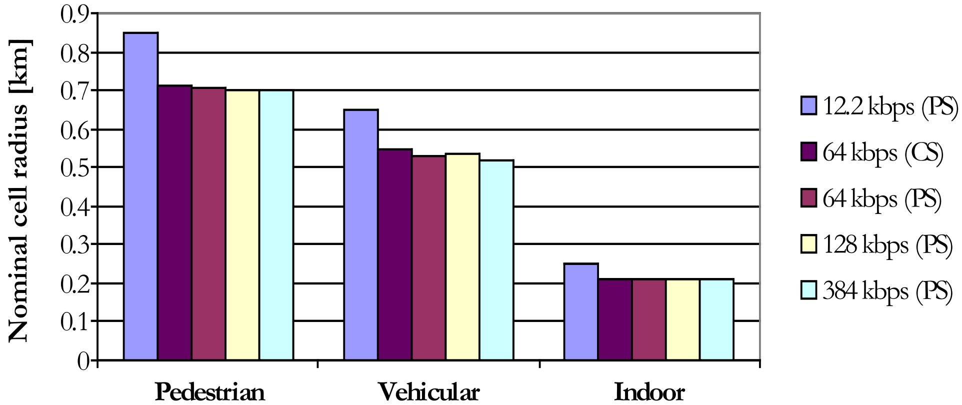


Figure 5.5 – Nominal cell radius for several service bearers.

The maximum BS transmission power and both the maximum load factor in UL and DL used in the network performance analysis are equal to 38 dBm, 0.50 and 0.70, respectively, which are the values used in Vodafone's network, [Voda05].

5.2 The Reference User Scenario

It is important to define the concept of the reference user scenario, to which all the results should be compared to: it must be one that represents a realistic view of a real network, allowing a good analysis of the performance parameters with the variation of some network parameters. So, one has to define ζ , $\gamma_{hotspot}$, $P_{\sup}$, the number of generated users, the reference service bearer, the reference user scenario, the service bearer distribution for all the services, etc.

The parameter ζ is found using information from Vodafone, [Voda05]: assuming that the operator places a GSM BS if the processed traffic is equal or larger than 10 Erlang. By considering a tri-sector BS, where each sector uses 2 carriers, in which 2 time-slots are taken for signalling and control, one has N_{ch} = 3.3 and N_{ch}^{av} = 14, which leads from (4.16) to ε = 24 %. Then, in order to have the same efficiency in the UMTS BS, and considering $A_{\sec}$ as the sector coverage area for a 128 kbps - pedestrian scenario (which is equal to 0.434 km^2), one obtains, by using (4.18), ζ = 55 km^{-2}.

From (4.19) one gets $\gamma_{hotspot}$ = 72 %.

The $P_{\sup}$ value, and the DL service bearer distribution for all the services were discussed with Vodafone, [Voda05]: the first one has a value of 30 % and the second one is presented in Table 5.5. One sees that users with speech-telephony and video-telephony have CS service bearers, while the others have PS ones. Besides, services with a higher volume data, like the file download and the web browsing, have service bearers with higher throughputs. The UL service bearer throughput is always equal to 12.2 kbps for voice, and 64 kbps for all the others.

Table 5.5 – Service bearer distribution for several services.

Service	**Throughput**	**Distribution [%]**
Speech-telephony	12.2 kbps (CS)	100
Video-telephony	64.0 kbps (CS)	100
Streaming Multimedia	64.0 kbps (PS)	50
	128.0 kbps (PS)	50
E-mail	64.0 kbps (PS)	99
	128.0 kbps (PS)	1
Location Based Service	64.0 kbps (PS)	99
	128.0 kbps (PS)	1
MMS	64.0 kbps (PS)	60
	128.0 kbps (PS)	40
File Download	64.0 kbps (PS)	30
	128.0 kbps (PS)	50
	384.0 kbps (PS)	20
Web Browsing	64.0 kbps (PS)	70
	128.0 kbps (PS)	25
	384.0 kbps (PS)	5

The BHCA grids are obtained from MOMENTUM project, [FCXV03], Annex E, using the algorithm described in Section 3.2. There is one grid for each of the 8 services that the network can provide to the users, Annex F: an example for a BHCA grid is presented in Figure 5.6. One verifies that areas with an urban (e.g., downtown) and CBD environment (e.g., *Avenidas Novas*) have a higher traffic, because they have a higher density of buildings and people, while in urban and sub-urban areas the traffic is lower (e.g., *Monsanto* Park and the airport area).

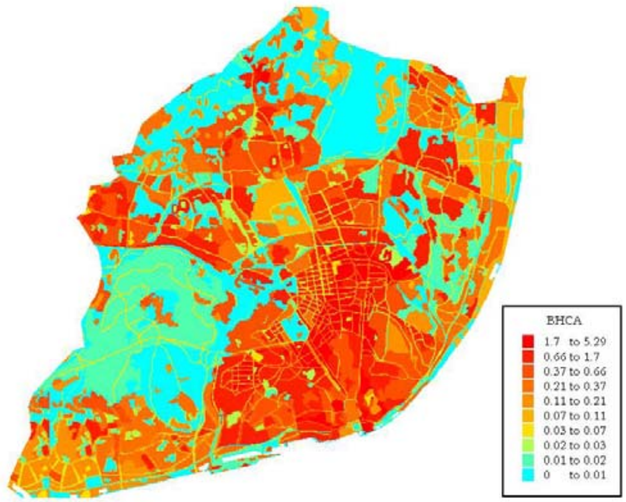


Figure 5.6 – BHCA grid for the voice service.

When considering the generated users in the reference scenario, one can see that the most frequent service is the speech-telephony, being requested by almost half of the generated active users, followed by the video-telephony and the streaming multimedia, Figure 5.7. These results are obtained from the information of the BHCA grids provided by the MOMENTUM project. As all the users that have the speech-telephony use the 12.2 kbps (CS) service bearer, Table 5.5, one verifies that the majority of the covered users request a service of 12.2 kbps (CS), Figure 5.8.

Using the correspondence between the operational environment and the user scenario, Table 5.3, parameter $\overline{\eta}_{bearer}^{user}$, Table 5.4, and the characteristics of the services, Table 5.6, it is possible, as described in Section 4.5.1, to get the spatial η_{DL}^{equiv} distribution for all the different services and for a certain service bearer distribution, which is represented by a grid of pixels similar to the BHCA ones, Figure 5.9. The characteristics of the service are defined in the MOMEMTUM project, [FCXV03], where there is information about $\overline{\tau}$, $\overline{V}$ and υ. The services are chosen in order to cover a wide range of information volume, Figure 3.3, as well as the 4 classes defined in 3GPP: the location based service, MMS and e-mail services have a low volume data, while the streaming multimedia, web browsing, and file download have higher ones.

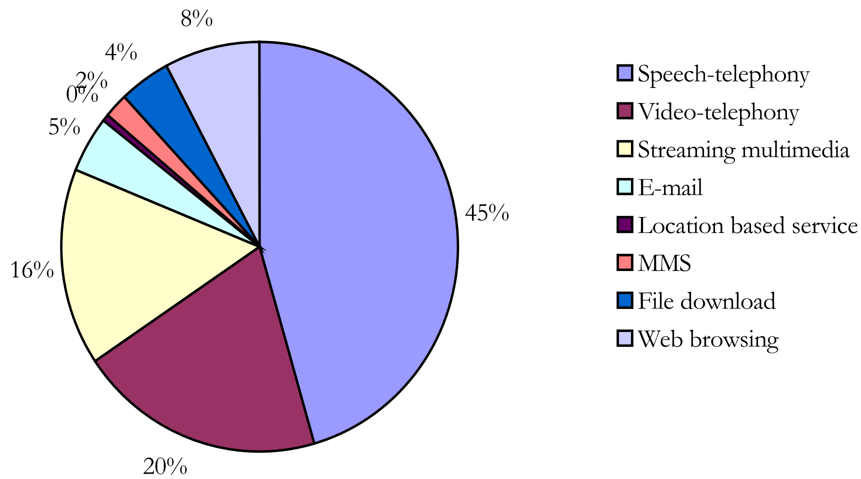


Figure 5.7 – Service distribution among the active users.

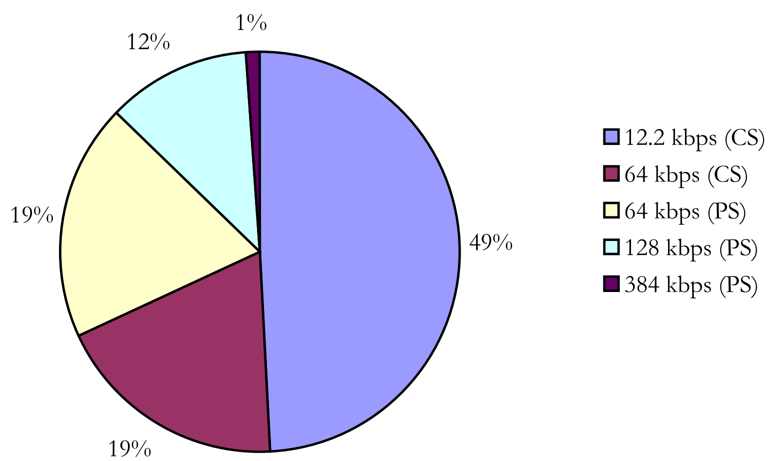


Figure 5.8 – Service bearer distribution among the covered users.

Table 5.6 – Service's characteristics, [FCXV03].

Service	$\overline{V}$ [kB]	$\overline{\tau}$ [s]	υ
Speech-telephony	-	120	0.5
Video-telephony	-	120	1.0
Streaming Multimedia	2 250	-	1.0
Web Browsing	1 125	-	1.0
Location Based Service	22.5	-	1.0
MMS	60	-	1.0
E-mail	10	-	1.0
File Download	1 000	-	1.0

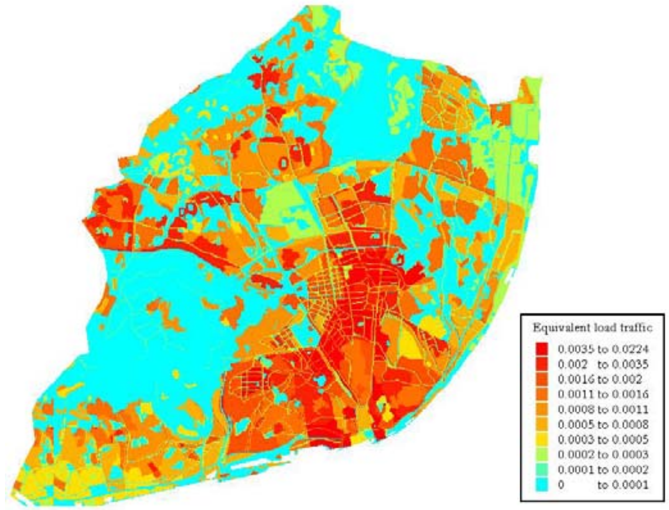


Figure 5.9 – Spatial η_{DL}^{equiv} distribution in Lisbon.

5.3 Area without Initial Network

The reference scenario used in the simulations is the 384 kbps (PS) – pedestrian one and the number of generated users is 9 000. This last number was chosen because it leads to a blocking probability near 1 %.

Simulations are made for several reference service bearers (12.2 kbps (CS), 64 kbps (PS), 128 kbps (PS) and 384 kbps (PS)), reference user scenarios (pedestrian, vehicular, indoor), and input parameters of the BS placement algorithm, like ζ , $\gamma_{hotspot}$ and $P_{\sup}$.

The first simulations were made without an initial network; therefore, the BS placement algorithm tries to fill in the service area with BSs in order to cover all areas with significant traffic. One can easily see what is the performance of the BS placement algorithm for the different reference service bearers and for the variation of the algorithm parameters.

Simulations were made for several scenarios with different service bearers and different user scenarios (pedestrian, vehicular, indoor). The first thing to be notice is that the algorithm does not place BSs in areas where there is not much traffic, like, for instance, the area of the airport and *Monsanto* Park, Figure 5.9, Figure 5.10, as the traffic density is lower than the threshold. On the other hand, in the downtown of Lisbon, the density of traffic is quite high and the density of placed BSs is higher; this means that the algorithm finds many hot spot surfaces in this zone, and therefore places BS in VSSs and SSs (with an area lower than 50 % of the nominal cell coverage area). One should notice that in this case P_{sup} = 100 %, so the algorithm adds a new BS even if the superposition area is quite high.

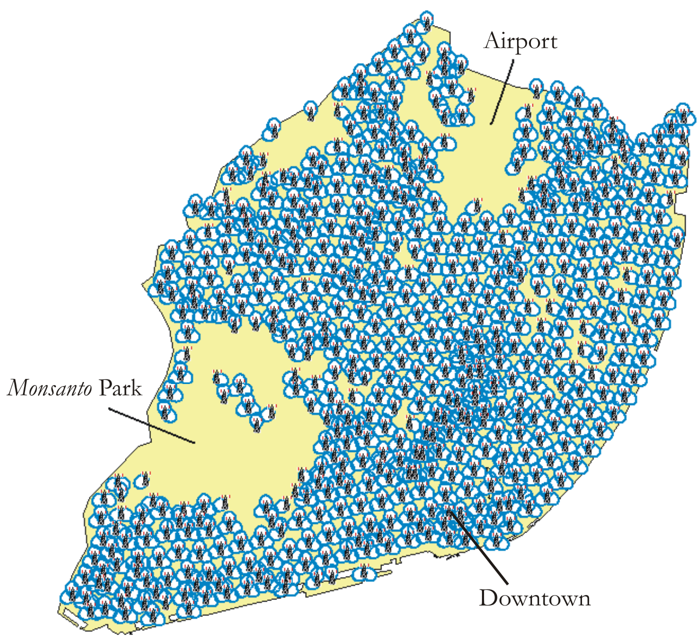


Figure 5.10 – Coverage of a network created by the BSs placement algorithm for a 64 kbps indoor reference service bearer and P_{sup} of 100 %.

Moreover, the number of placed BSs increases with the service bearer bit rate, Table 5.7, because the nominal BS coverage radius decreases with the latter one, Figure 5.5; therefore, the BS coverage being lower, more BSs are needed to cover the same area. For the same reason, there are more BSs placed in the indoor cases and less in the pedestrian ones. There are cases where there is no data, because the simulation could not be performed. The simulator runs over *MapInfo*, which is a program that uses many computational resources; therefore, for cases where the nominal cell coverage radius is quite low, *MapInfo* does not assure a good performance of the simulator: in some cases (384 kbps (PS) – vehicular, 128 kbps (PS) – indoor, and 384 kbps (PS) – indoor) the information generated by the GIS tool is so large that there are not enough resources to handle it.

Many times, the number of sectors with a certain orientation is different from the number of placed BSs, being always smaller, Figure 5.11: this means that some BSs do not have 3 sectors, because the missing ones would cover a low traffic area. This can also be seen in Figure 5.10 where in *Monsanto* Park there are BSs with only 1 or 2 sectors.

Table 5.7 – Number of placed BSs for several reference service bearers without initial network.

Number of placed BSs			
Reference service bearer	**Reference user scenario**		
	Pedestrian	**Vehicular**	**Indoor**
12.2 kbps (CS)	48	71	331
64 kbps (PS)	67	96	452
128 kbps (PS)	93	147	-
384 kbps (PS)	117	-	-

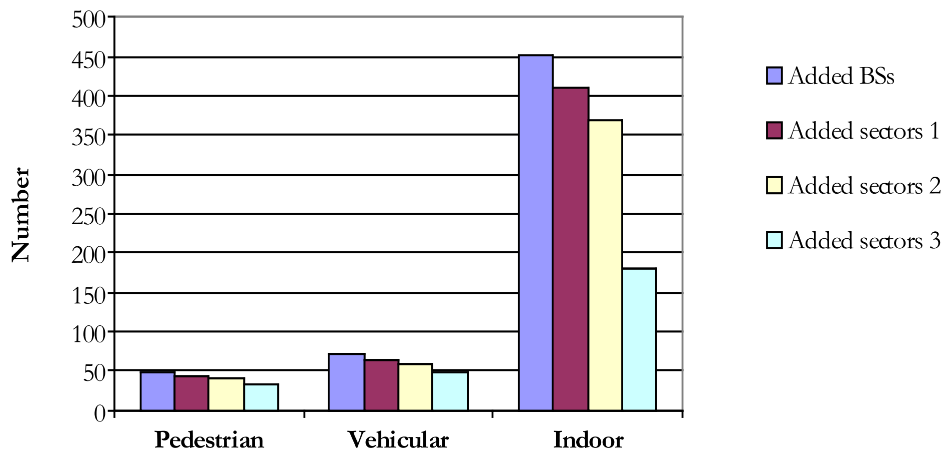


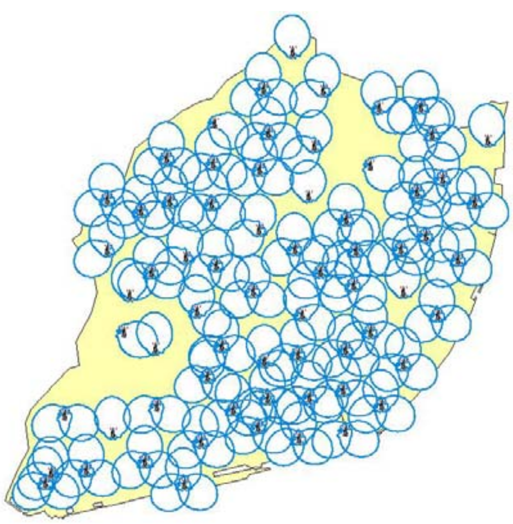
Figure 5.11 – Number of BSs and of sectors for a reference service bearer of 12.2 kbps (CS).

The runtime of the simulator is quite dependent of the reference service bearer and the number of BSs that are placed: for the cases where the number of added BSs is low, the simulator runtime is up to 2 hours, while for the indoor ones, where the number of added BS is quite high (the number of placed BSs is 452 for the 64 kbps (PS) – indoor reference scenario), the runtime can reach more than 10 hours, always using a Pentium 4 processor. The spatial η_{DL}^{equiv} distribution input data has about 30 MB of memory and the simulation results required memory depends also from the number of placed BSs: for the 12.2 kbps (PS) – pedestrian scenario, the results have about 2 MB of memory, while for the 64 kbps (PS) – indoor scenario, the results have about 21 MB, where the memory is mainly allocated to data concerning the graphical representation of the area that is covered by the network.

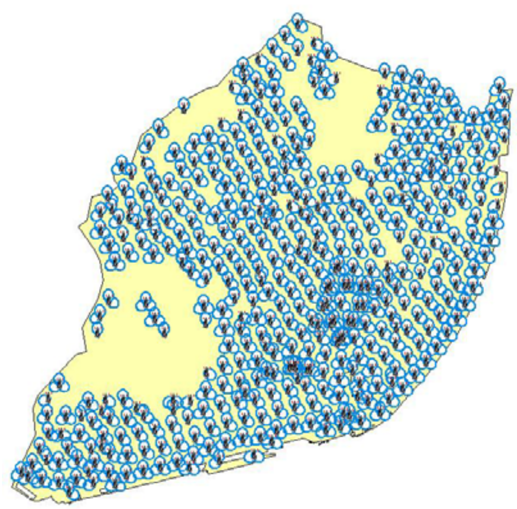
The uncovered area tends to increase with the decreasing of the nominal cell radius, although there is an increase of added BSs, Table 5.8, resulting from the fact that the algorithm takes into account not only the surface that is not covered but also the traffic distribution. When the nominal cell coverage area is large, there are many cases where a sector covers a high traffic density area as well as a low one: as long as the mean traffic density inside the sector is higher than the given threshold, the sector is added into the network. However, when the nominal coverage area decreases, the sectors placed by the algorithm tend to cover only the high-density areas; therefore, the size of the LSs that have a low traffic density increases, Figure 5.12.

Table 5.8 – Uncovered area for several reference service bearers.

Uncovered area [%]			
Reference service bearer	**Reference user scenario**		
	Pedestrian	**Vehicular**	**Indoor**
12.2 kbps (CS)	24.8	28.3	44.7
64 kbps (PS)	22.4	31.0	49.6
128 kbps (PS)	36.7	34.2	-
384 kbps (PS)	29.7	-	-



(a) 64 kbps (PS) – pedestrian.



(b) 64 kbps (PS) – indoor.

Figure 5.12 – Network coverage for 2 different reference service bearers.

The uncovered area percentage, the area covered by one, two, and more than two sectors is presented in Figure 5.13 for the network in the 64 kbps (PS) reference bearer cases. At first sight, the sum of these 4 percentages should be equal to 100 %, because they are related to the service area. However, one can see that the sum of the percentages is always greater than 100 %. This means that, by considering all the areas described before, one is covering an area that is larger than the service one. In fact, one can see that the BSs near the borders of the service area are also covering an area outside Lisbon, this extra coverage area being larger in cases with a higher nominal cell coverage area. One can see that, as mentioned before, the percentage of the uncovered area increases with the decrease of the nominal cell coverage radius, despite of the fact of the percentage of the area covered by 1 sector being almost constant. This means that the area covered by more than 1 sector (SHO area) percentage decreases. The percentage of the area that is covered by more than 1 sector should be below or near P_{sup}, which is 30 % in this case. In fact, it is equal to 35.2 % in the worst case (64 kbps (PS) – pedestrian). This percentage can be above the threshold value, because in hot spot areas the algorithm places a BS with all 3 sectors even if the superposition area is quite high.

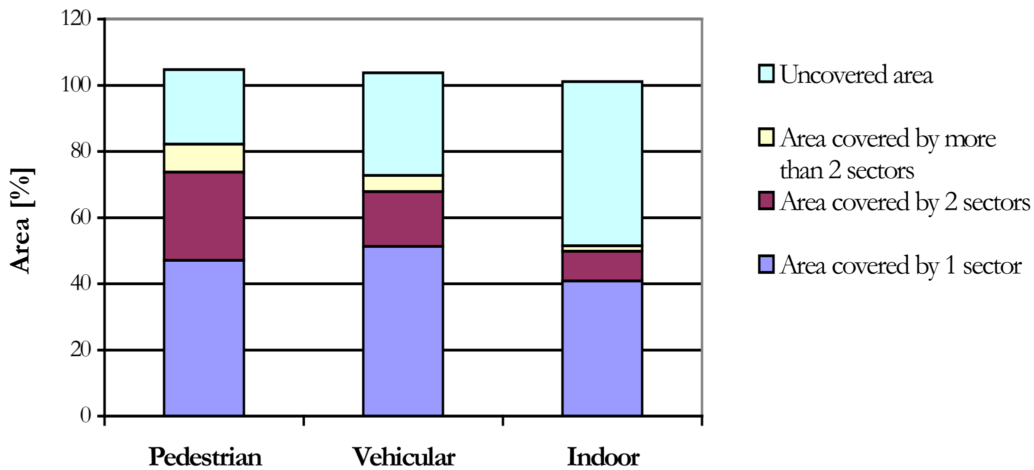


Figure 5.13 – Percentages of the several areas for the 64 kbps (PS) reference service bearer cases.

The ζ input parameter used in these simulations is equal to 0.55 km^{-2}, which corresponds to ξ = 0.38 km^{-2}, so, the ξ performance parameter should be always below or near this value. Despite of that, ξ is always quite above this value, Table 5.9, because there are always areas with significant traffic that are not covered: they are classified either as VSSs, or SSs and the traffic inside is not sufficient to be considered a hot spot, or as MSs or LSs and the places of the candidate sites lead to a superposition area greater than P_{sup} = 30 %. Then, one way to decrease ξ is to increase P_{sup} (for P_{sup} = 100 % and a 384 kbps (PS) – pedestrian scenario, one has ξ = 0.35 km^{-2}). Moreover, one should note that the algorithm was developed with the goal of filling in uncovered areas of an already existing network, and not to create a completely new one.

Parameter ξ varies a lot with the reference service bearer and it seems to have no apparent tendency. As it was already said, there are areas not covered that have significant traffic, the size of these areas being dependent on the disposition of the placed BSs: one can have the same number of BSs and completely different uncovered areas shapes. Moreover, the traffic in these surfaces depends of the location of it, which also depends on the BSs disposal.

Table 5.9 – ξ for several reference service bearers.

ξ [km^{-2}]			
Reference service bearer	**Reference user scenario**		
	Pedestrian	**Vehicular**	**Indoor**
12.2 kbps (CS)	1.56	1.15	1.61
64 kbps (PS)	0.61	0.98	1.61
128 kbps (PS)	1.05	1.28	-
384 kbps (PS)	1.17	-	-

The uncovered traffic varies when the reference service bearer changes as expected. In fact, as previously mentioned, the uncovered area tends to slightly increase when the nominal cell coverage radius decreases; therefore, the uncovered traffic also tends to increase with the decrease of the latter parameter: for the pedestrian cases (high nominal cell radius) the uncovered traffic (η_{DL}^{equiv}) is always below 25 % of the total one in the service area, and for the indoor ones (small nominal cell radius) this parameter is always above 35 %, Table 5.10, Table 5.11, Table 5.12. However, there are cases where this does not happen, because the uncovered traffic depends not only on the size of the uncovered areas but also in their locations.

Table 5.10 – η_{DL}^{equiv} uncovered traffic for the pedestrian reference user scenario cases.

Reference service bearer	η_{DL}^{equiv} **uncovered traffic [%]**		
	VSS and SS	**MS and LS**	**All surfaces**
12.2 kbps (CS)	6.9	13.2	20.1
64 kbps (PS)	7.5	4.1	11.6
128 kbps (PS)	4.8	16.6	21.4
384 kbps (PS)	6.4	14.4	20.8

Table 5.11 – η_{DL}^{equiv} uncovered traffic for the vehicular reference user scenario cases.

Reference service bearer	**η_{DL}^{equiv} uncovered traffic [%]**		
	VSS and SS	**MS and LS**	**All surfaces**
12.2 kbps (CS)	8.6	11.6	20.2
64 kbps (PS)	7.8	12.2	20.0
128 kbps (PS)	6.0	18.8	24.8
384 kbps (PS)	-	-	-

Table 5.12 – η_{DL}^{equiv} uncovered traffic for the indoor reference user scenario cases.

Reference service bearer	**η_{DL}^{equiv} uncovered traffic [%]**		
	VSS and SS	**MS and LS**	**All surfaces**
12.2 kbps (CS)	3.5	32.5	36.0
64 kbps (PS)	2.0	39.5	41.5
128 kbps (PS)	-	-	-
384 kbps (PS)	-	-	-

In almost all cases, one can see that the uncovered traffic in both MSs and LSs is quite higher than in the VSSs and SSs, because the total area of MSs and LSs is larger than the VSSs and SSs one, Table 5.13, and many of the MSs and LSs are not covered by BSs, not because there is low traffic but rather because the candidate BSs have a high superposition area.

Table 5.13 – Uncovered area for the vehicular reference user scenario cases.

Reference service bearer	**Uncovered area [%]**	
	VSS and SS	**MS and LS**
12.2 kbps (CS)	5.6	18.4
64 kbps (PS)	3.8	22.5
128 kbps (PS)	2.3	26.7
384 kbps (PS)	-	-

Simulations were done for the 384 kbps (PS) – pedestrian case, as this is a demanding scenario.

The first parameter to be analysed is the ζ one. When this parameter decreases, the algorithm tends to place sectors in areas with low-density traffic, so, it is expected that the number of placed BSs increases with the decrease of ζ. However, this does not always happen. In fact, in Table 5.14 one can see that the number of added BSs is the same for ζ = 55 km^{-2} and for ζ = 90 km^{-2}, because the nominal cell coverage radius changes with M_i, and the latter depends on the traffic threshold; therefore, one can see that the nominal coverage radius, R_{cell}, decreases with ζ, Figure 5.14. This variation can be expressed by the following linear tendency:

$$R_{cell[\text{km}]} = -0.0007\zeta_{[\text{km}]} + 0.7356 \tag{5.1}$$

So, ζ being lower, the coverage area of each cell is higher and the algorithm tends to place less BSs. This implies that it is difficult to predict the tendency of the number of BSs with ζ. However, one verifies that the uncovered area increases with ζ, because, in this case, the number of placed BSs tends to decrease and the cell coverage area also decreases. The variation of ξ seems to have no tendency, because this parameter depends a lot on the location of the BSs. When ζ changes, the nominal cell coverage radius also changes, as well as the location of the BSs that are placed by the algorithm, therefore, the variation of ξ is unpredictable.

Table 5.14 – Algorithm performance with the variation of ζ for a 384 kbps (PS) – pedestrian scenario.

	ζ [km^{-2}]		
	30	**55**	**90**
Number of added BSs	118	117	117
Uncovered area [%]	27.2	29.7	34.6
ξ **[km^{-2}]**	1.10	1.17	1.09

When $\gamma_{hotspot}$ is low, then the algorithm classifies more often SSs as being hot spots, therefore, it places a BS in the geometric centre of these surfaces with all 3 sectors. So, one can see, as expected, that the number of placed BSs decreases with $\gamma_{hotspot}$ (for $\gamma_{hotspot}$ = 30 % the number of BSs is 140, and for $\gamma_{hotspot}$ = 100 % the number is 108), Table 5.15. Moreover, the variation of the number of BSs and the sectors with a certain orientation is exactly the same, Figure 5.15. This means that all BSs that are placed when $\gamma_{hotspot}$ is increased have always 3 sectors, since they are associated to hot spots. As more of these areas with high-density traffic are covered, the uncovered area and ξ decrease; therefore, these two last performance parameters increase with $\gamma_{hotspot}$ (for $\gamma_{hotspot}$ = 30 % the uncovered area is 21.8 %, and it is equal to 33.7 % for $\gamma_{hotspot}$ = 100 %).

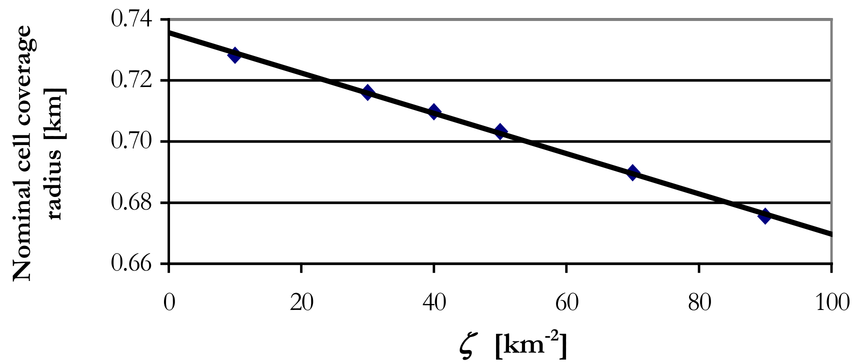


Figure 5.14 – Variation of the nominal cell radius with ζ for a 384 kbps (PS) – pedestrian scenario.

Table 5.15 – Algorithm performance with the variation of $\gamma_{hotspot}$ for a 384 kbps (PS) – pedestrian scenario.

	$\gamma_{hotspot}$ [%]		
	30	**72**	**100**
Number of added BSs	140	117	108
Uncovered area [%]	21.8	29.7	33.7
ξ **[km^{-2}]**	0.94	1.17	1.39

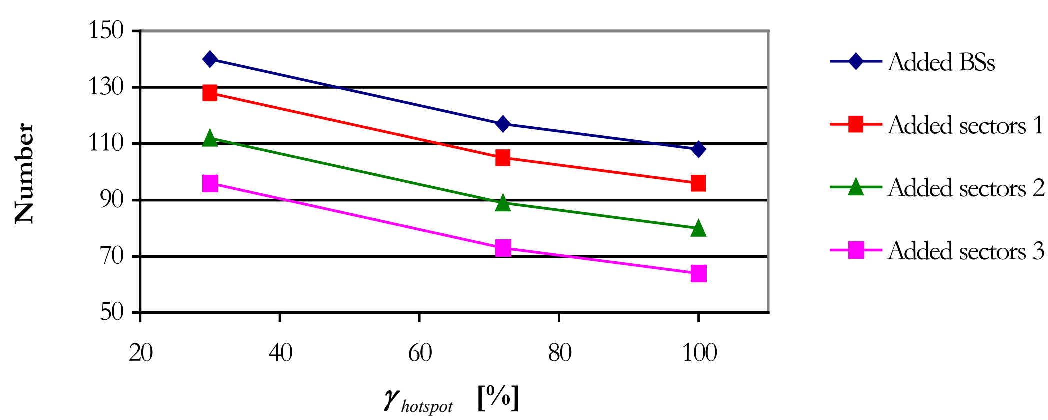


Figure 5.15 – Number of BSs and of each kind of sector for 384 kbps (PS) – pedestrian reference service bearer and for several $\gamma_{hotspot}$ values.

In a hot spot, sectors are placed without taking the superposition area into account. As these areas have always a small size (between 10 and 50 % of the nominal cell coverage area), it is natural that the percentage area of each added sector that is also covered by the surrounding BSs is high. For that reason, one can see that the percentage of the area that is covered by more than one sector increases with the number of BSs that are placed in hot spots, and, consequently, decreases with $\gamma_{hotspot}$, Figure 5.16.

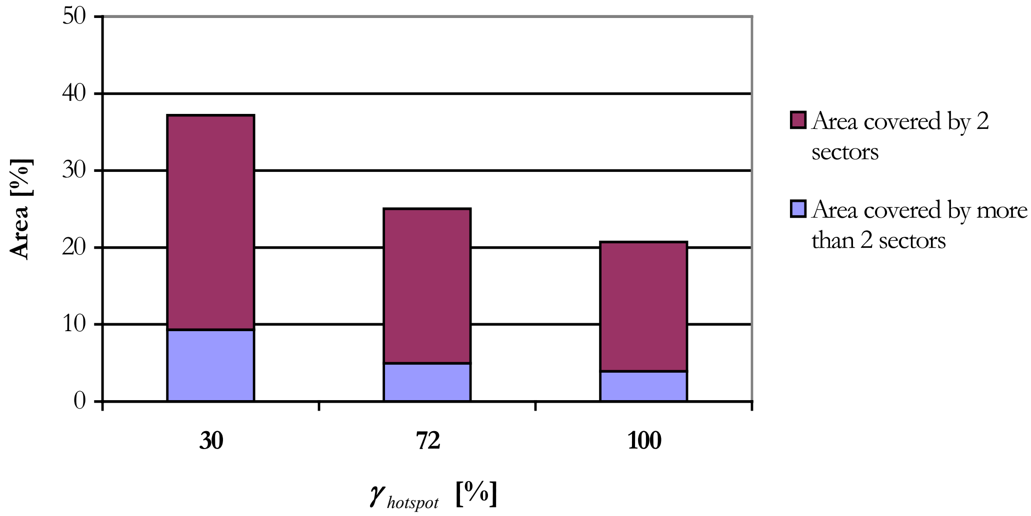


Figure 5.16 – Variation of the superposition area for a 384 kbps (PS) – pedestrian scenario as function of $\gamma_{hotspot}$.

The number of placed BSs increases with $P_{\sup}$, Table 5.16: when this parameter is higher, the BSs placed in MSs and LSs can have a larger superposition area. For more placed BSs and the nominal cell coverage area being constant, the uncovered area decreases with ξ. The parameter also decreases, but in this case the variation is quite high. As previously mentioned, the mainly reason for having a huge ξ (it should be lower than 0.38 km^{-2}) is the existence of MSs and LSs that have significant traffic, but are not covered by new BSs, since they would have a high superposition area. When $P_{\sup}$ is increased, the algorithm starts to put BSs in those surfaces, and ξ parameter decreases a lot. In Figure 5.17, one can see that only the uncovered area related with MSs and LSs decreases. One should note that for $P_{\sup}$ = 100 %, ξ is below the target value. On the other hand, as expected, one sees that the superposition area increases with the input parameter.

5.4 Area with Initial Network

The second part of the analysis is to make the simulation over an already existing network: in this work one will use the Lisbon Vodafone's one, which is co-located with a GSM network. This network has a high density of BSs in the downtown area, Figure 5.1, because it is the place where the traffic density is higher; therefore, for the 128 kbps (PS) – pedestrian scenario there is no uncovered area in that zone, Figure 5.18. On the other hand, in the other areas the BS density is lower, being almost equal to zero in areas like *Monsanto* Park and the airport (in some parts it is exactly zero). The duration of each simulation is about 1 hour and 30 minutes, using a Pentium 4 processor.

Table 5.16 – Algorithm performance with the variation of P_{sup} for a 384 kbps (PS) – pedestrian scenario.

	P_{sup} [%]			
	10	**30**	**50**	**100**
Number of added BSs	98	117	122	124
Uncovered area [%]	38.4	29.7	25.1	20.9
ξ **[km^{-2}]**	1.59	1.17	0.61	0.35
Superposition area [%]	18.4	25.0	31.1	39.3

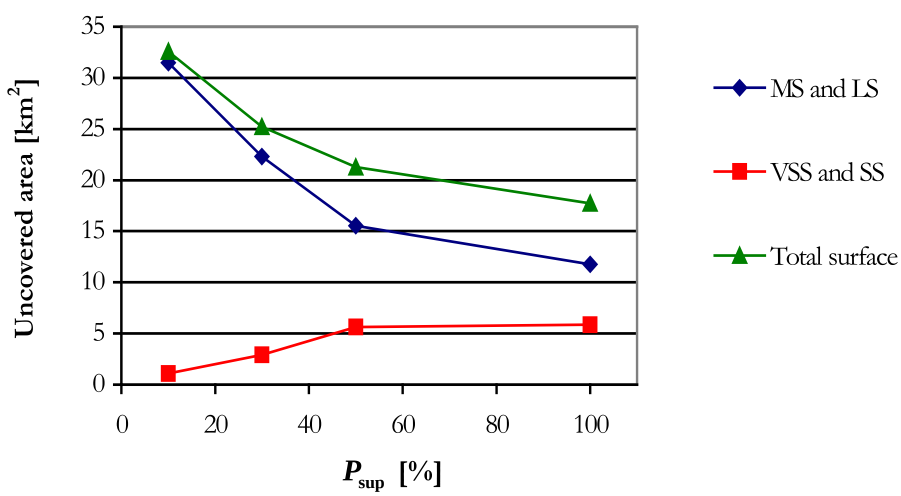


Figure 5.17 – Uncovered area variation with P_{sup} for a 384 kbps (PS) – pedestrian scenario.

The simulator was run in the initial network without placing new BSs in order to see its performance and to compare it with the one obtained in the last section, where there is no initial network, for the same service bearer (384 kbps (PS) – pedestrian). One can see that the network has 194 BSs, all of them with 3 sectors, a lot more than the number of BSs in the network that was completely created by the BS placement algorithm for the 384 kbps (PS) – pedestrian reference service bearer (117 BSs), Table 5.17. Despite of that, the uncovered area is only a bit smaller (18.2 % in the first one and 29.7 % in the other one), Figure 5.18, because many of the initial BSs are concentrated in downtown; therefore, they have a quite high superposition. In fact, the percentage of the area covered by more than 1 sector is equal to 58.5 % in the first network, while in the second one it is equal to 25.0 %. As the high-density traffic areas in the downtown are completely covered by the GSM co-located network, ξ is low.

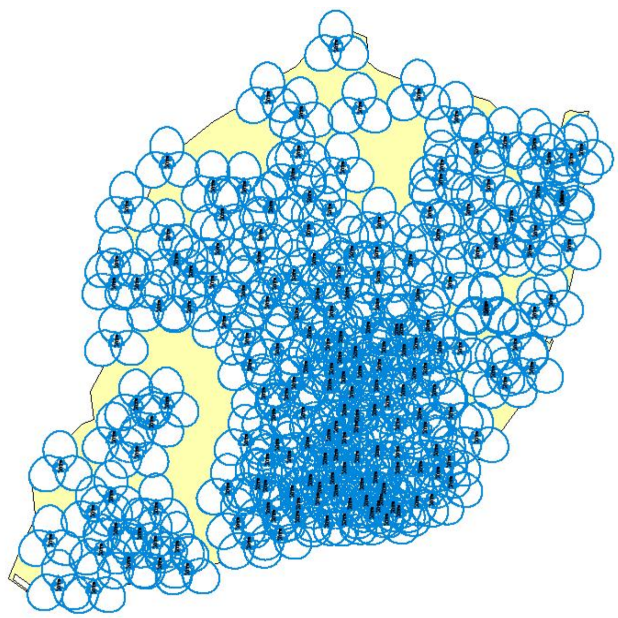


Figure 5.18 – Initial network coverage for a 128 kbps (PS) – pedestrian scenario.

Table 5.17 – Characteristics of the initial and new networks for a 384 kbps – pedestrian scenario.

	Network	
	Initial	**New**
Number of BSs	194	117
Number of sectors 1	194	105
Number of sectors 2	194	89
Number of sectors 3	194	73

One has varied both reference service bearers and reference user scenarios, running the BS placement algorithm in order to see what is the difference between these cases, where the nominal cell radius changes. As expected, the number of added BSs increases when the nominal cell coverage radius decreases, Table 5.19. For the 12.2 kbps (CS) – pedestrian and 64 kbps (PS) – pedestrian cases, the number of placed BSs is equal to zero because the nominal cell radius is so large that the service area is almost totally covered. In fact, on sees that for the first one the uncovered area is 2.2 % of the service area and that the uncovered traffic is 0.4 %. Some of the other cases do not have any data because the simulator failed to place BSs there. The number of BSs is smaller than the ones obtained in the last section, because in this situation one already has a set of BSs as a starting point, which covers a significant part of the service area.

Table 5.18 - Comparison of the performance of the initial and new network, which was created over Lisbon without initial network, for a 384 kbps – pedestrian scenario.

		Network	
		Initial	**New**
Uncovered area [%]		18.2	29.7
ξ [km^{-2}]		0.51	1.17
Equivalent uncovered traffic [%]	**VSS and SS**	1.9	6.4
	MS and LS	3.7	14.4
Area covered by 1 sector [%]		31.1	49.7
Area covered by 2 sectors [%]		23.3	20.0
Area covered by more than 2 sectors [%]		35.2	5.0

Table 5.19 – Number of placed BSs for several reference service bearers in the initial network.

Number of placed BSs		
Reference service bearer	**Reference user scenario**	
	Pedestrian	**Vehicular**
12.2 kbps (CS)	0	1
64 kbps (PS)	0	8
128 kbps (PS)	3	15
384 kbps (PS)	10	-

When the network is totally created by the BS placement algorithm, the density of the BSs changes with the nominal cell radius: when the latter is lower the density is higher. However, now one has a network that has a set of BSs which position does not change with the variation of the reference service bearer. So, it is expectable to see that the superposition area increases a lot when the nominal cell radius also increases (for 12.2 kbps (CS) – pedestrian the superposition area is 99.7 % and for 384 kbps (PS) – pedestrian is 61.1 %), Figure 5.19.

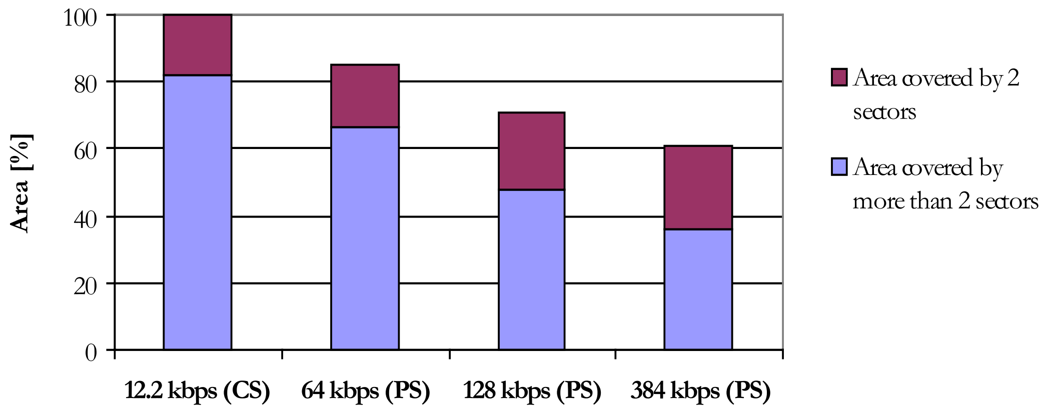


Figure 5.19 – Variation of the superposition area for several reference service bearers (all pedestrian).

One can see that the uncovered traffic is always low (always below 7.5 %), tending to increase with the decrease of the nominal cell coverage radius, Figure 5.20, which was expected, since a lower nominal radius leads to a lower coverage area; therefore, when the latter is decrease, some uncovered VSSs and SSs begin to appear in the high density area, like downtown, and that are not covered by the new BSs placed by the algorithm, because they do not have sufficient area or sufficient traffic (it is not a hot spot) for that. Moreover, the large uncovered surfaces with low traffic density that are not covered by the new network also increase, Figure 5.21. This is also the reason why the uncovered area tends to increase with the decrease of the nominal cell radius, Table 5.20.

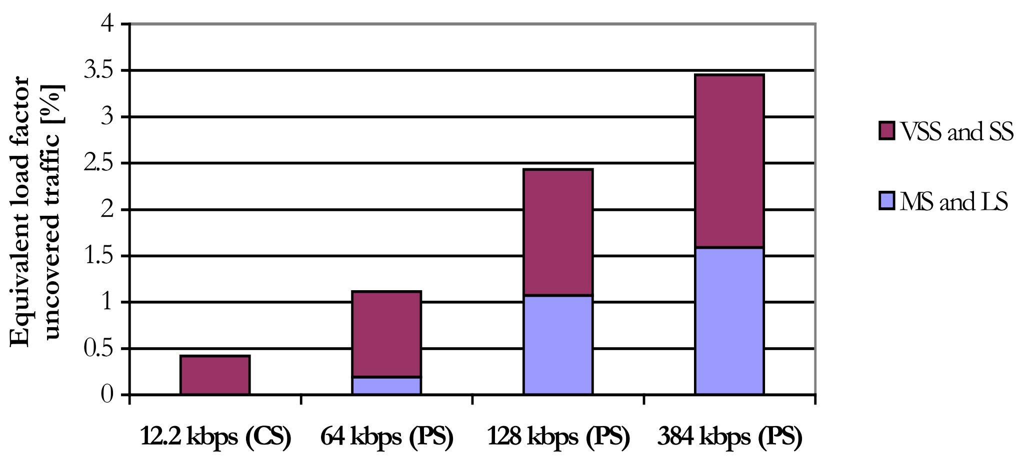


Figure 5.20 – η_{DL}^{equiv} uncovered traffic for the pedestrian reference user scenario cases.

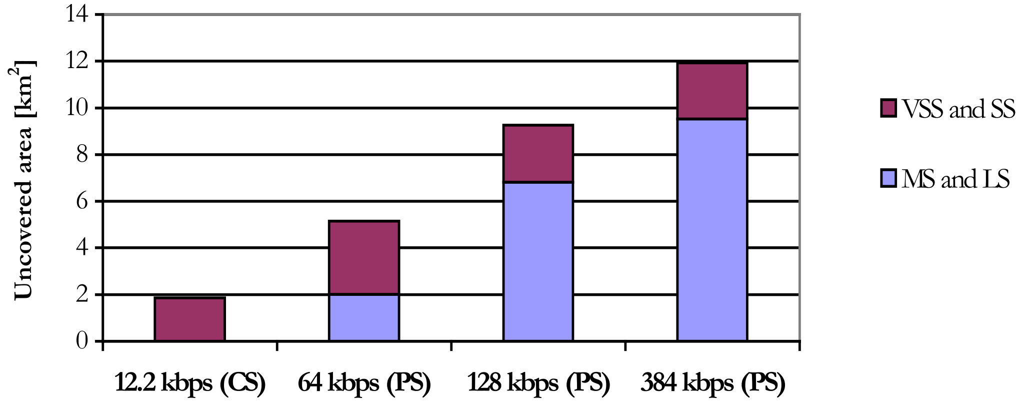


Figure 5.21 – Uncovered area for the pedestrian reference user scenario cases.

Table 5.20 – Uncovered area for several reference service bearers.

Uncovered area [%]		
Reference service bearer	**Reference user scenario**	
	Pedestrian	**Vehicular**
12.2 kbps (CS)	2.2	7.9
64 kbps (PS)	6.1	13.6
128 kbps (PS)	11.2	21.4
384 kbps (PS)	14.1	-

The ξ parameter is almost always below the value corresponding to traffic threshold, which, as one has seen before, is equal to 0.38 km^{-2}, Table 5.21, decreasing with the nominal cell radius. However, there are cases where ξ is above this value (for the 128 kbps (PS) – vehicular scenario the parameter is 0.61 km^{-2}), because the nominal cell radius is low; therefore, uncovered areas with significant traffic appear, which are not always covered by new BSs, because they are SSs and are not classified as a hot spot, or are considered to be MSs or LSs, and the superposition area is high for the BSs placed in the candidate sites, Figure 5.22. A simulation was made for a 128 kbps (PS) – vehicular scenario using P_{sup} = 100 %; therefore, the algorithm does not take into account the superposition area of the candidates BSs in MSs and LSs. As a result, ξ decreases a lot (now it is equal to 0.43 km^{-2}), being near the target value. One verifies that, when the coverage of the existing network covers almost all high-density areas, P_{sup} should be low in order to have new BSs with small superposition area, but when there are gaps in the coverage of these areas, then the input parameter must be high, making the simulator able to put new BSs there.

Table 5.21 – ξ for several reference service bearers in the new network.

ξ [km^{-2}]		
Reference service bearer	**Reference user scenario**	
	Pedestrian	**Vehicular**
12.2 kbps (CS)	0.00	0.18
64 kbps (PS)	0.17	0.32
128 kbps (PS)	0.28	0.62
384 kbps (PS)	0.30	-

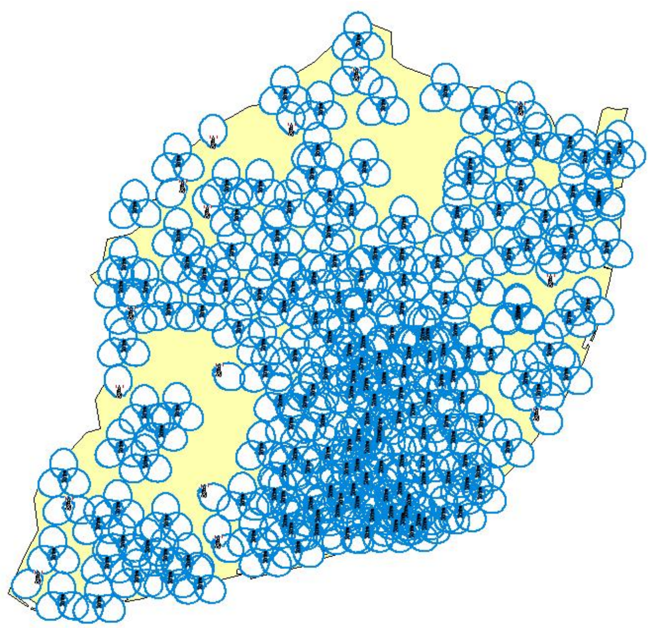


Figure 5.22 – Coverage of the new network for a 128 kbps (PS) – vehicular scenario.

It is also possible to compare the performance of the initial and new network for the 128 kbps (PS) – pedestrian scenario. Obviously, the new network has more BSs, the added ones not having always 3 sectors, Table 5.22. In the new network the uncovered area is smaller and the new BSs are placed in specific areas, which leads to the decrease of ξ (in the initial network ξ = 0.36 km^{-2} and in the new one ξ = 0.28 km^{-2}). As the uncovered area decreases from one network to another, the uncovered traffic also decreases, the variation being larger in both MSs and LSs than in the VSSs and SSs.

Table 5.22 – Characteristics of the initial and new networks for a 128 kbps – pedestrian scenario.

	Network	
	Initial	**New**
Number of BSs	194	197
Number of sectors 1	194	196
Number of sectors 2	194	195
Number of sectors 3	194	196

One can compare the performance of the initial network for the 128 kbps (PS) – pedestrian, Table 5.23, and the 384 kbps (PS) – pedestrian scenarios, Table 5.18. As the nominal cell radius is lower for the second case, one sees that the uncovered traffic and the uncovered area are higher, and that the superposition area is lower (58.5 % instead of 69.4 %).

Table 5.23 – Comparison of the performance of the initial and new networks for a 128 kbps – pedestrian scenario.

		Network	
		Initial	**New**
Uncovered area [%]		12.5	11.2
ξ **[km^{-2}]**		0.36	0.28
C_{unc}^{BH} **[MB/h]**		3 477	2 766
Equivalent uncovered traffic [%]	**VSS and SS**	1.4	1.4
	MS and LS	1.7	1.1
Area covered by 1 sector [%]		28.7	29.0
Area covered by 2 sectors [%]		22.1	22.7
Area covered by more than 2 sectors [%]		47.3	47.9

Other simulations were made, generating users in order to make a performance analysis of the initial and new networks for 128 kbps (PS) – pedestrian. As users are generated in a random way, as described in Section 4.2.2, 10 independent simulation were made for each network, each one about 1 hour and 30 minutes, in order to have some statistic relevance.

One can note that both blocking and delay probabilities decrease when the algorithm placed new BSs (with 3 BSs placed, the blocking probability decrease from 0.8 to 0.7 % and the delay one from 1.1 to 0.9 %), Table 5.24. However, the placement of new BSs into the network is not enough to see these variations in the parameters: their location is also very important. In fact, if the new BSs are placed in areas with no traffic, they will not cover any user; therefore, the performance of the network remains unchanged. In this case, the probabilities change because of two reasons: in the first one, blocked and delayed users decrease a little, Figure 5.23, because the users covered by the new BSs are not enough to be blocked or delayed and because they cover users that were already covered by the initial BSs, decreasing the load there; in the second reason, the main one, the number of uncovered users decreases (2 582 for the initial network and 2 564 for the new one). The total number of users being constant, one verifies that the number of covered users increases as well as the CS and PS calls; therefore, the blocking and the delay probabilities decrease. This result, where the number of uncovered users decreases, shows that the new BSs are placed by the algorithm in areas where the traffic is significant.

Table 5.24 – Comparison of the performance analysis between the initial and new networks for a 128 kbps (PS) – pedestrian scenario, in terms of blocking and delay probabilities.

Network	P_b [%]	P_d [%]	N_{unc}	R_{global} [kbps]
Initial	0.8	1.1	2 582	354
New	0.7	0.9	2 564	352

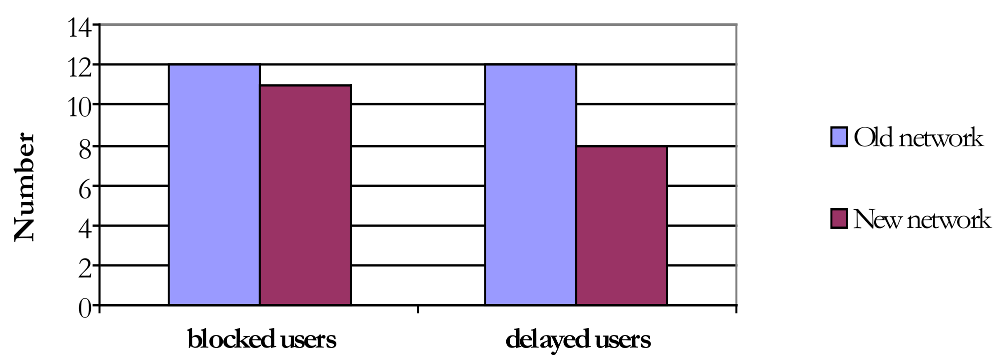


Figure 5.23 – Number of the blocked and delayed users in the initial and new networks for the 128 kbps (PS) – pedestrian scenario.

The R_{global} parameter decreases a little in the new network: this results from the fact that the new BSs are not placed in high-density traffic areas; therefore, they do not serve many users, decreasing the average number of users per cell, and, consequently, the average R_{global} among sectors. From the UL/DL load factors and the BS transmission power performance parameters, the only one that has a maximum value near the corresponding threshold is the first one (equal to 50 %), Table 5.25. This means that for both simulated cases, the number of users in each sector is always limited by the load factor in UL: there can be also cases where users are blocked by the number of available codes, but that is improbable, since the former parameters are much more restricting. The minimum value for the load factor in UL/DL is equal to zero, because there is at least one sector that is serving no user.

Table 5.25 – Comparison of the performance analysis between the initial and new networks for a 128 kbps (PS) – pedestrian scenario, in terms of load and BS transmission power.

Network	η_{DL} [%]			η_{UL} [%]			P_{Tx}^{BS} [dBm]		
	Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Initial	0.00	64.44	29.13	0.00	49.99	27.66	-82.15	23.26	12.31
New	0.00	65.95	29.05	0.00	49.97	27.73	-82.15	22.10	12.33

The mean value for the cell radius is equal to the maximum one, which means that the radius is not decreased a lot for the sets of users that are simulated, Table 5.26. Furthermore, the maximum value is equal to the nominal cell radius for the considered scenario (considering M_i and L_F equal to zero). For the case where one has a new network, the minimum value for the mean cell radius is equal to zero, because the BS placement algorithm places BSs without some sectors: obviously, in these missing sectors the cell radius is null.

Table 5.26 - The cell radius for the initial and new networks for a 128 kbps (PS) – pedestrian scenario.

Network	Cell radius [km]		
	Min.	Max.	Mean
Initial	0.70	0.72	0.72
New	0.00	0.72	0.72

Although there is an improvement in the initial network when the BS placement algorithm is used for the 128 kbps (PS) – pedestrian scenario, one sees that it is quite low, since the variation in the performance parameters is very small, being almost negligible, because the uncovered area of the initial network is small and the algorithm places a few BSs (only 3). Therefore, other simulations were made for a scenario that leads to a lower nominal cell radius (128 kbps (PS) – vehicular).

One can see that the uncovered area of the initial network is higher for the 128 kbps (PS) – vehicular scenario than for the 128 kbps (PS) – pedestrian one (it is equal to 28.1 instead of 12.5 %), Table 5.27, the number of BS placed by the algorithm being also higher (it is equal to 15 instead of 3), Table 5.28. As a result, one can see higher variations in the performance parameters, observing a decrease in the uncovered area, uncovered traffic (decreases from 11.5 to 7.4 %), and ξ.

Table 5.27 – Comparison of the performance of the initial and new networks for a 128 kbps – vehicular scenario.

		Network	
		Initial	**New**
Uncovered area [%]		28.1	21.4
ξ **[km^{-2}]**		0.75	0.62
C_{unc}^{BH} **[MB/h]**		13 278	8 453
Equivalent uncovered traffic [%]	**VSS and SS**	2.7	2.0
	MS and LS	8.8	5.4
Area covered by 1 sector [%]		34.2	36.6
Area covered by 2 sectors [%]		21.6	23.7
Area covered by more than 2 sectors [%]		21.0	24.4

Table 5.28 – Characteristics of the initial and new networks for a 128 kbps – vehicular scenario.

	Network	
	Initial	**New**
Number of BSs	194	209
Number of sectors 1	194	203
Number of sectors 2	194	202
Number of sectors 3	194	200

Simulations were not done for the 128 kbps (PS) – vehicular scenario, using generated users, in order to obtain performance parameters, like the blocking and delay probabilities. However, ones verifies that these parameters are not the adequate ones for analysing the improvement of the network with the BS placement algorithm usage, since its change with the number of placed BSs is negligible.

A good parameter to analyse the improvement of the network is the C_{unc}^{BH} one. One can see that for the 128 kbps (PS) – pedestrian scenario, the difference of C_{unc}^{BH} between the initial and the new networks is equal to 711 MB/h, Table 5.23, which means that each new sector covers on average 142 MB/h of traffic that were not covered yet. In the 128 kbps (PS) – vehicular case, more BSs are placed by the algorithm, in areas where the traffic is higher; therefore, the difference in C_{unc}^{BH} is higher, being equal to 4 825 MB/h, which means that each new sectors covers 210 MB/h that were not covered by the initial network (more than in the last case). These values can be compared with the mean traffic that is covered by each initial sector, Table 5.29. Obviously, as the nominal cell radius is higher for the 128 kbps (PS) – pedestrian scenario, the traffic covered by each sector is also higher. One sees that the traffic covered by each new sector that was not initially covered in 128 kbps (PS) – vehicular is significant, since its value is equal to 39 % of the mean traffic that is covered by each initial sector.

Table 5.29 – Traffic covered by each initial sector for different scenarios.

Scenario	Traffic covered by each sector [MB/h]			
	Min.	**Max.**	**Mean**	**Stand. Deviation**
128 kbps (PS) – pedestrian	17	4 400	967	825.0
128 kbps (PS) – vehicular	5	2 847	543	487.2

When the ζ input parameter is higher one sees that the number of BSs is lower, Table 5.30. As described in the last section, one has to consider two things to explain this result. On the one hand, when ζ increases, there is less area with sufficient traffic density to place a BS, and the number of added BSs tends to decrease; on the other, the nominal cell coverage radius and, consequently, the nominal cell coverage area becomes smaller; therefore, the number of BSs tends to increase. In the end, one sees that the number of BSs effectively decreases with ζ. The number of placed BSs and the nominal cell coverage area being both higher, it is natural to verify that the uncovered area and ξ decrease, since the placement of the BSs is almost constant: the majority of them belong to the initial network.

As seen in the last section, the number of BSs placed by the algorithm in the initial network decreases with $\gamma_{hotspot}$, Table 5.31. In fact, if the traffic threshold for the hot spot areas increases, the numbers of small areas that are classified as hot spot is lower; therefore, the number of added BSs decreases. For the same reason, the uncovered area and ξ increase with the analysed parameter. However, these two last performance parameters are always lower than the ones obtained for the initial network and the same reference service bearer, Table 5.22. Furthermore, one can see that when $\gamma_{hotspot}$ = 100 %, the number of sectors, with a 120 º orientation, added to the network is equal to zero, which means that there are no BSs placed by the algorithm in hot spot areas; therefore, the 2 added BSs are placed in MSs and LSs. This means that if one increases $\gamma_{hotspot}$ to values above 100 % the result will be exactly the same.

Table 5.30 – Algorithm performance with the variation of ζ for a 128 kbps (PS) – pedestrian scenario in the new network.

	ζ [km^{-2}]		
	30	**55**	**70**
Number of added BSs	4	3	2
Uncovered area [%]	10.1	11.2	12.0
ξ **[km^{-2}]**	0.24	0.28	0.28

Table 5.31 – Algorithm performance with the variation of $\gamma_{hotspot}$ for a 128 kbps (PS) – pedestrian scenario.

	$\gamma_{hotspot}$ [%]		
	30	**72**	**100**
Number of added BSs	6	3	2
Uncovered area [%]	10.3	11.2	11.7
ξ **[km^{-2}]**	0.28	0.28	0.34

In Figure 5.24, one verifies that the variation for both placed BSs and each one of the sectors with $\gamma_{hotspot}$ is the same, because the BSs within this variation are all placed in hot spot areas; so, they all have the 3 sectors.

When $P_{\sup}$ increases, the added sectors can have a higher superposition area; therefore, it is natural to see that the number of placed BSs increases with this parameter, Table 5.32. More MSs and LSs with significant traffic being covered by the new BSs, the uncovered area and ξ decrease. In contrast, the superposition area increases. For $P_{\sup}$ = 10 % the only added BSs is placed in a hot spot and has all 3 sectors.

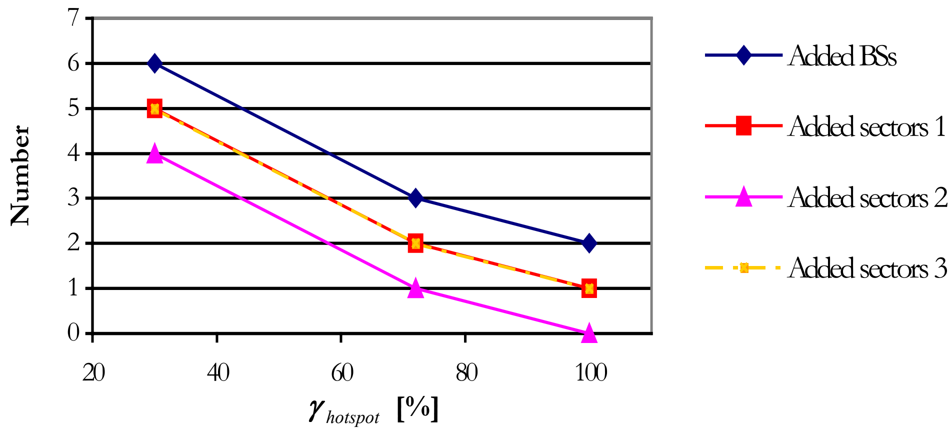


Figure 5.24 – Number of BSs and sectors for a 128 kbps (PS) – pedestrian scenario and several $\gamma_{hotspot}$ values.

Table 5.32 – Algorithm performance with the variation of $P_{\sup}$ for a 128 kbps (PS) – pedestrian scenario in the new network.

	$P_{\sup}$ [%]		
	10	**30**	**50**
Number of added BSs	1	3	5
Uncovered area [%]	11.9	11.2	10.6
ξ **[km^{-2}]**	0.31	0.28	0.28
Superposition area [%]	70.3	70.5	70.9

Simulations were also made using different service bearer distributions, Table 5.33, where users have higher throughputs. This variation has two opposite effects in the calculation of η_{DL}^{equiv} in each pixel of the input grid. On the one hand, the increase of $\overline{R}_b$ leads to a higher $\overline{\eta}_{serv}^{user}$, (4.8), therefore, η_{DL}^{equiv} should increase; on the other, one sees from (4.6) that $\overline{N}_{users}^{active}$ decreases, because λ_{BHCA} is always constant in each pixel, which makes η_{DL}^{equiv} to decrease. The result is not easy to predict, but one can verify that in these cases the total traffic in the service area tends to decrease with $\overline{R}_b$, Figure 5.25.

One can see that the variation of η_{DL}^{equiv} is not sufficient to make a difference in the number of added BSs or sectors (in the 3 simulations, the number of added BSs is always equal to 3 and the sector distribution is always the same), Table 5.34. Therefore, the uncovered area remains constant, as well as the superposition one. The only difference is in the uncovered traffic percentage: it increases with $\overline{R}_b$, opposite to the total traffic in the service area. This means that η_{DL}^{equiv} decreases differently from one pixel to another.

Table 5.33 – Different service bearer distributions for several scenarios.

		Distribution [%]	
Service	**Throughput**	**Scenario 1**	**Scenario 2**
Speech-telephony	12.2 kbps (CS)	100	100
Video-telephony	64.0 kbps (CS)	100	100
Streaming Multimedia	64.0 kbps (PS)	50	50
	128.0 kbps (PS)	50	40
	384.0 kbps (PS)	0	10
E-mail	64.0 kbps (PS)	80	60
	128.0 kbps (PS)	20	20
	384.0 kbps (PS)	0	20
Location Based Service	64.0 kbps (PS)	80	60
	128.0 kbps (PS)	20	20
	384.0 kbps (PS)	0	20
MMS	64.0 kbps (PS)	50	40
	128.0 kbps (PS)	50	40
	384.0 kbps (PS)	0	20
File Download	64.0 kbps (PS)	20	10
	128.0 kbps (PS)	60	50
	384.0 kbps (PS)	20	40
Web Browsing	64.0 kbps (PS)	50	20
	128.0 kbps (PS)	40	40
	384.0 kbps (PS)	10	40

Other simulations were made using the same service bearer distributions as the ones described before (scenario 1 and 2), but with an increase of λ_{BHCA}, which is equivalent to the increase of $\overline{\eta}_{serv}^{user}$ from the default scenario to the new ones; therefore, one has increased the parameter by 5 % and 30 % for scenarios 1 and 2, respectively. When λ_{BHCA} is kept constant, one has previously seen that the total traffic in the service area tends to decrease with $\overline{R}_b$, but, now that this does not happen, this last parameter tends to increase with $\overline{R}_b$ when the different service bearer distributions gets higher, Figure 5.26.

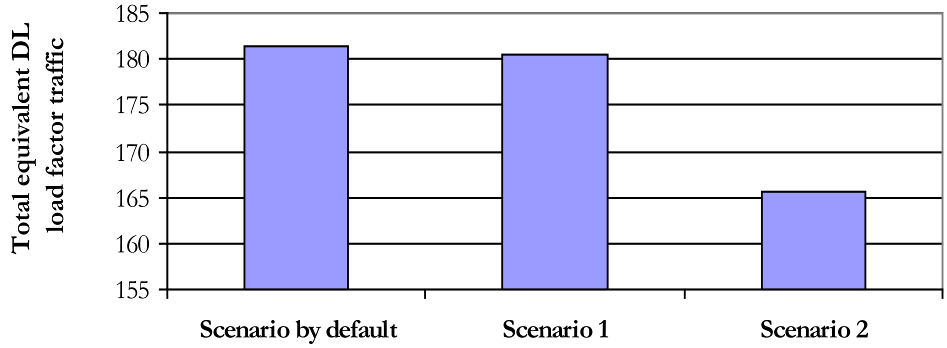


Figure 5.25 – The variation of η_{DL}^{equiv} in the service area with the change of the service bearer distribution.

Table 5.34 – Network performance for different service bearer distributions.

		Service bearer distribution		
		Default scenario	Scenario 1	Scenario 2
Number of added BSs		3	3	3
Uncovered area [%]		11.2	11.2	11.2
ξ [km^{-2}]		0.28	0.28	0.26
Equivalent uncovered traffic [%]	VSS and SS	1.4	1.4	1.4
	MS and LS	1.1	1.1	1.1

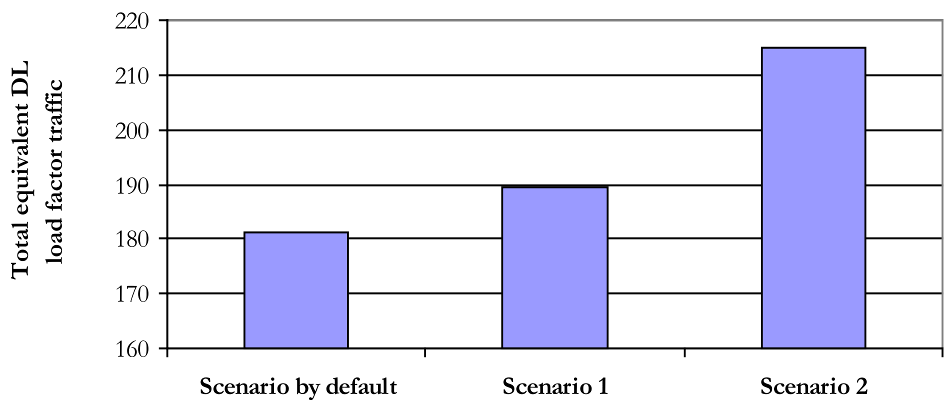


Figure 5.26 – The variation of η_{DL}^{equiv} in the service area with the change of the service bearer distribution when λ_{BHCA} is increased.

The number of BSs placed in the network by the algorithm remains the same for the several service bearer distributions; however, one verifies that the number of added sectors increases with $\overline{R}_b$ (it is equal to 5 and 6 in the default scenario and scenario 2, respectively), Table 5.35. This happens because η_{DL}^{equiv} in each pixel increases from the default scenario to scenario 1 and from the latter to scenario 2; therefore, as ζ is the same, the algorithm tends to decide more often to add a sector. Consequently, the uncovered area and the uncovered traffic decrease. As the traffic increases everywhere, the traffic density also increases in the MSs and LSs that are not covered by the new network, ξ being higher. Despite that, the performance parameter is always below 0.38 km^{-2}, which is the corresponding value for ζ .

Table 5.35 – Network performance for different service bearer distributions when λ_{BHCA} is increased.

		Service bearer distribution		
		Default scenario	**Scenario 1**	**Scenario 2**
Number of added BSs		3	3	3
Uncovered area [%]		11.2	11.2	11.1
ξ **[km^{-2}]**		0.28	0.30	0.32
Equivalent uncovered traffic [%]	**VSS and SS**	1.4	1.4	1.3
	MS and LS	1.1	1.1	1.0

5.5 Comparison with other Simulator

Other simulations using the simulator from [SeCa04] were made in order to compare its performance with the one from this work. This simulator spreads the BSs in the network coverage gaps in a uniform way without taking the traffic distribution in the area into account. All the simulations were made for a 128 kbps (PS) – pedestrian scenario.

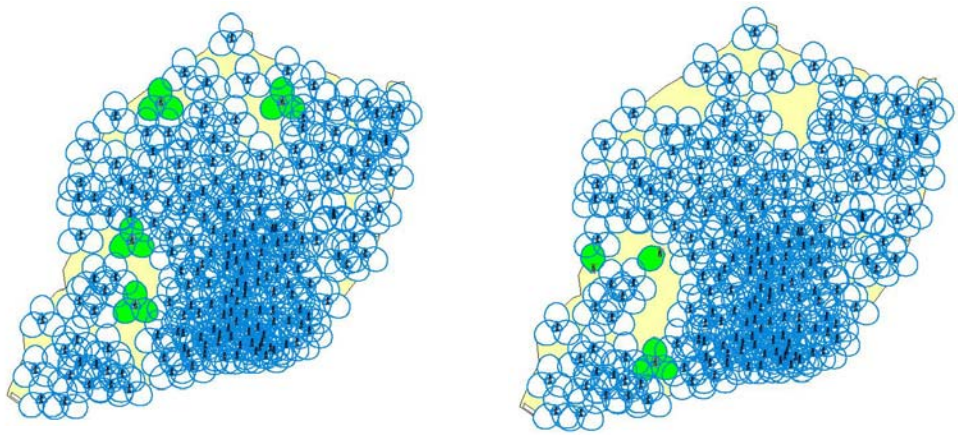
The old simulator places new BSs in the initial network, and, then, the simulator developed in this work is used to analyse the performance of the new network in terms of coverage, Table 5.36, Table 5.37. One can see that the old simulator places one more BS than the new one; therefore, the uncovered area is lower. The algorithm from [SeCa04] places the BSs always with 3 sectors, so the difference between the numbers of added sectors is greater than the numbers of added BSs (12 added sectors for the first and 5 for the second one). Despite the uncovered area being lower, one can see that ξ is higher: this means that the new BSs are not placed in the areas with more traffic. In fact, one can see that, since the old simulator does not take the traffic distribution into account, the BSs are placed in the uncovered LSs, where the traffic density is almost equal to zero: the airport and *Monsanto* Park, Figure 5.27. Furthermore, the simulator does not consider the superposition area of the sectors, so it places sectors even if the superposition is quite high. This is the reason why the area covered by more than 1 sector is higher in the network created by the old simulator (it is equal to 74.6 %) than the one created by the simulator developed in this work (it is equal to 70.6 %).

Table 5.36 – Characteristics of the new network created by the simulator from [SeCa04] and the one developed in this work, for a 128 kbps – pedestrian scenario.

	New network	
	From [SeCa04]	**From this work**
Number of added BSs	4	3
Number of added sectors 1	4	2
Number of added sectors 2	4	1
Number of added sectors 3	4	2

Table 5.37 – Comparison of performance in terms of coverage of the new network created by the simulator from [SeCa04] and the one developed in this work, for a 128 kbps – pedestrian scenario.

		New network	
		From [SeCa04]	**From this work**
Uncovered area [%]		7.6	11.2
ξ **[km^{-2}]**		0.39	0.28
Equivalent uncovered traffic [%]	**VSS and SS**	1.4	1.4
	MS and LS	0.9	1.1
Area covered by 1 sector [%]		29.5	29.0
Area covered by 2 sectors [%]		23.0	22.7
Area covered by more than 2 sectors [%]		51.6	47.9



(a) Simulator from [SeCa04]. (b) Simulator developed in this work.

Figure 5.27 – Network coverage for the new networks created by different simulators for a 128 kbps (PS) – pedestrian scenario (new BSs are presented in green).

As described in the last section, the network analysis performance is done by making 10 independent simulations in order to have some statistic relevance. At first, one can verify that the new network created by the simulator from [SeCa04] is better than the initial one, since the number of uncovered users and the both blocking and delay probabilities are lower. However, when it is compared with the one obtained by the simulator developed in this project, one sees that the network is not so good. Despite the fact of having more BSs and the uncovered area being lower, the number of uncovered users is higher, because the new BSs are placed in areas with almost no traffic; therefore, both blocking and delay probabilities are higher, Table 5.38. Having the new BSs almost no covered users, the average R_{global} among sectors is lower.

Table 5.38 – Comparison of the performance of the several simulated networks, in terms of blocking and delay probabilities.

Network		P_b [%]	P_d [%]	N_{unc}	R_{global} [kbps]
Initial		0.8	1.1	2 582	354
New	**[SeCa04]**	0.8	1.0	2 573	353
	Developed here	0.7	0.9	2 564	350

Once more, one verifies that the number of users in the sectors is limited by the load factor in UL, since this is the only parameter which maximum value is quite near the corresponding threshold, Table 5.39.

Table 5.39 – Comparison of the performance of the several simulated networks, in terms of load and BS transmission power.

Network		η_{DL} [%]			η_{UL} [%]			P_{Tx}^{BS} [dBm]		
		Min.	Max.	Mean	Min.	Max.	Mean	Min.	Max.	Mean
Initial		0.00	64.44	29.13	0.00	49.99	27.66	-82.15	23.26	12.31
New	[SeCa04]	0.00	61.89	28.86	0.00	49.99	27.50	-82.15	22.40	12.27
	Developed here	0.00	65.95	29.05	0.00	49.97	27.73	-82.15	22.10	12.33

The mean coverage radius does not change when considering all the cases: for the simulations using the [SeCa04] BS placement algorithm, the value for the parameter continues to be equal to 0.72, which is the value of the nominal cell coverage radius for the considered scenario (128 kbps – pedestrian). However, in contrast to the case where the algorithm used in the simulation is the one developed here, the minimum value for the coverage radius is not zero (it is equal to 0.70), because the existing algorithm only adds BSs with 3 sectors.

As the variation of the performance parameters is quite low, other simulations were done for the 128 kbps (PS) – vehicular scenario, where the nominal cell radius is lower, and the number of BSs placed by the algorithm is higher (it is equal to 21 instead of 4). Now, one can see a higher variation in the results between the algorithm developed in this work, and the one from [SeCa04], Table 5.40.

Table 5.40 – Comparison of the performance in terms of coverage of the new network, created by the simulator from [SeCa04], and the one developed in this work, for a 128 kbps – vehicular scenario.

		New network	
		From [SeCa04]	From this work
Uncovered area [%]		12.5	21.4
ξ [km^{-2}]		0.83	0.62
Equivalent uncovered traffic [%]	VSS and SS	4.6	2.0
	MS and LS	1.9	5.4
Area covered by 1 sector [%]		39.2	36.6
Area covered by 2 sectors [%]		27.4	23.7
Area covered by more than 2 sectors [%]		27.9	24.4

As seen in Section 5.4, C_{unc}^{BH} is the best performance parameter to analyse the improvement of the network with the use of the BS placement algorithm. One can see that the [SeCa04] algorithm places more sectors for 128 kbps (PS) - vehicular than the other one (places 63 sectors instead of 23), C_{unc}^{BH} decrease being higher (it is equal to 5 809 instead of 4 825 MB/h), Table 5.41. However, the old algorithm has a worst performance, since each new sector covers an average of 92 MB/h of traffic that was not covered yet by the initial network (only 17 % of the mean traffic that is covered by each initial sector), while in the algorithm developed in this work the value is quite higher (it is equal to 210 MB/h).

Table 5.41 – Variation of C_{unc}^{BH} for the new network, created by the simulator from [SeCa04], and the one developed in this work, for a 128 kbps – vehicular scenario.

	C_{unc}^{BH} **[MB/h]**	
	Initial network	**New network**
From [SeCa04]	13 278	7 469
From this work	13 278	8 453

Finally, one concludes that the simulator developed here is better than the already existing one, because with less BSs and sectors (lower cost to the network operator) it achieves a lower ξ (it is equal to 0.62 instead of the 0.83 km^{-2} for the 128 kbps (PS) – vehicular scenario), and the new sectors cover more traffic that was not covered yet by the initial network.

Chapter 6

Conclusions

In this chapter some conclusions are drawn, some ideas for future work being presented at the end.

In this thesis, one has developed a model that is able to place new BSs in order to improve the coverage, taking into account the multi-service traffic distribution in the service area in UMTS-FDD networks. The simulator that implements the model is also capable of performing the performance analysis of the network. The program is composed of several blocks: the first is the users generator, which is built using *C++* programming and generates users, with their own characteristics, according to input data, like the traffic distribution. Other blocks run over *MapInfo* and are developed in both *C++* and *MapBasic* languages, creating the network and evaluating its performance. Furthermore, the simulator user has the possibility to change some network characteristics. Finally, there is a block that is responsible for the automatic placing of new BSs, which is the main focus of this work. The BS placement algorithm is implemented using *MapBasic* programming and runs over *MapInfo* in order to take advantage of the GIS tools.

The simulator is based on [SeCa04], adding new features in the frequency allocation and in the selection of the covered users and accounting for the active set threshold. In this already developed simulator, the implemented BS placement algorithm is not quite good, because it spreads new BSs through the uncovered areas in a uniform way and without taking the traffic distribution into account. In this work, a completely new algorithm was developed: one that uses a different heuristic for different types of uncovered areas, spreading the BSs in a non-uniform way, and that takes the traffic distribution into account, placing the new BSs in uncovered areas that have significant traffic. The algorithm was implemented in the simulator, substituting the old one.

The BS placement model starts by classifying uncovered areas into 4 classes, regarding the relation between these areas and the coverage area of a BS with 3 sectors (VSSs, SSs, MSs and LSs). For each one of these types of areas, the model uses a different heuristic to deal with it. For VSSs, no BS is placed. For SSs, a BS with 3 sectors is only placed in its geometric centre if the traffic inside it is above $\gamma_{hotspot}$. In MSs, the algorithm tries to place a BS in its geometric centre, but if the area is not duly covered, several BSs are spread over this uncovered area. Finally, for LSs, several BSs are spread over it. In MSs and LSs, sectors are only added into a placed BS if the traffic density inside it is above ζ, and if the relation between the superposition area and the sector coverage area is below $P_{\sup}$. If a BS has no sectors, then it is removed from the network.

Simulations were made to analyse the performance of the BS placement algorithm with the variation of several input parameters, for different conditions. The simulator ran over Lisbon, first without an initial network, therefore, in this case, the algorithm creates a totally new network in the service area. The quantity of placed BSs is quite high and it is easy to verify the variation of the network performance, by observing the performance parameters in each simulation for different algorithm configurations. Other simulations were made over an initial network, which one considers to be the UMTS Vodafone's network for Lisbon, co-located with the GSM one. One can see how the algorithm works in the improvement of the network coverage for different characteristics, like the reference service bearer, and the algorithm input parameters. Besides, a performance analysis was made for the initial and the new networks, observing the difference between the two in terms of both blocking and delay probabilities, uncovered users, etc.. Finally, a comparison between the performance of the BSs placement algorithm developed here and the one from [SeCa04] was done.

First, one concludes that the BS placement algorithm places new BSs in areas with significant traffic: it creates a network in Lisbon with a high density of BSs in areas like downtown. In areas like the airport or the *Monsanto* Park, where there is almost no traffic, the number of placed BSs is quite low. For P_{sup} = 100 %, the network covers almost all the areas with significant traffic, nevertheless, still existing some coverage gaps between the consecutive BSs. The simulator places many BSs with 3 sectors, but some of them have less sectors (2 or 1 sectors), especially in areas with lower traffic.

One verifies that the use of *MapBasic* consumes many computer resources, becoming quite slow when the algorithm is more complex; therefore, for cases where the nominal cell coverage area is smaller, the simulator simply crashes, being impossible to obtain results in these situations. The algorithm runtime varies a lot with the network that is being improved and the reference scenario that is being considered; for the service area without any BSs in an indoor reference user scenario, the runtime can reach more than 10 hours, while, for the initial network in a pedestrian reference user scenario, the runtime is about 1 hour and 30 minutes, using a Pentium 4 processor.

One concludes that when the reference service bearer bit rate increases, the nominal cell coverage radius decreases and, consequently, the number of BSs that are placed by the algorithm tends to be higher, since each BS covers a smaller area. As an example, one can see that, considering Lisbon without initial network, the simulator places 48 and 117 BSs for a 12.2 kbps (CS) – pedestrian and a 384 kbps (PS) – pedestrian reference scenarios, respectively. Furthermore, the number of added BSs is higher in the indoor reference user scenario, and lower in the pedestrian one (the number of added BSs without initial network is equal to 48 and 331 for the 12.2 kbps (CS) – pedestrian and the 12.2 kbps (CS) – indoor reference scenarios, respectively). When one considers the initial network, there are cases where the nominal cell radius is so high that the already existing BSs cover almost all the service area, therefore, the algorithm does not place any BS; this is the case for the 12.2 kbps (CS) and 64 kbps (PS) reference service bearers, both for pedestrian reference user scenarios.

As the nominal cell radius decreases, both uncovered area and uncovered traffic tend to increase, although the number of placed BSs increases (the uncovered area is equal to 22.4 % for 64 kbps (PS) – pedestrian and is 29.7 % for 384 kbps (PS) – pedestrian, both without initial network). This happens because the simulator adds a new sector if the mean traffic density inside it is above a given threshold; so, high nominal cell coverage areas can lead to the placement of BSs with sectors that cover areas with both high and low traffic, part of the low-density traffic being covered by the added BSs. This does not happen when the nominal cell radius is lower, the uncovered area being larger.

In the simulation without initial network, ξ has values quite above the expected one, which corresponds to the traffic density threshold input parameter (the minimum obtained value is equal to 0.60 km^{-2}, while the expected one is 0.38 km^{-2}). This happens, because for these cases there are MSs and LSs that are not covered by BSs, not because there is not enough traffic there, but because the superposition area in those BSs would be above the allowed one. However, one should note that the algorithm is developed to improve the coverage of an already existing network and not to create a new one: when the simulator is run in the initial network, ξ is quite low, in almost all cases being below 0.38 km^{-2} (the maximum value is equal to 0.62 km^{-2}). One way to decrease this performance parameter is to increase P_{sup}: as an example, when this latter parameter is increased from 30 to 100 %, ξ decreases from 1.16 to 0.35 km^{-2}, for the 384 kbps (PS) – pedestrian reference scenario without initial network.

On the other hand, the variation of ξ with the nominal cell radius is unpredictable, because it depends a lot on the shape, dimension and location of areas that are not covered by the network, since they lead to a high superposition area or because they are too small. Then, one concludes that ξ has quite a dependence on the placement of the BSs, which is always changing from one scenario to another.

The variation of the superposition area varies in a different way with the nominal cell radius when considering, as a starting point, Lisbon with and without an initial network. In the second case, one concludes that when the nominal cell radius decreases the number of placed BSs and their placement changes a lot, resulting in a decrease of the superposition area. In the case where the simulator is run over the initial network, there are many BSs that are already placed in the service area, therefore, the majority of the BSs of the new network remain always the same for the several scenarios. Then, when the nominal cell radius and, consequently, the nominal cell coverage area, increase, the superposition area also increases (for 12.2 kbps (CS) – pedestrian the superposition area is 99.7 % and for 384 kbps (PS) – pedestrian it is 61.1 %).

When ζ is increased, the portion of the uncovered area that has sufficient traffic density to place a new BS and the nominal cell radius decrease, therefore, it is difficult to predict how the number of placed BSs varies with this parameter. For all the simulations made, one sees that the number of added BSs decreases with ζ, and that, consequently, the uncovered area increases.

The increase of $\gamma_{hotspot}$ leads to a decrease of the number of added BSs (without initial network, the number decreases from 140 to 108 when the input parameter increases from 30 to 100 %), and, consequently, the uncovered area and ξ increase.

One verifies that the number of placed BSs increases with $P_{\sup}$, leading to a decrease of both uncovered area and ξ; however, the superposition area increases. So, when the coverage of the existing network covers almost all high-density areas, $P_{\sup}$ should be low in order to have new BSs with small superposition area. In contrast, when there are gaps in the coverage of these high-density areas, then the input parameter must be high, allowing the simulator to put new BSs there.

When the service bearer distribution is changed in order to increase the average transmission throughput for a certain service, $\overline{R}_b$, the BHCA values from the BHCA grids being also increased, the simulator tends to place more BSs.

By comparing the performance parameters from the performance analysis of the initial and the new network, one concludes that the new network is better, because more BSs and lower uncovered area leads to a decrease of C_{unc}^{BH} from 13 278 to 8 453 MB/h for the 128 kbps (PS) – vehicular case. This means that each new sector covers 210 MB/h that were not covered yet in the initial network, where each initial sector covers on average 543 MB/h.

A comparison between the BS placement algorithm developed in this work and the one from [SeCa04] was made, analysing the performance of the networks that were created by both algorithms. One concludes that the former is the best, because it creates a new network that is more efficient, since each new sector covers more traffic that was not covered yet by the initial network (210 MB/h instead of 92 MB/h for the 128 kbps (PS) – vehicular case).

For future work, one could improve the algorithm, considering that:

- the propagation model can change from one area to another, depending on its characteristics, in contrast with the method used here where the propagation model is always the same for the whole service area;
- the simulator can have several network BSs with different characteristics, like the maximum BSs transmission power, having different nominal cell coverage radius;
- the algorithm runtime can be improved in order to decrease the simulation duration;
- the BS Placement model can consider the mutual existence of FDD and TDD UMTS networks;
- the BS Placement model can consider the effect of other mobile communications systems, like WiFi or WiMAX, on the UMTS coverage;
- the BS Placement model can consider different types of cells (macro-, micro- and pico-cells), in contrast with this one that only deals with macro-cells;
- the BS Placement model can use the BS placement cost as a decision parameter;
- the users are moving.

Annex A

The Propagation Model

In this annex, the propagation model used for the current work is described in detail.

It is important to know the propagation model to be used in a network design because it helps to find the propagation attenuation of a certain link. An example for a model application is the calculation of de cell radius. There are many propagation models that must be applied in different situations. They can be divided in two families: the empiric and the semi-empiric ones. Normally, semi-empiric models, like the COST 231 – Okumura-Hata and the model COST 231 – Walfisch-Ikegami, are used, [Corr03], [DaCo99], [Pars92]. The former is used when the distance from the MT to the BS is large (more than 5 km) and the latter is used for small distances (less than 5 km).

This work is applied to an urban environment, therefore, the cell radius is small, being always lower than 2 km. The best model for these conditions is the COST 231 – Walfisch-Ikegami one, which was developed in the COST 231 project [DaCo99]. In this model, the electro-magnetic field received by the MT is given by the sum of the fields that are reflected and diffracted by the closest buildings. The field in the top of the MT closest building, in the BS direction, is calculated considering the diffraction caused by the several knifes (representing the buildings) that intersect the Fresnel ellipsoid, Figure A.1. A regular urban structure is assumed, and buildings have all the same height. The model is valid for the following set of values:

- [800, 2 000] MHz for the frequency;
- [20, 5 000] m for the distance between the MT and the BS;
- [4, 50] m for the BS height;
- [1, 3] m for the MT height.

The input parameters of the model are:

- BS height (h_b);
- Buildings height (H_B);
- MT height (h_m);
- Streets width (w_s);
- Distance between buildings (w_B);
- Distance between the MT and the BS (d);
- Streets orientation angle (Ψ);
- Frequency of the electro-magnetic field (f).

When the propagation is done in the same direction as the street (the streets orientation angle, Ψ, being equal to zero) and there is **L**ine **o**f **S**ight (LoS) the propagation attenuation is given by:

$$L_{p[\mathrm{dB}]} = 42{,}6 + 26\log\left(d_{[\mathrm{km}]}\right) + 20\log\left(f_{[\mathrm{MHz}]}\right)\ ,\ d > 0{,}02\ \mathrm{km} \qquad \text{(A.1)}$$

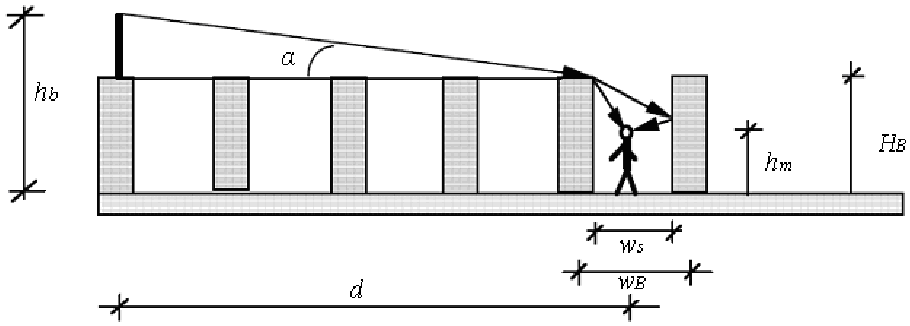


Figure A.1 – The input parameters of the COST 231 – Walfisch-Ikegami model, [Corr03].

In the other cases, the propagation attenuation is given by:

$$L_{p[\mathrm{dB}]} = \begin{cases} L_{0[\mathrm{dB}]} & , L_{tt} + L_{tm} \le 0 \\ L_{0[\mathrm{dB}]} + L_{tt[\mathrm{dB}]} + L_{tm[\mathrm{dB}]} & , L_{tt} + L_{tm} > 0 \end{cases} \qquad \text{(A.2)}$$

where:

- L_0 is the attenuation in free space;
- L_{tt} is the attenuation due to the existence of multi-knifes edges;
- L_{tm} is the attenuation from the diffractions and reflections of the signal in the roof of the buildings and on the streets.

Their values are given by the following expressions:

$$L_{0[\mathrm{dB}]} = 32{,}44 + 20\log\left(d_{[\mathrm{km}]}\right) + 20\log\left(f_{[\mathrm{MHz}]}\right) \qquad \text{(A.3)}$$

$$L_{tt[\mathrm{dB}]} = L_{bsh[\mathrm{dB}]} + k_a + k_d \cdot \log\left(d_{[\mathrm{km}]}\right) + k_f \cdot \log\left(f_{[\mathrm{MHz}]}\right) - 9\log\left(w_{B[\mathrm{m}]}\right) \qquad \text{(A.4)}$$

$$L_{tm[\mathrm{dB}]} = -16{,}9 - 10\log\left(w_{s[\mathrm{m}]}\right) + 10\log\left(f_{[\mathrm{m}]}\right) + 20\log\left(H_{B[\mathrm{m}]} - h_{m[\mathrm{m}]}\right) + L_{ori[\mathrm{dB}]} \qquad \text{(A.5)}$$

where:

$$L_{bsh[\mathrm{dB}]} = \begin{cases} -18\log\left(h_{b[\mathrm{m}]} - H_{B[\mathrm{m}]} + 1\right) & , h_b > H_B \\ 0 & , h_b \le H_B \end{cases} \qquad \text{(A.6)}$$

$$k_{a[\text{dB}]} = \begin{cases} 54 & , \quad h_b > H_B \\ 54 - 0{,}8\left(h_{b[\text{m}]} - H_{B[\text{m}]}\right) & , d \geq 0{,}5\text{km} \\ 54 - 1{,}6\left(h_{b[\text{m}]} - H_{B[\text{m}]}\right) \cdot d_{[\text{km}]} & , d < 0{,}5\text{km} \end{cases} \left.\right\} h_b \leq H_B \tag{A.7}$$

$$k_d = \begin{cases} 18 & , h_b > H_B \\ 18 - 15\dfrac{h_b - H_B}{H_B} & , h_b \leq H_B \end{cases} \tag{A.8}$$

$$k_f = \begin{cases} -4 + 0,7\left(\dfrac{f_{[\text{MHz}]}}{925} - 1\right) & , \text{ urban and sub-urban zones} \\ -4 + 1,5\left(\dfrac{f_{[\text{MHz}]}}{925} - 1\right) & , \text{ urban centers} \end{cases} \tag{A.9}$$

$$L_{ori[\text{dB}]} = \begin{cases} -10{,}0 + 0{,}354 \cdot \psi_{[°]} & , \quad 0° < \psi \leq 35° \\ 2{,}5 + 0{,}075 \cdot \left(\psi_{[°]} - 35\right) & , 35° < \psi \leq 55° \\ 4{,}0 - 0{,}114 \cdot \left(\psi_{[°]} - 55\right) & , 55° < \psi \leq 90° \end{cases} \tag{A.10}$$

In this work, it is assumed that there is no LoS; therefore the latter case is adopted, being also assumed that:

- $\Psi = 90°$;
- $h_b > H_B$;
- The area where the network is implemented is an urban and a sub-urban zone.

Annex B

Defining the Cell Radius

This annex presents an overview on the steps performed to calculate the cell radius. Some considerations about some of the parameters that are used are also made.

The knowledge of the cell radius is very important in network design. The method to calculate it uses the link budget, defining the maximum distance from the BS for which the MT has 50 % coverage. The cell radius is defined for a certain reference service case that is defined by a service bearer and a usage scenario (indoor, pedestrian, vehicular).

The first thing is to calculate the minimum received power, $P_{r\min}$, which is given by:

$$P_{R\min[\mathrm{dBm}]} = N_{[\mathrm{dBm}]} - G_{P[\mathrm{dB}]} + E_b/N_{0\,[\mathrm{dB}]} \tag{B.1}$$

where:

- N is the noise power;
- G_P is the processing gain;
- E_b is the bit energy;
- N_0 is the noise power spectral density.

The value of the processing gain is given by the following expression, Table B.1:

$$G_{P[\mathrm{dB}]} = 10\log(R_C/R_b) \tag{B.2}$$

where:

- R_C is the chip rate;
- R_b is the transmission throughput of the reference service bearer.

Table B.1 – Processing gain for different services.

Service	Processing gain [dB]
12.2 kbps (CS)	24.98
64 kbps (CS/PS)	17.78
128 kbps (PS)	14.77
384 kbps (PS)	10.00

The noise power is calculated by:

$$N_{[\mathrm{dBm}]} = -174 + 10\log(\Delta f_{[\mathrm{Hz}]}) + F_{[\mathrm{dB}]} + M_{i[\mathrm{dB}]} \tag{B.3}$$

where:

- $\Delta f_{[\text{Hz}]}$ is the signal bandwidth that is equal to 3.84 MHz;
- F is the noise factor that is equal to 5 dB in UL and 9 dB in DL;
- M_i is the interference margin that is equal to 3.0 dB in UL and 5.2 dB in DL.

The results are presented in Table B.2.

Table B.2 – Values for the noise power.

	UL	DL
Noise power [dBm]	- 100.16	- 93.96

The ratio between the bit energy and the noise power spectral density, E_b/N_0, is obtained from [RFHL03], where it is assume that pedestrian users move with a velocity of 3 km/h and vehicular ones with a velocity of 50 km/h, Table B.3.

Afterwards, the maximum propagation attenuation of the link is calculated, $L_{P\max}$. This is obtained by using the values of the minimum received power already known, and considering the effect of fading and soft/softer handover:

$$L_{P\max[\text{dB}]} = EIRP_{[\text{dBm}]} - P_{r\min[\text{dBm}]} + G_{r[\text{dBi}]} + M_{SF[\text{dB}]} + M_{FF[\text{dB}]} + L_{F[\text{dB}]} - G_{SHO[\text{dB}]} \quad \text{(B.4)}$$

where:

- $EIRP$ is the effective isotropic radiated power;
- G_r is the receiving antenna gain;
- M_{SF} is the slow fading margin;
- M_{FF} is the fast fading margin;
- L_F is the indoor penetration;
- G_{SHO} is the soft/softer handover gain.

The $EIRP$ is defined as:

$$EIRP_{[\text{dBm}]} = P_{t[\text{dBm}]} + G_{t[\text{dBi}]} - L_{cu[\text{dB}]} \quad \text{(B.5)}$$

where:

- P_t is the transmission power;

- G_t is the transmission antenna gain;
- L_{cu} represents existing losses. In UL these losses result from the presence of the user near the antenna and in DL it represents the losses in the cables that connect the transmitter to the antenna.

Table B.3 – E_b/N_0 values for different service bearers, [RFHL03].

Service [kbps]	Switch type	Type of user	E_b/N_0 [dB] Link UL	E_b/N_0 [dB] Link DL
12.2	CS	Indoor	5.5	7.5
		Pedestrian	5.5	7.5
		Vehicular	6.5	8.1
64	CS	Indoor	4.1	6.7
		Pedestrian	4.2	6.7
		Vehicular	5.2	7.3
64	PS	Indoor	4.3	6.0
		Pedestrian	4.3	6.0
		Vehicular	5.7	7.3
128	PS	Indoor	4.3	6.0
		Pedestrian	4.5	6.0
		Vehicular	5.6	7.1
384	PS	Indoor	1.7	3.7
		Pedestrian	1.9	3.9
		Vehicular	3.5	5.5

Some values for the radio parameters that are used in the work were provided by Vodafone, [Voda05], Table B.4.

For the receiving antenna gain in UL and the transmission antenna gain in DL, the value of the BS antenna gain is considered. This value is obtained from the radiation pattern, which was used in the MOMENTUM project [MOME04], considering the arrival and departure angle, respectively, Figure 5.3.

One should notice that the antenna can have diversity. If it is the case, then the new antenna gain is given by:

$$G_{a\,div[\text{dBi}]} = G_{[\text{dBi}]} + G_{div[\text{dB}]} \quad \text{(B.6)}$$

where:

- $G_{a\,div}$ is the new antenna gain with diversity;
- G is the antenna gain;
- G_{div} is the diversity gain.

Table B.4 – Values of some radio parameters.

	Voice	**Data**
$EIRP$ **in UL [dBm]**	18	21
G_r **in DL [dBi]**	0	0
P_t **in DL [dBm]**	33	37
Cable losses [dB]	3	3

The values for the both slow and fast margin, the indoor penetration attenuation and the SHO/SSHO gain for the several user scenarios were provided by Vodafone, [Voda05], Table B.5.

Table B.5 – Values for the fading margins, indoor penetration attenuation and soft/softer gain, for several usage scenarios.

	Usage scenario		
	Indoor	**Pedestrian**	**Vehicular**
M_{SF} [dB]	7.6	7.6	5.0
M_{FF} [dB]	2.0	2.0	0.0
L_F [dB]	20.0	0.0	8.0
G_{SHO} [dB]	1.5	1.5	1.5

Using the propagation model from Annex A, which depends on the distance between the MT and the BS, $L_P(d)$, the distance d for which the propagation attenuation is equal to the one that was calculated through (B.4) can be found: the result is the cell radius.

Annex C

Manual

This section shows how to use the simulator developed in this work.

C.1 – User Generator (*SIM*)

The User Generator is composed by a main window where the simulator user has access to several menus that execute different options of the software. These menus are: *File*, *Parameters*, *Results*, *Run* and *Output*. In the beginning, only the two firsts are available, Figure C.1. The options can be selected by clicking on the menus or using a specific shortcut.

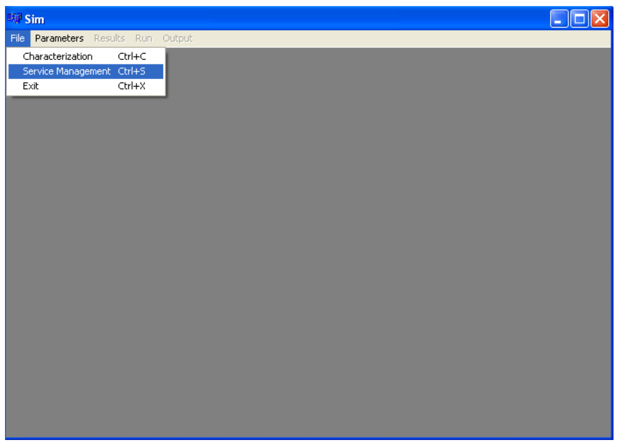


Figure C.1 – Main window of the User Generator.

On the *File* menu, one can load the operational environment input file where there is the characterisation about the terrain (*File -> Characterization*), Figure C.2, add or remove services (*File -> Services Management*), Figure C.3, and exit the program (*File -> Exit*). For adding a service, one has to insert in the window the service name and select the file where the corresponding BHCA grid is stored, Figure C.4. When the services are defined in the *Service Management*, the *Results* menu is enabled.

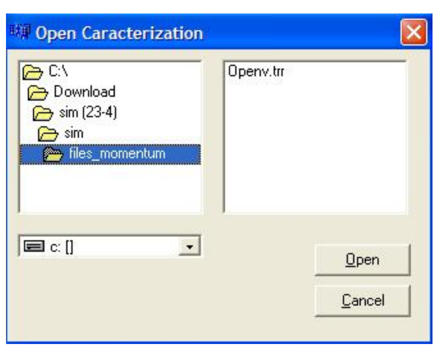


Figure C.2 – *Characterization* window.

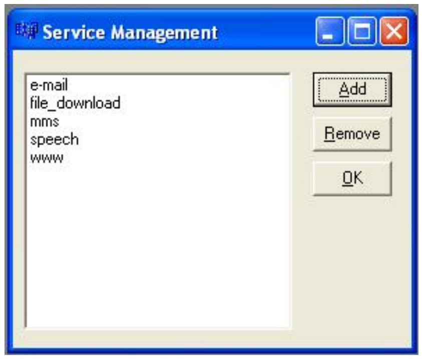


Figure C.3 – *Service Management* window.

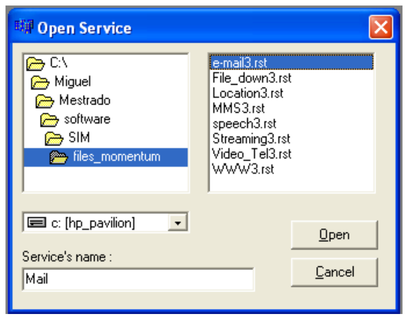


Figure C.4 – Adding service window.

On the *Parameters* menu, one can change the different scenario characteristics, like its distribution and the indoor penetration attenuation for each possible scenario (*Scenario's attenuation*), Figure C.5: the values by default are the ones provided by Vodafone. It is also possible to change in the same window the geographical data related with the BHCA grids, like its dimension, the size of each pixel, and the coordinates of the first pixel in UTM Cartesian projection coordinates (*Geographical info*), Figure C.6. Thus, it is possible to use different kinds of BHCA grids in this generator.

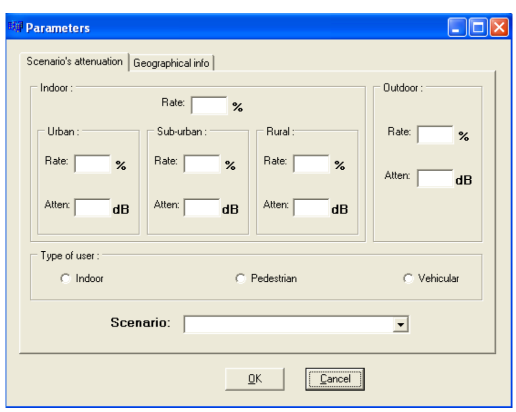


Figure C.5 – *Scenario's attenuation* window.

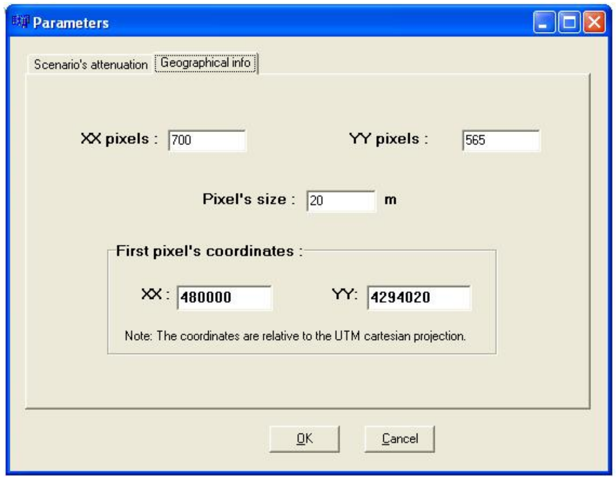


Figure C.6 – *Geographical info* window.

When the services are defined and the operational environment file is loaded, the *Run* option is enabled and the simulator user can run the generation algorithm; the users are generated for all the considered services, Figure C.7.

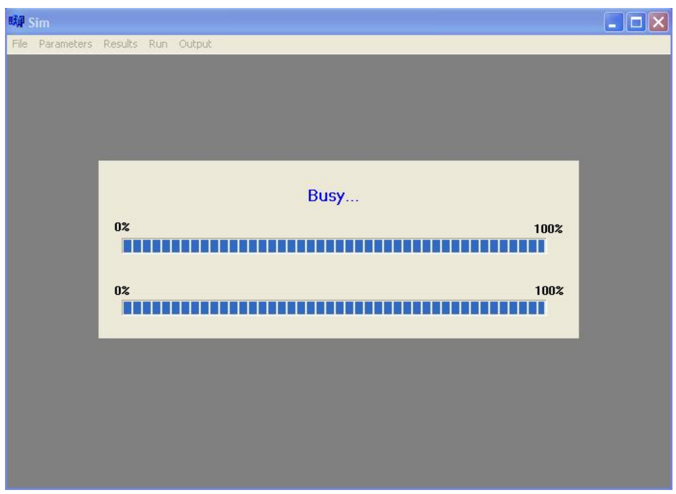


Figure C.7 – The generator algorithm execution.

The results of the user generation can be seen in the *Results* option, the total number of generated users and the user distribution along the several services being presented in the window, Figure C.8. It is possible to change these values and use them in the next user generation by selecting it in a proper check box. This input data can be inserted before or after the first execution of the generation algorithm.

Finally, the list of generated users can be saved into an output file by executing the *Output* option, which is enabled after the user generation.

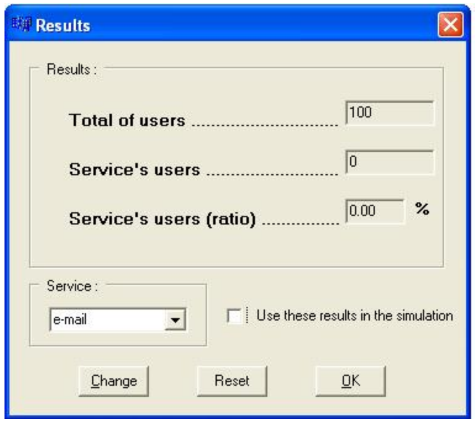


Figure C.8 – *Results* window.

C.2 – GIS application (*UMTS_Simul*)

The GIS software is responsible for the Network Creation, its analysis and the placement of new BSs. At first, it asks for some input files, like the BS antenna radiation pattern, E_b/N_0 values for the different services bearers and user scenarios, and the data related with the service area where the network will be placed, Figure C.9.

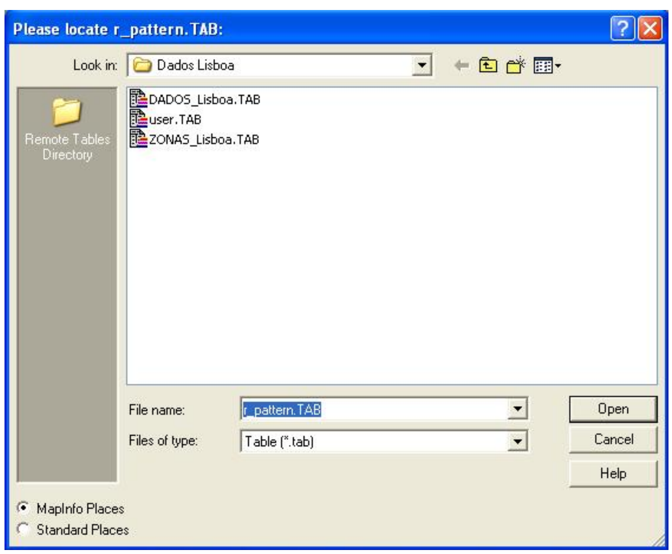


Figure C.9 – Input files load window.

The service area is displayed, Figure C.10, and the *UMTS* menu appears on the software, where the simulator user has access to a panopoly of functionalities that can be called through the menu or specific buttons. It is possible to change the several propagation model parameters (*UMTS* ->

Edit Parameters -> Propagation Model), Figure C.11, the network configuration parameters (*UMTS -> Edit Parameters -> Net Settings*), Figure C.12, the services provided by the network (*UMTS -> Edit Parameters -> Services*), Figure C.13, the service bearer distribution for all considered services (*UMTS -> Edit Parameters -> Service Throughput*), Figure C.14, the UL bit rate for the different service bearers (*UMTS -> Edit Parameters -> Uplink Service*), and the E_b/N_0 values for the different services bearers and user scenarios (*UMTS -> Edit Parameters -> Eb_N0*).

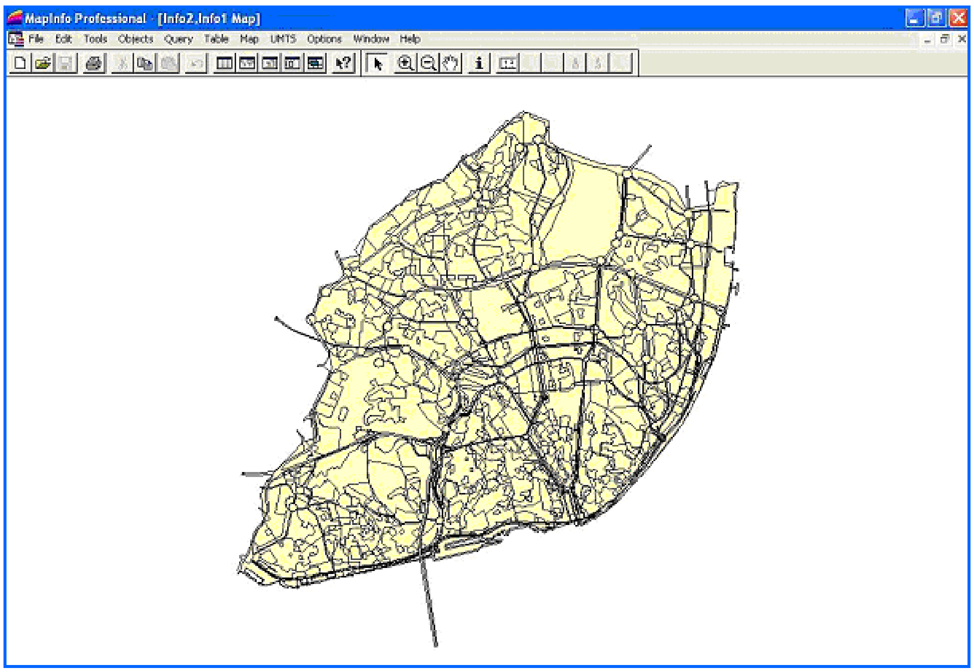


Figure C.10 – Service area display.

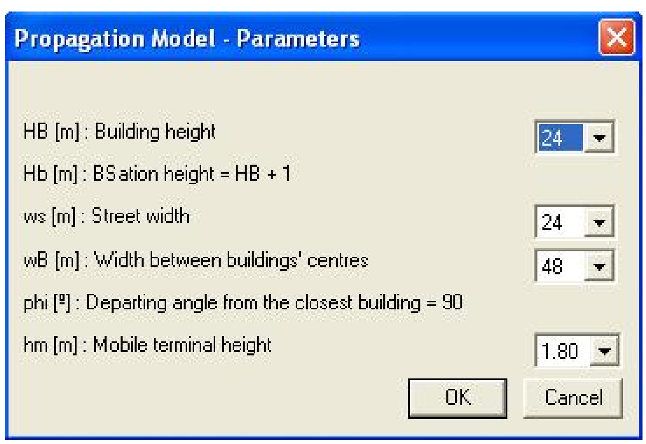


Figure C.11 – *Propagation Model* window.

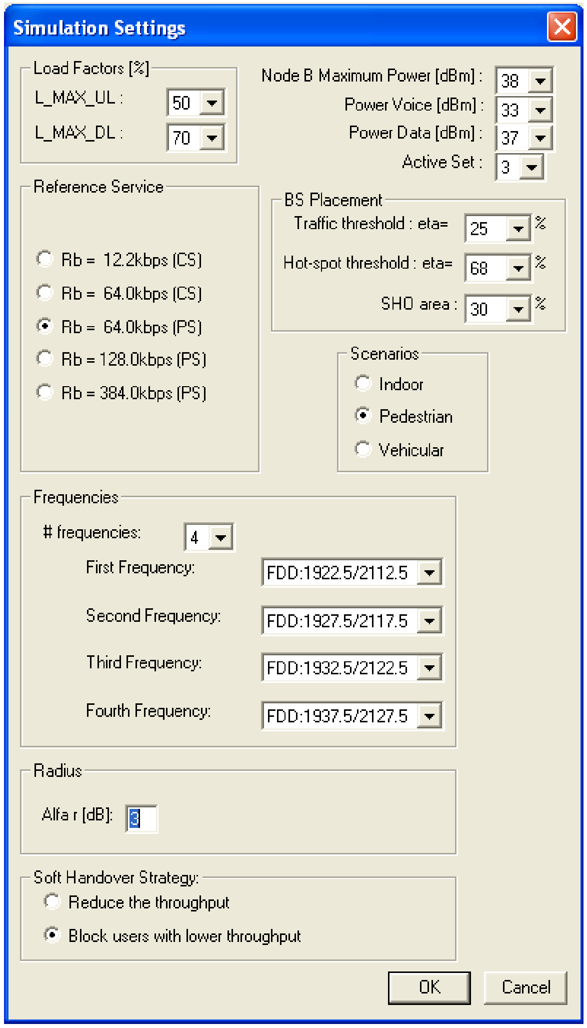


Figure C.12 – *Net Settings* window.

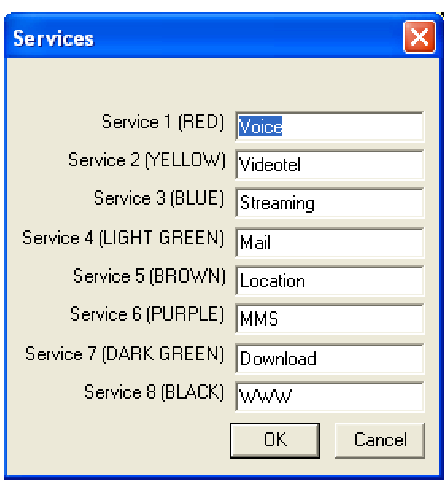


Figure C.13 – *Services* window.

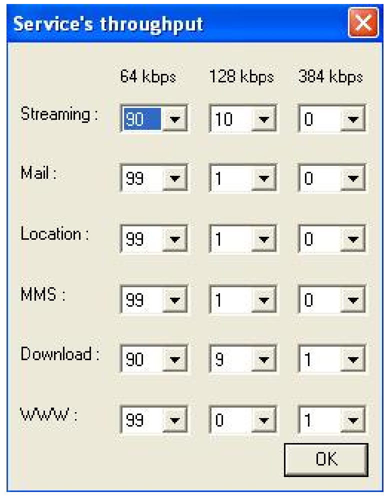


Figure C.14 – *Service Throughput* window.

By clicking in the *Insert Users* option (*UMTS -> Run -> Insert Users*), the simulator asks for the user input file and displays them in the service area. Afterwards, in the *Display Network* (*UMTS -> Run -> Display Network*), the software presents the network with all BSs and its nominal coverage areas, Figure C.15. It is also possible to load the coverage area from an already created network (*UMTS -> Run -> Load Network*). Afterwards, the simulator enables the option to make the network analysis (*UMTS -> Run -> Run Simulation*), to place new BSs in order to improve the network coverage (*UMTS -> Run -> Add BSs in Open Spaces*), and to see the network performance parameters in terms of coverage (*UMTS -> Run ->Bs Placement Statistics*), Figure C.16.

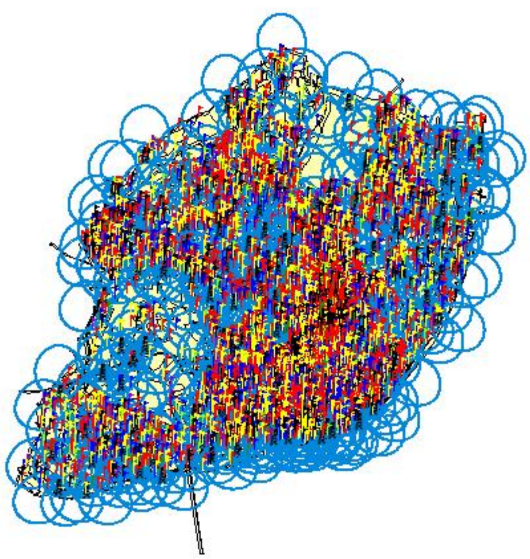


Figure C.15 – Network display.

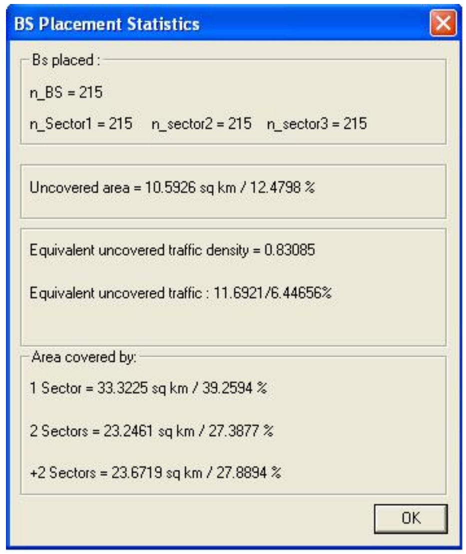


Figure C.16 – *Bs Placement Statistics* window.

In the end of the Network Performance Analysis, the simulator shows a window with information about some of the performance parameters, Figure C.17. The other parameters are written into output files.

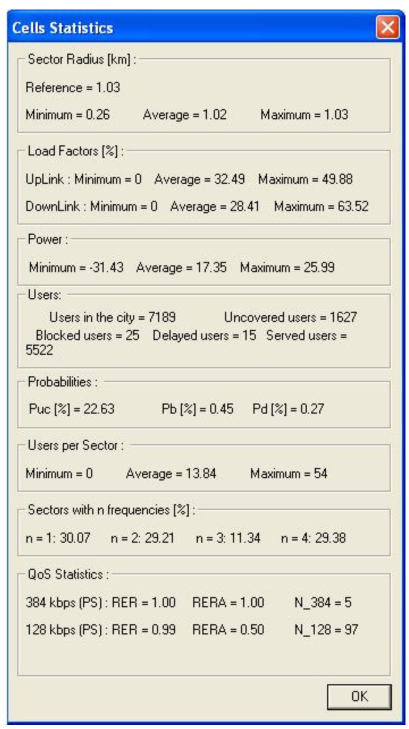


Figure C.17 – Network Performance Analysis results.

Annex D

Fluxograms

Fluxograms representing the existing processes in the simulator are shown in this annex.

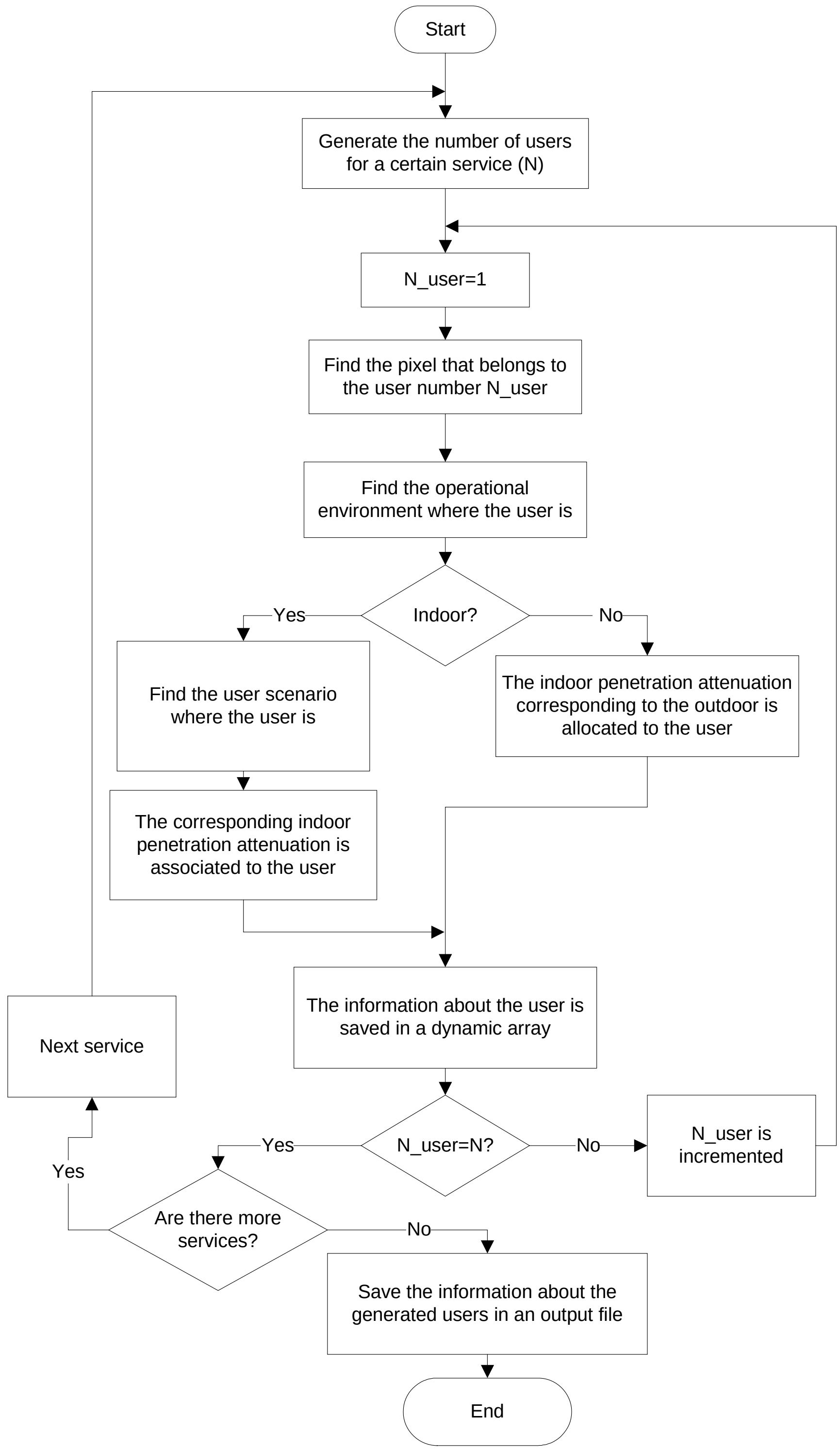


Figure D.1 – User Generator fluxogram.

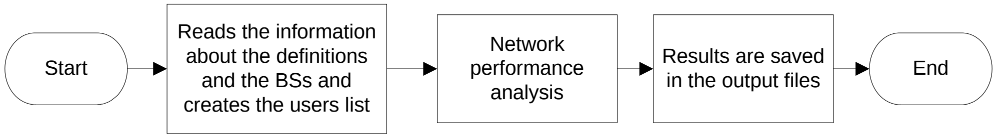


Figure D.2 – *Net_opt* fluxogram.

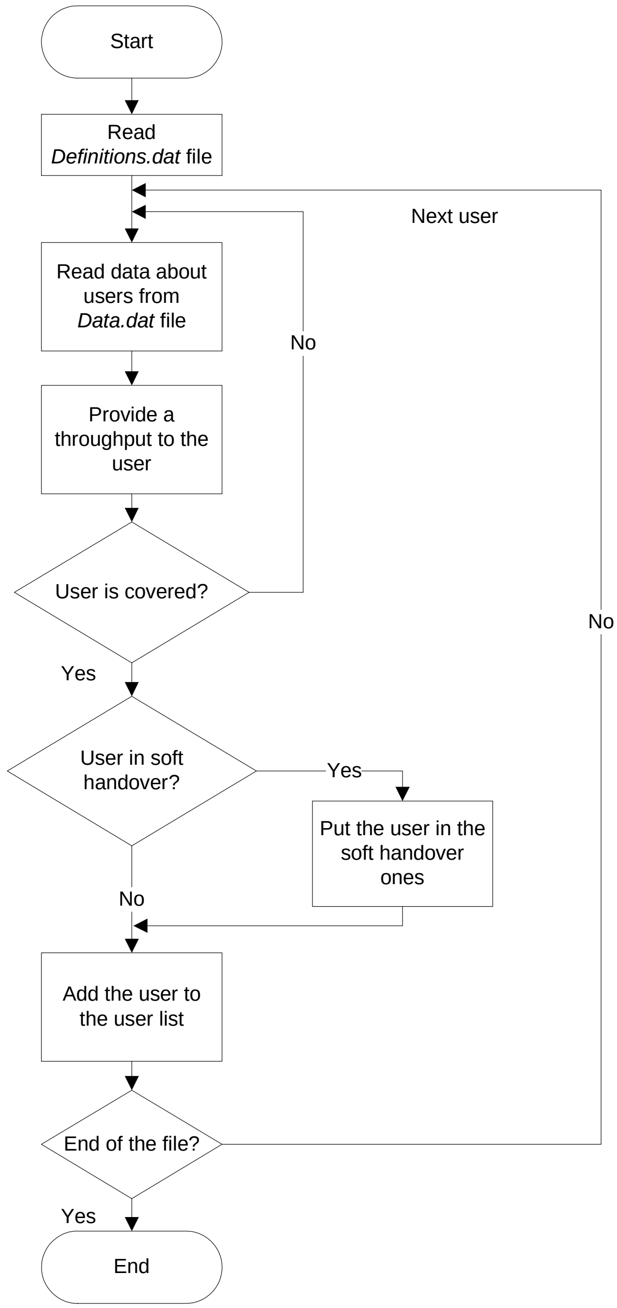


Figure D.3 – User list creation fluxogram.

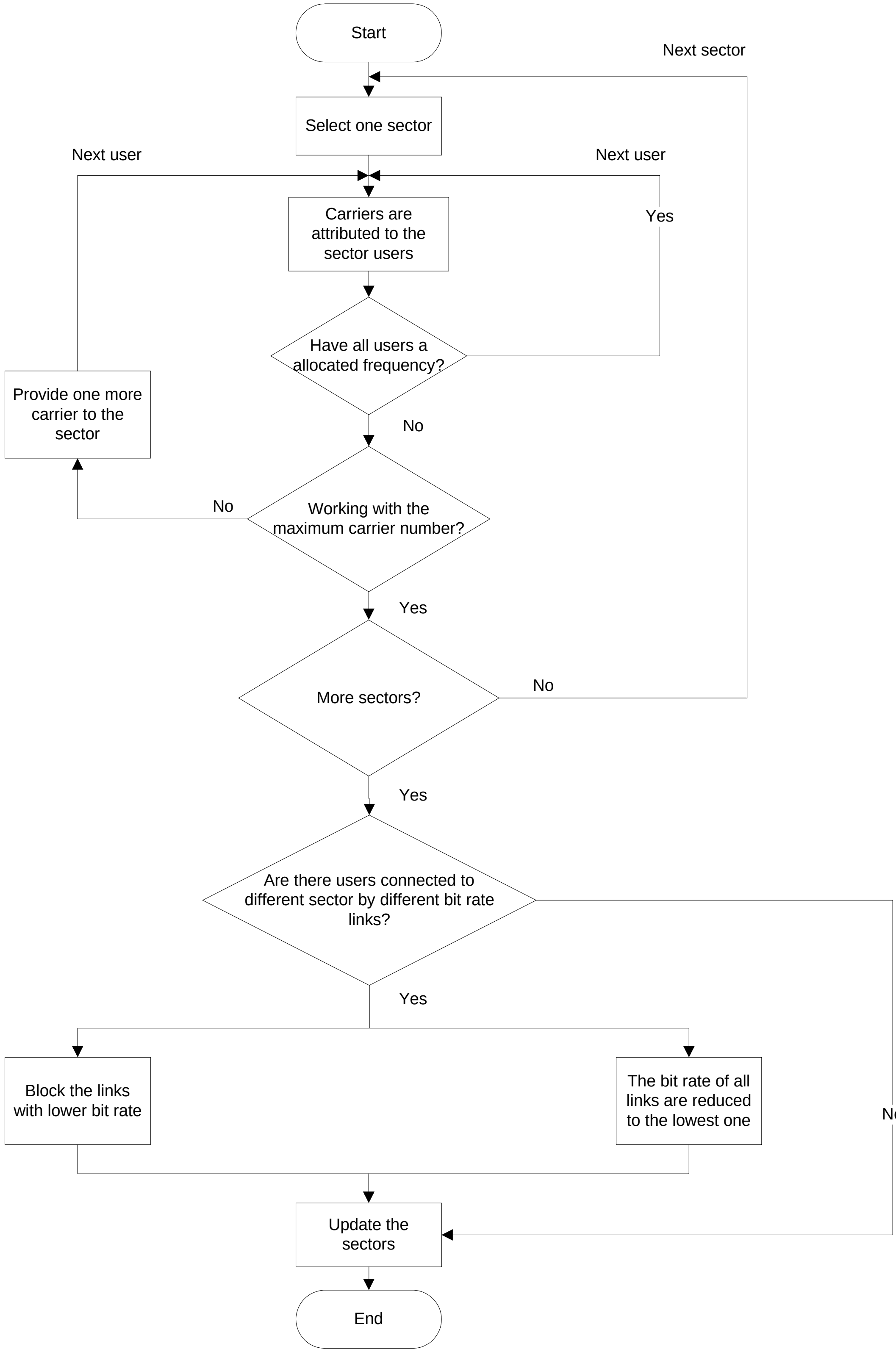


Figure D.4 – Network Performance Analysis block fluxogram.

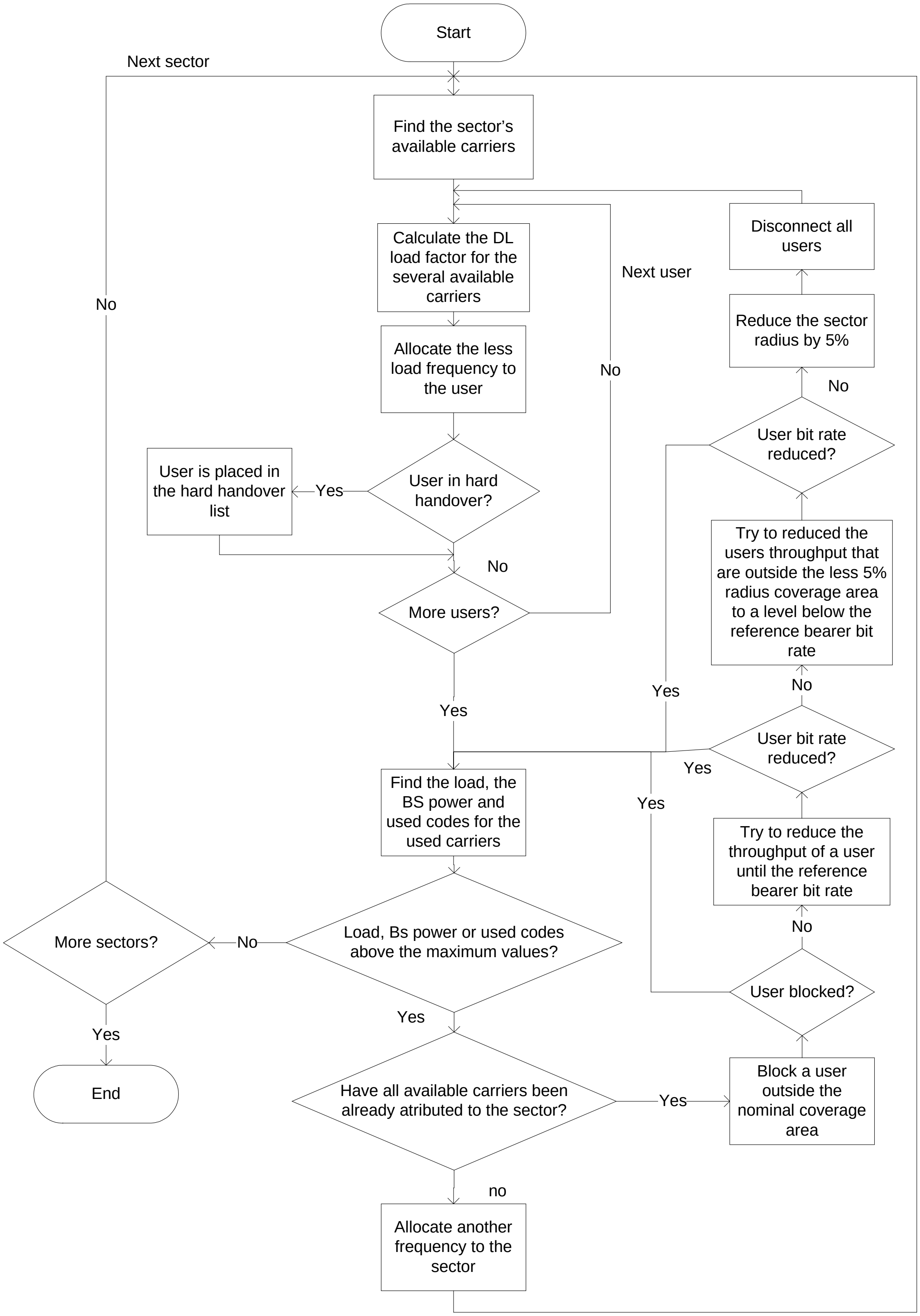


Figure D.5 – Frequency attribution fluxogram.

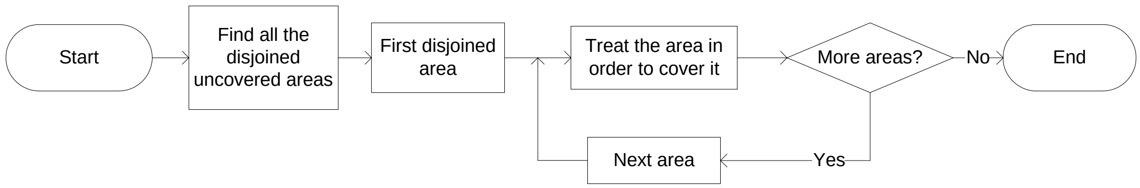


Figure D.6 – New BS Placement algorithm.

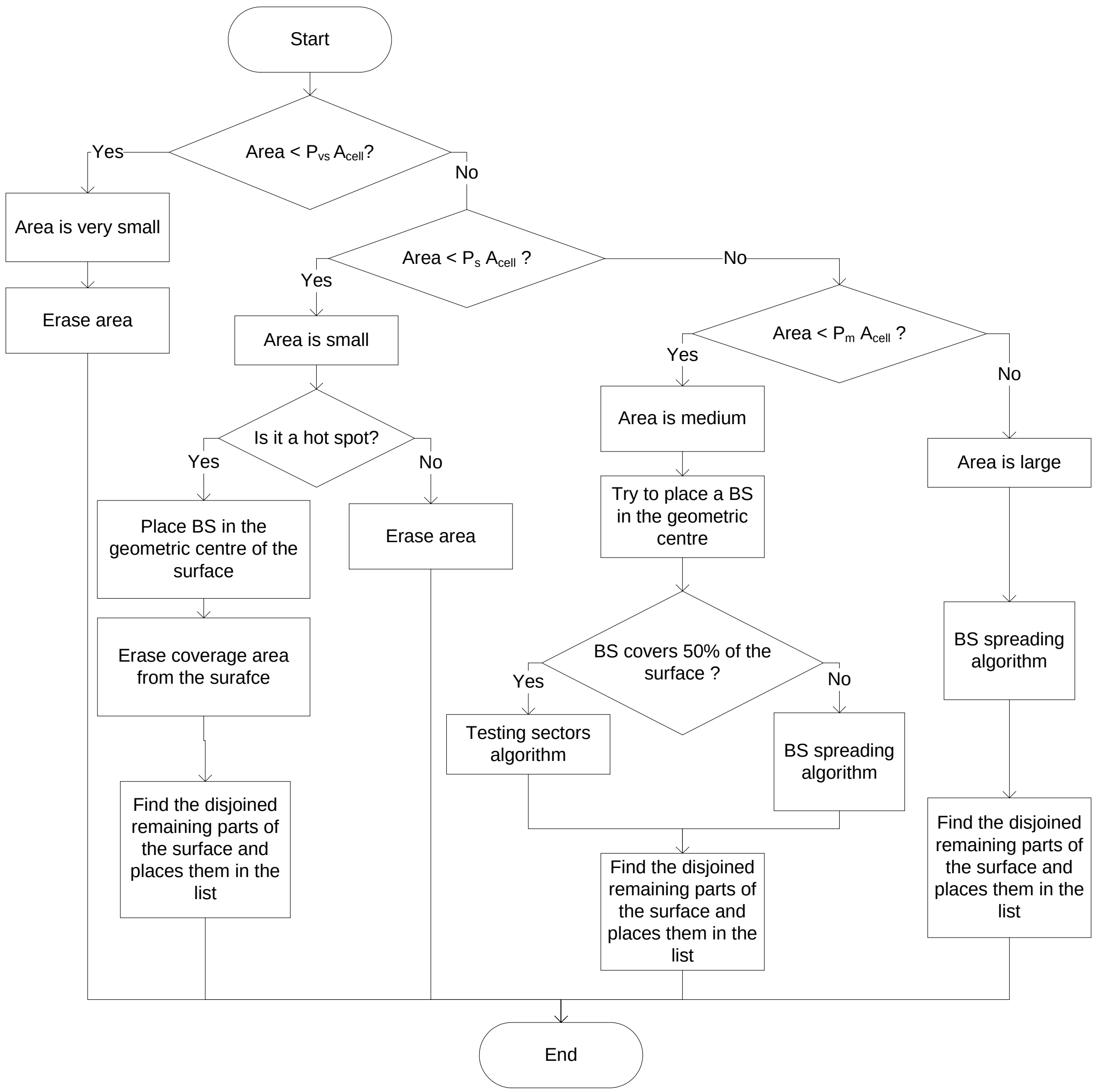


Figure D.7 – Area analysis for BS placement fluxogram.

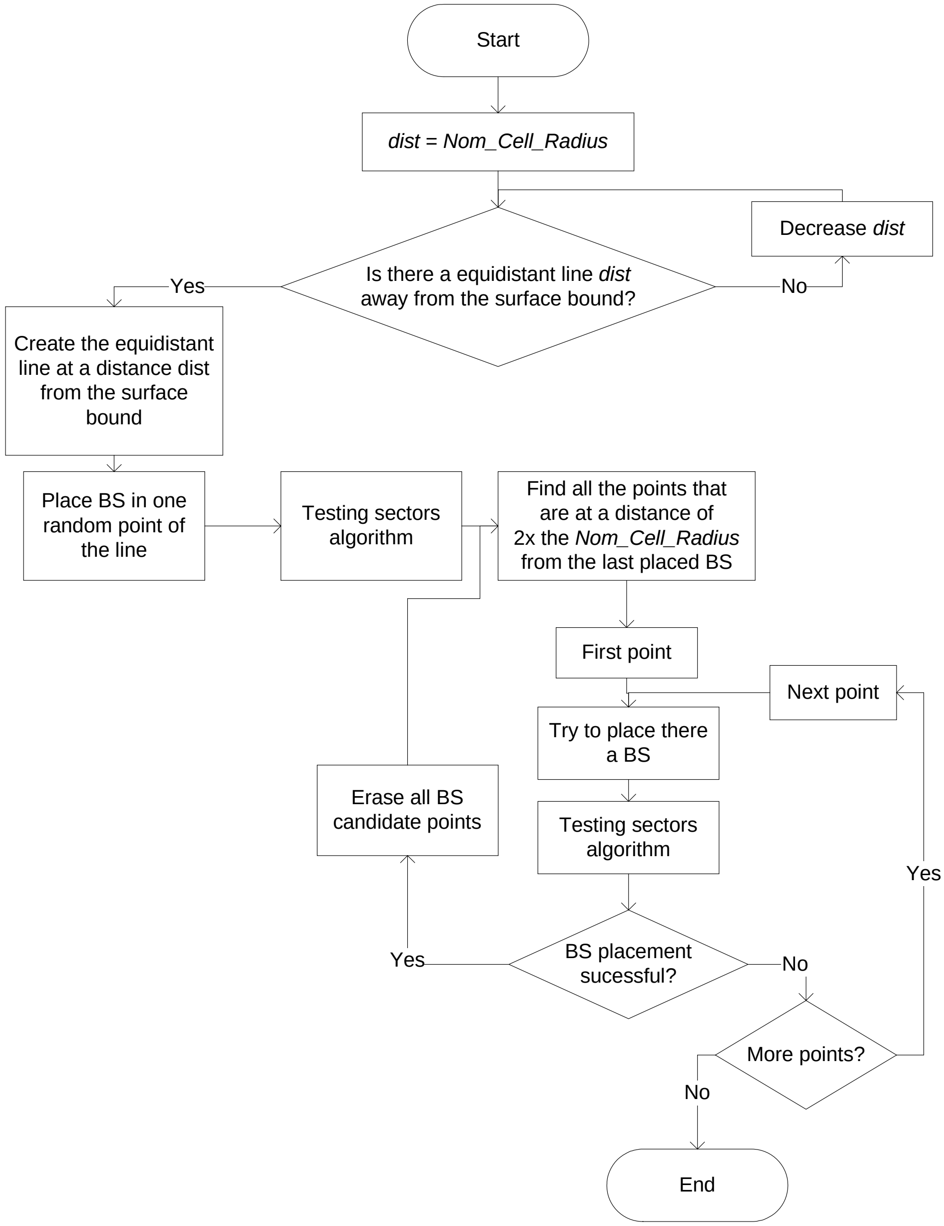


Figure D.8 – BS spreading fluxogram.

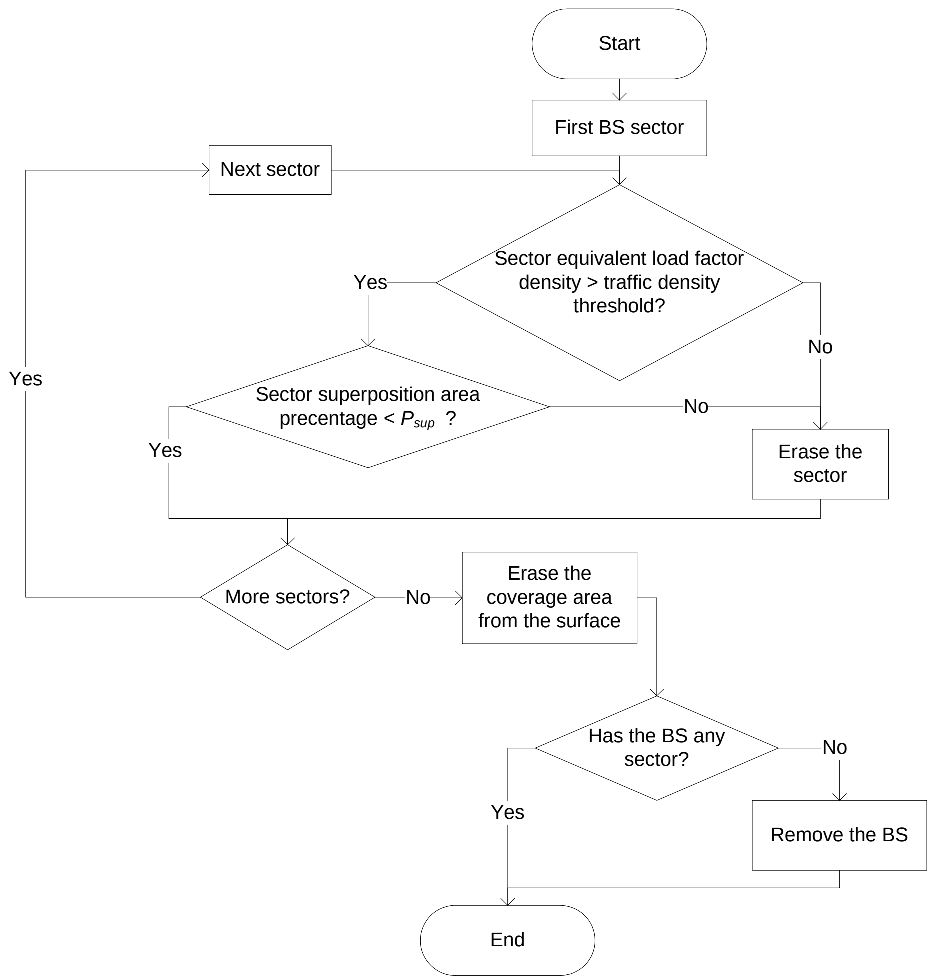


Figure D.9 – Testing sectors fluxogram.

Annex E

Information Used in the BHCA Grids Creation

This annex presents some information that was used in the MOMENTUM project, [MOME04], in order to obtain the BHCA grids that are used in the simulator as input data.

Table E.1 – Number of calls per day and per customer segment.

Service	Business	SOHO	Mass-Market
Speech-telephony	4.167	2.400	1.768
Video-telephony	0.900	0.864	0.679
Streaming Multimedia	0.600	0.576	0.170
Web Browsing	0.400	0.256	0.075
Location Based Service	0.023	0.022	0.013
MMS	0.230	0.221	0.078
E-mail	0.138	0.110	0.087
File Download	0.180	0.115	0.068

Table E.2 – Busy hour usage per costumer segment.

Costumer Segment	Busy hour usage [%]
Business	20
SOHO	15
Mass-market	7

Table E.3 – Average number of calls in the busy hour for several customer segment subscribers.

Service	BHCA per user		
	Business	SOHO	Mass-market
Speech-telephony	0.833	0.360	0.124
Video-telephony	0.180	0.130	0.048
Streaming Multimedia	0.120	0.086	0.012
Web Browsing	0.080	0.038	0.005
Location Based Service	0.005	0.003	0.001
MMS	0.046	0.033	0.005
E-mail	0.028	0.017	0.006
File Download	0.036	0.017	0.005

Table E.4 – Operational environment share between customer segments.

Operational environment class	Distribution [%]		
	Business	SOHO	Mass-market
Water	35	35	30
Railway	20	40	40
Highway	60	30	10
Highway with jam	60	30	10
Main road	30	40	30
Street	10	20	70
Rural	2	3	95
Sub-urban	5	15	80
Open	25	40	35
Urban	25	40	35
CBD	80	10	10

Annex F

Traffic Distributions

This annex shows the BHCA traffic distributions grids, the operational environment and an example for the equivalent load traffic distribution.

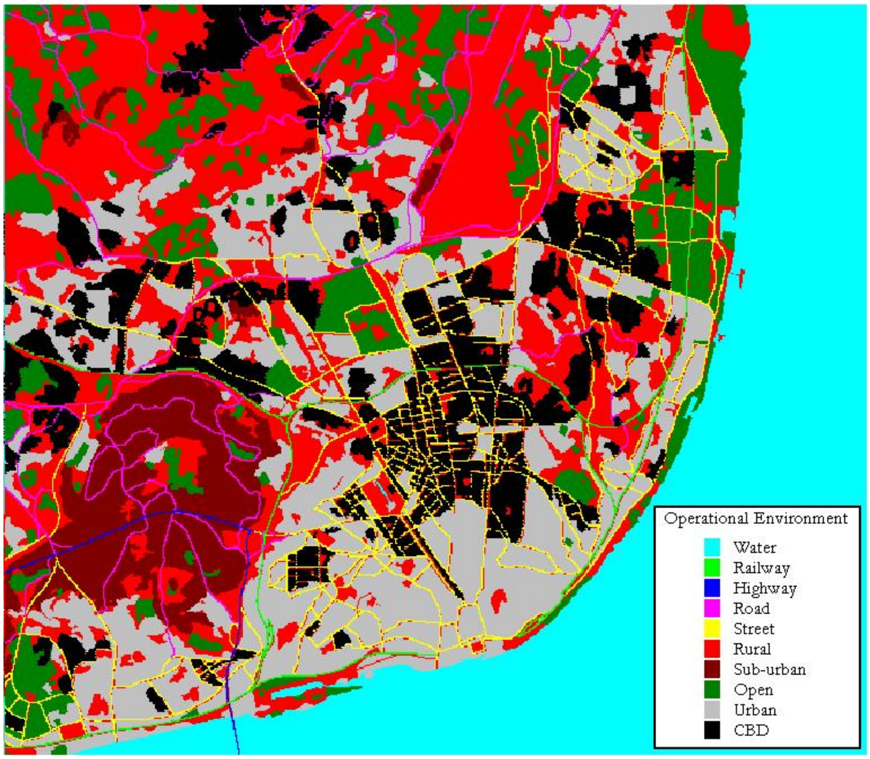


Figure F.1 – Operational environment grid.

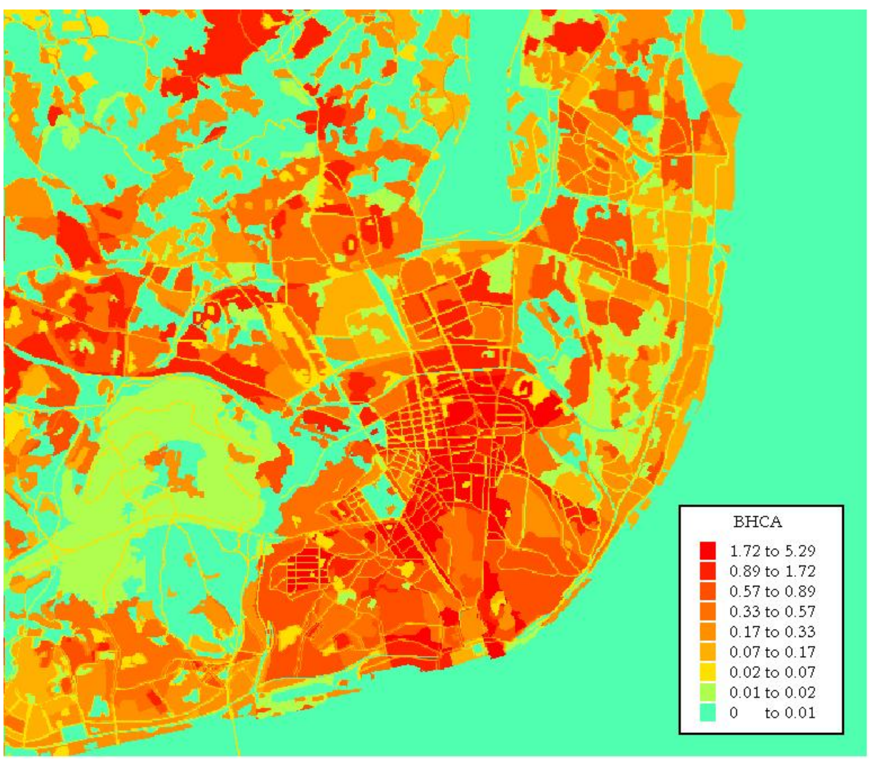


Figure F.2 – BHCA grid for Speech-telephony.

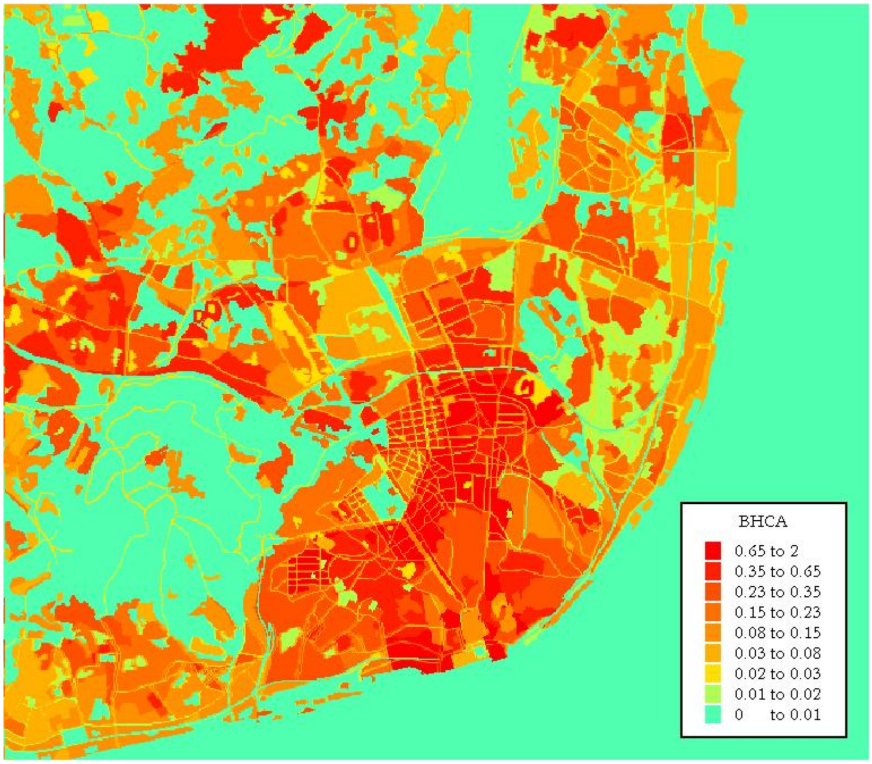


Figure F.3 – BHCA grid for Video-telephony.

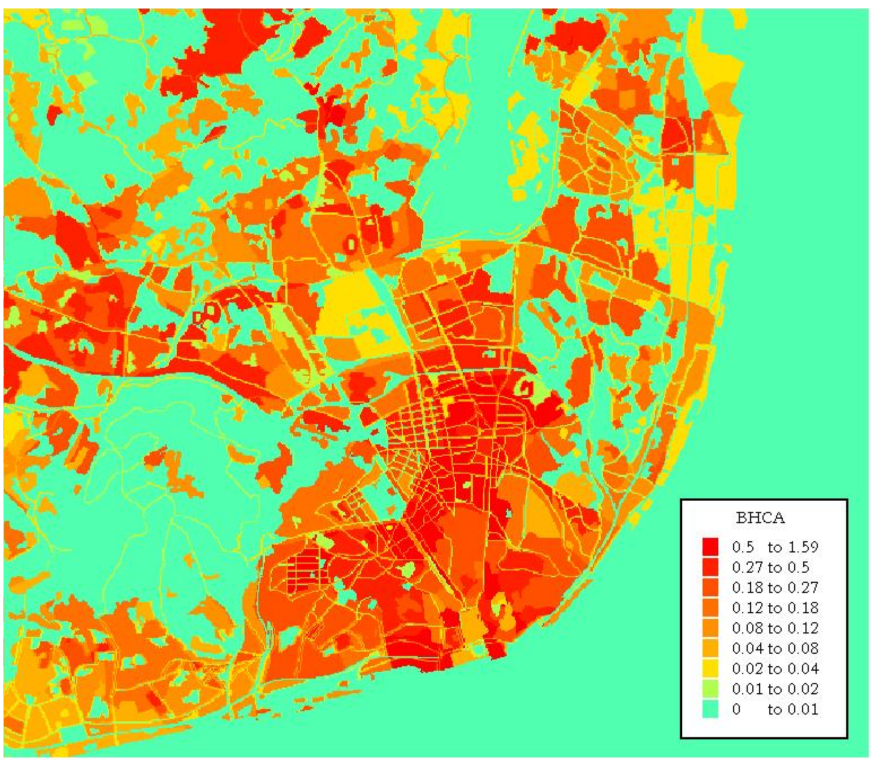


Figure F.4 – BHCA grid for Streaming Multimedia.

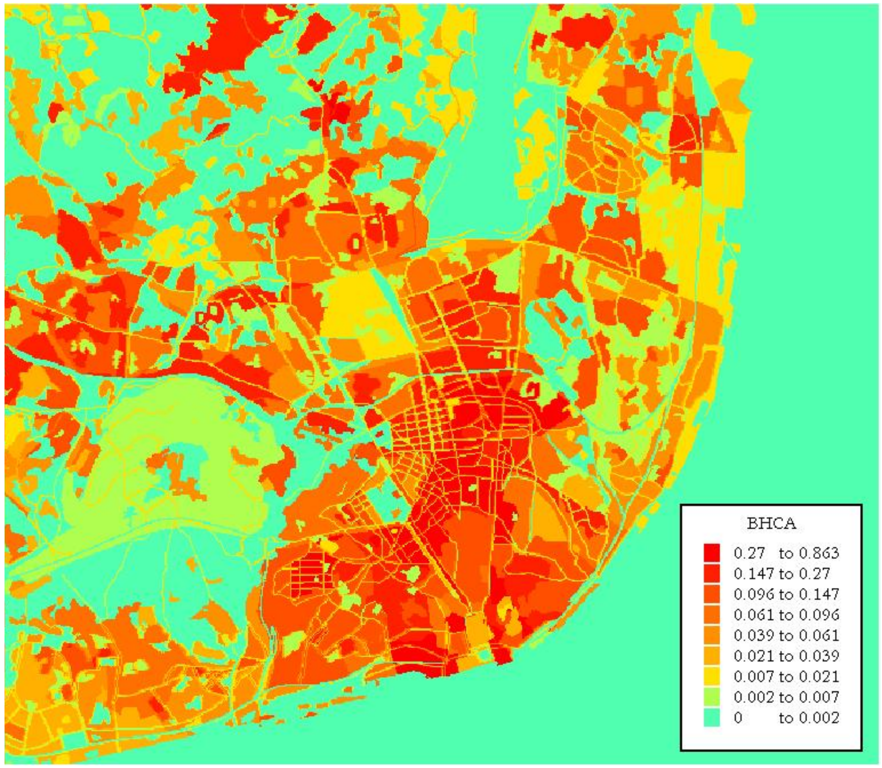


Figure F.5 – BHCA grid for Web Browsing.

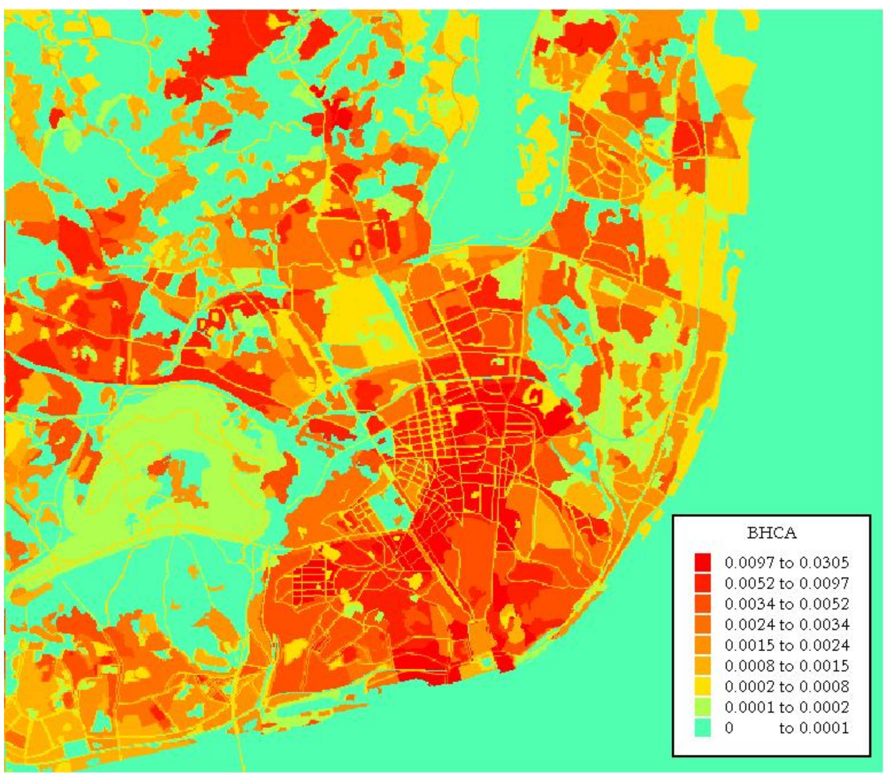


Figure F.6 – BHCA grid for Location Based Service.

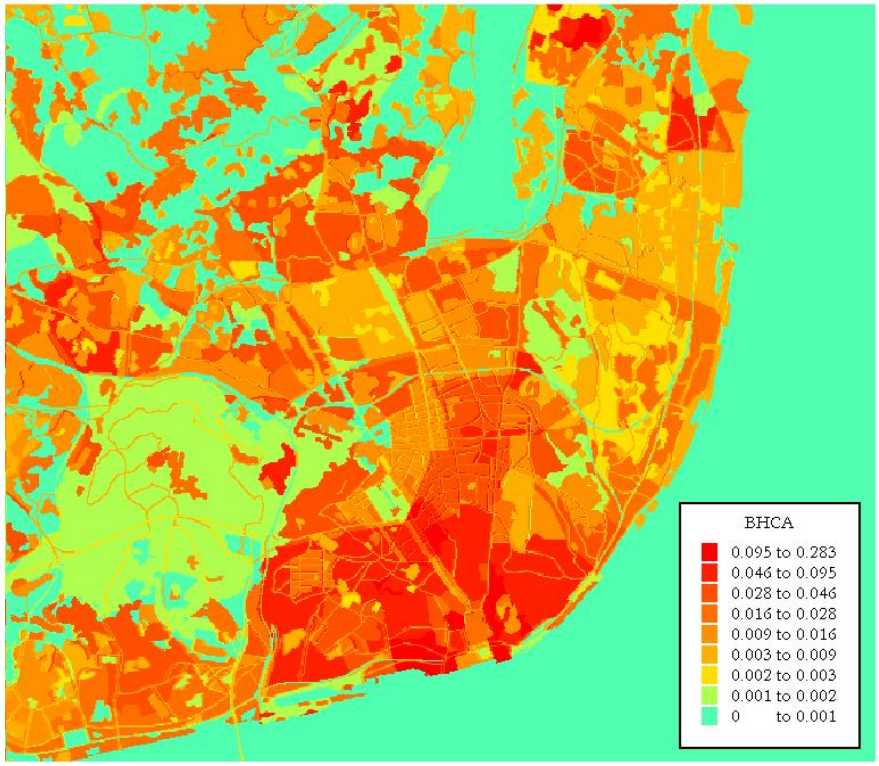


Figure F.7 – BHCA grid for MMS.

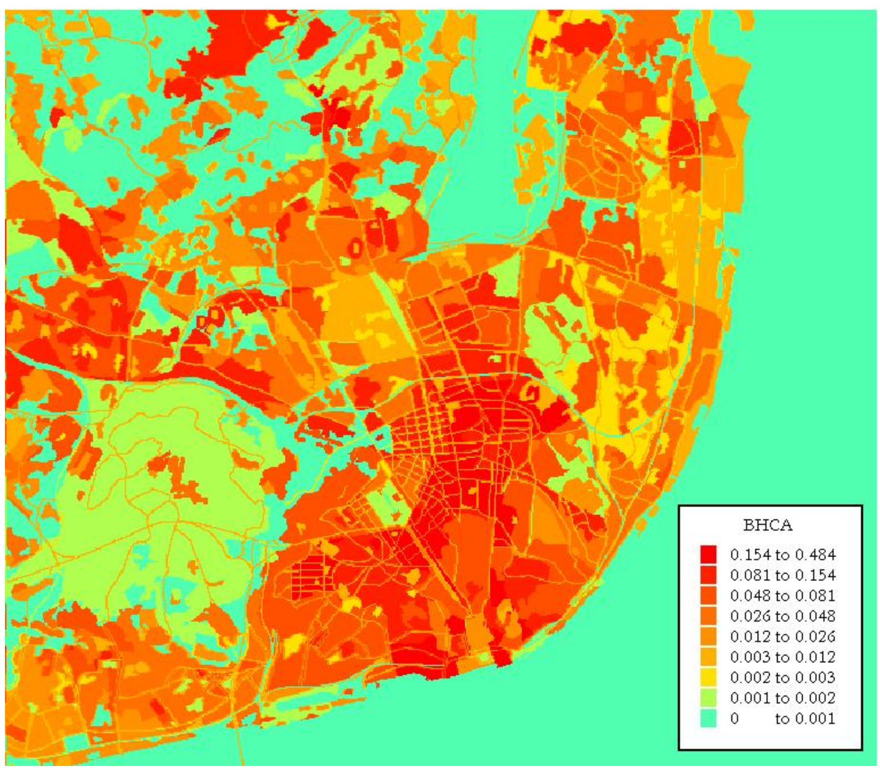


Figure F.8 – BHCA grid for E-mail.

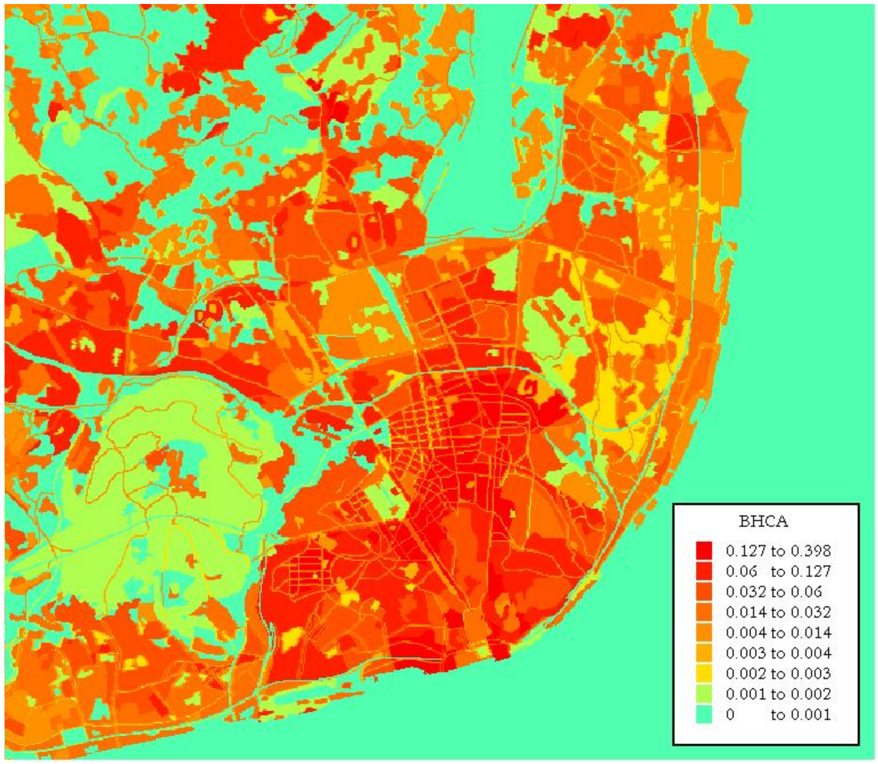


Figure F.9 – BHCA grid for File Download.

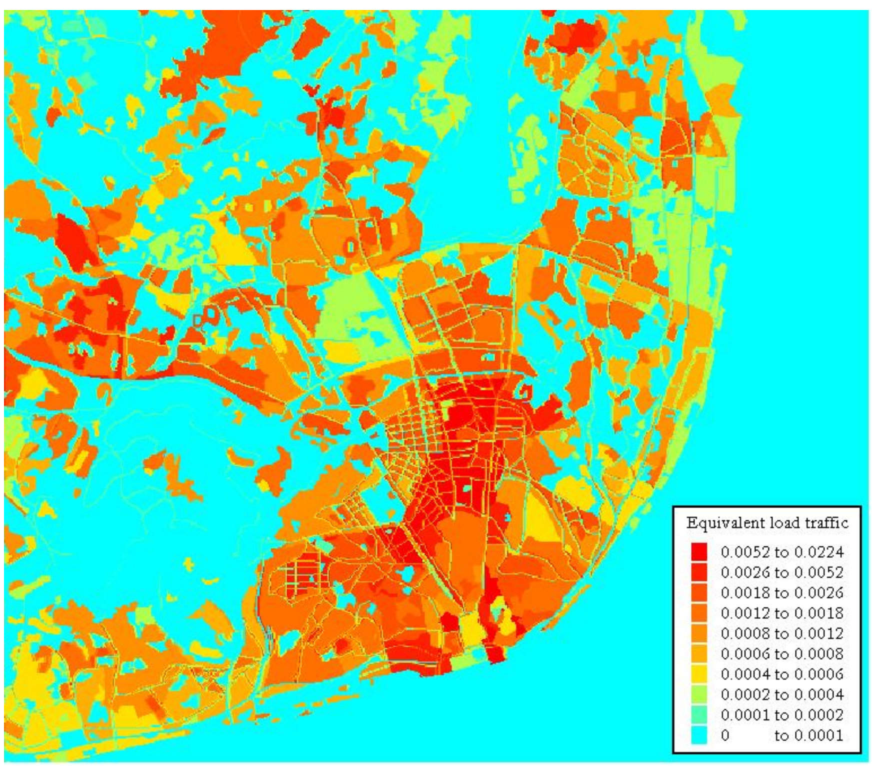


Figure F.10 – η_{DL}^{equiv} distribution.

Annex G

DL Load Factor per User for Different Service Bearers

Parameters values used for the DL load factor per user for each service bearer are presented here. This parameter is used to obtain the equivalent load traffic distribution.

For the values presented in Table G.1, Table G.2, Table B.3 and for $i = 0.5$, the load factors per user for different service bearers are presented below, Table G.3.

Table G.1 – Activity factor for the several service bearers, [Voda05].

Service bearer	Activity factor
12.2 kbps (CS)	0.5
64 kbps (CS)	1.0
64 kbps (PS)	1.0
128 kbps (PS)	1.0
384 kbps (PS)	1.0

Table G.2 – Orthogonality factor for the several user scenarios, [Voda05].

User scenario	Orthogonality factor
Indoor	0.9
Pedestrian	0.7
Vehicular	0.5

Table G.3 – DL load factor per user for several service bearers.

Service bearer	User scenario	DL load factor per user
12.2 kbps (CS)	Indoor	0.0054
	Pedestrian	0.0071
	Vehicular	0.0103
64 kbps (CS)	Indoor	0.0468
	Pedestrian	0.0624
	Vehicular	0.0895
64 kbps (PS)	Indoor	0.0398
	Pedestrian	0.0531
	Vehicular	0.0895
128 kbps (PS)	Indoor	0.0796
	Pedestrian	0.1062
	Vehicular	0.1710
384 kbps (PS)	Indoor	0.1407
	Pedestrian	0.1964
	Vehicular	0.3548

Annex H

Results

In this section, one shows the results that were obtained in the different simulations.

Table H.1 – Results no initial network and for a 12.2 kbps (CS) scenario.

		User Scenario		
		Pedestrian	**Vehicular**	**Indoor**
Number of added BSs		48	71	331
Number of added sectors 1		42	63	300
Number of added sectors 2		40	59	266
Number of added sectors 3		33	49	176
Uncovered area [%]		24.8	28.3	44.7
ξ **[km^{-2}]**		1.56	1.15	1.61
Equivalent uncovered traffic [%]	**VSS and SS**	6.9	8.6	3.5
	MS and LS	13.2	11.6	32.5
Area covered by 1 sector [%]		53.7	50.9	43.7
Area covered by 2 sector [%]		25.1	18.0	10.4
Area covered by more than 2 sector [%]		6.9	7.0	2.3

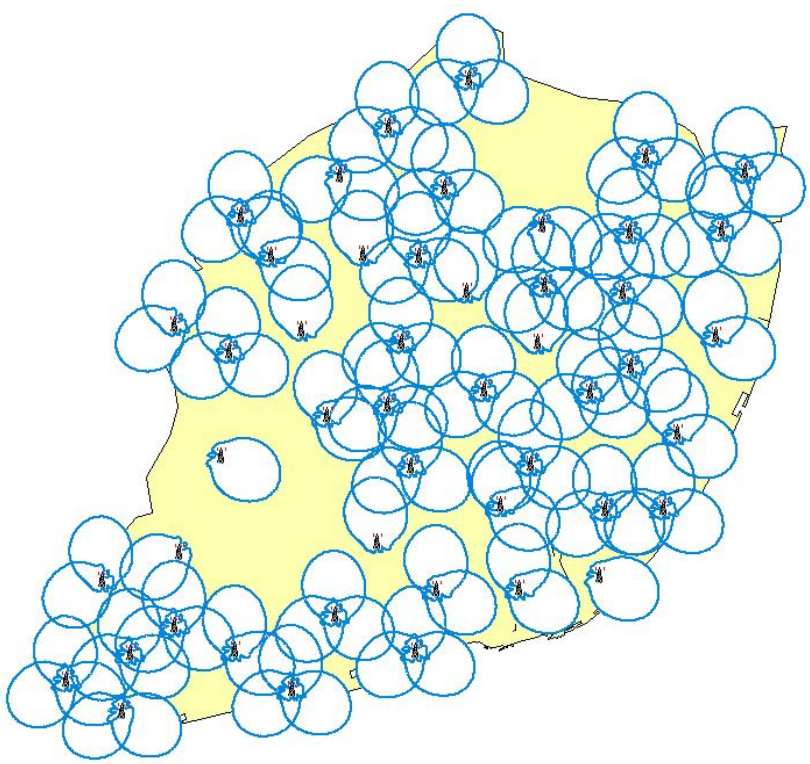


Figure H.1 – Coverage of the new network for no initial network and for a 12.2 kbps (CS) – pedestrian scenario.

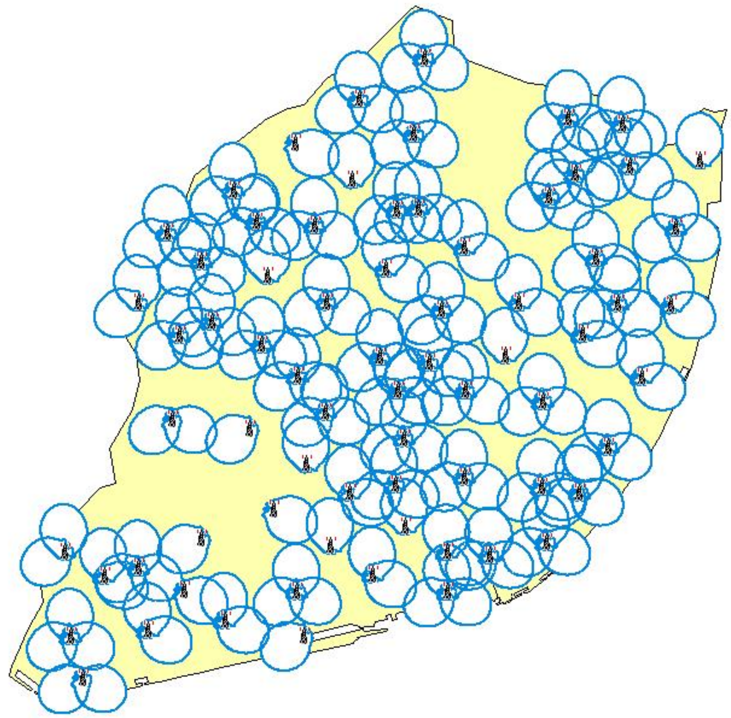


Figure H.2 – Coverage of the new network for no initial network and for a 12.2 kbps (CS) – vehicular scenario.

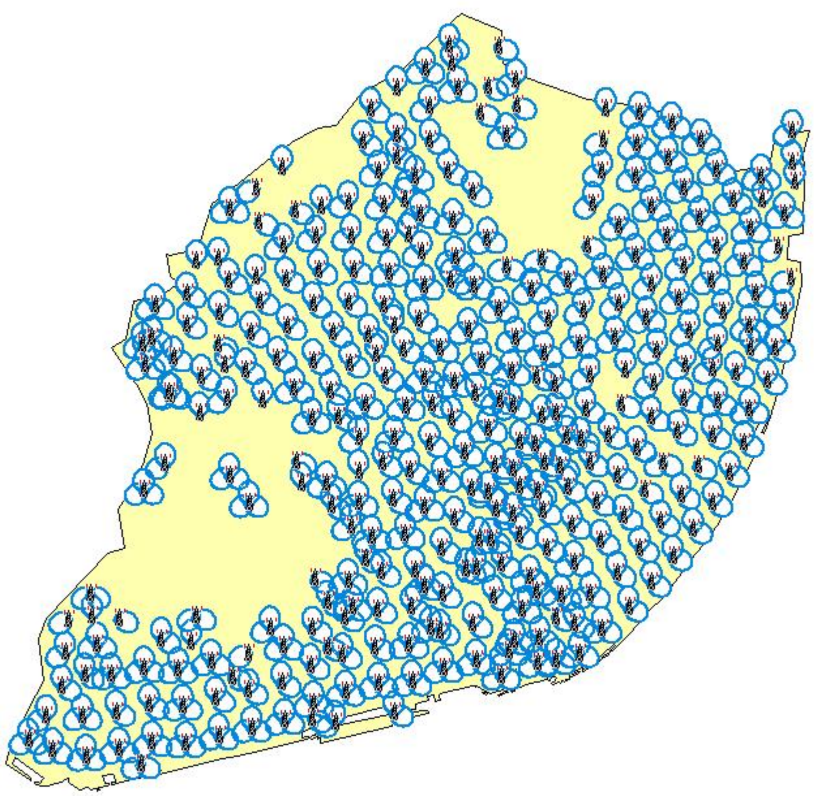


Figure H.3 – Coverage of the new network for no initial network and for a 12.2 kbps (CS) – indoor scenario.

Table H.2 – Results for no initial network and for a 64 kbps (PS) scenario.

		User Scenario		
		Pedestrian	Vehicular	Indoor
Number of added BSs		67	96	452
Number of added sectors 1		61	84	411
Number of added sectors 2		54	84	370
Number of added sectors 3		53	67	181
Uncovered area [%]		22.4	31.0	49.6
ξ [km^{-2}]		0.61	0.98	1.61
Equivalent uncovered traffic [%]	VSS and SS	7.5	7.7	2.0
	MS and LS	4.1	12.2	39.5
Area covered by 1 sector [%]		47.1	51.3	40.9
Area covered by 2 sector [%]		26.6	16.6	9.0
Area covered by more than 2 sector [%]		8.5	4.8	1.6

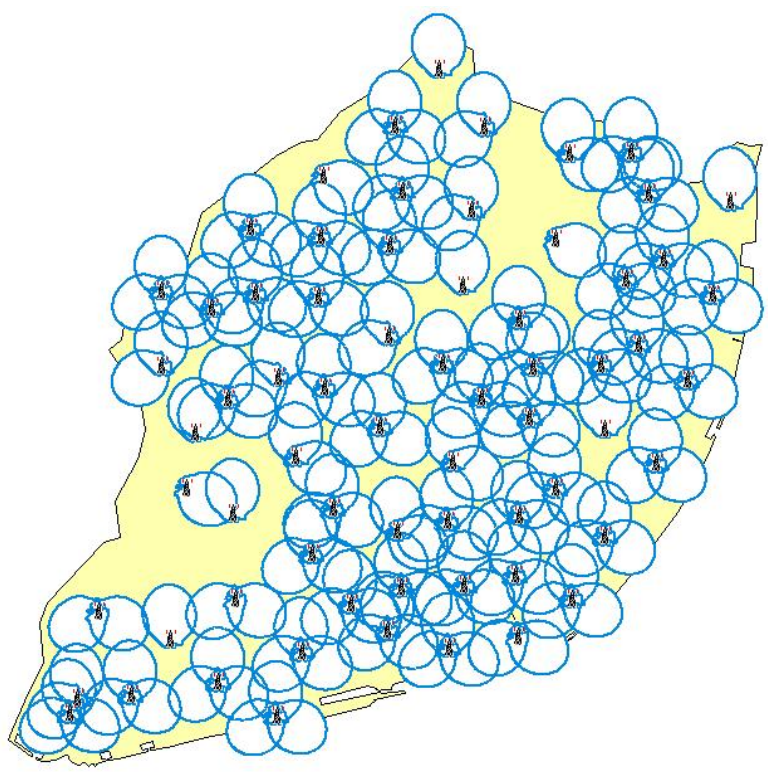


Figure H.4 – Coverage of the new network for no initial network and for a 64 kbps (PS) – pedestrian scenario.

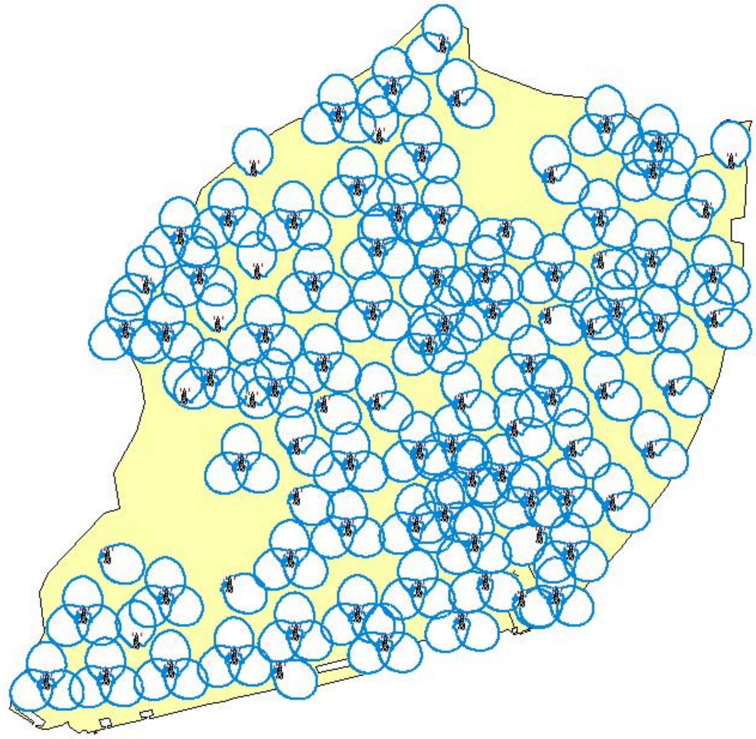


Figure H.5 – Coverage of the new network for no initial network and for a 64 kbps (PS) – vehicular scenario.

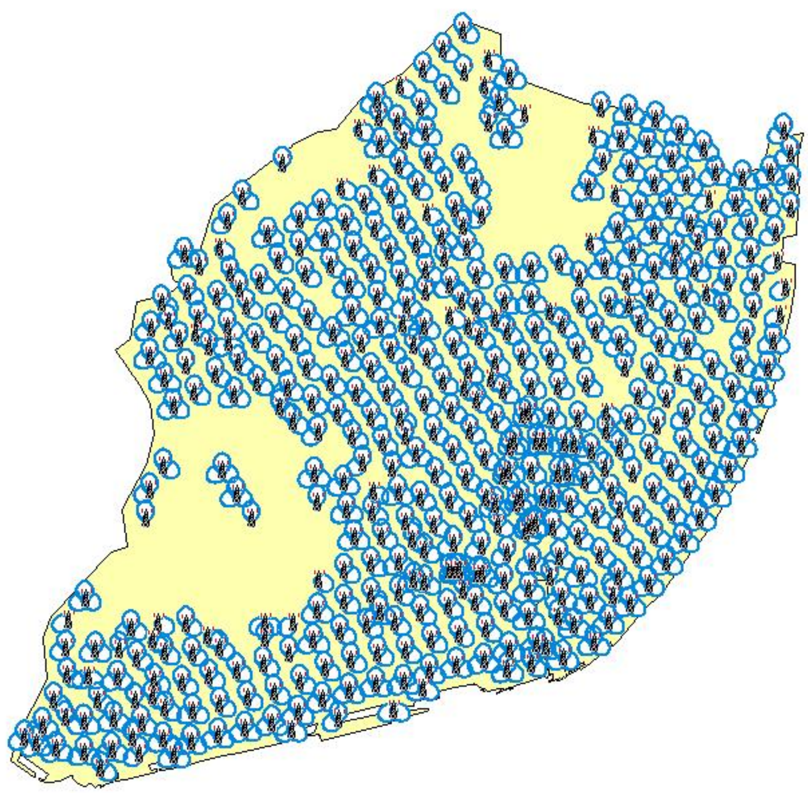


Figure H.6 – Coverage of the new network for no initial network and for a 64 kbps (PS) – indoor scenario.

Table H.3 – Results for no initial network and for a 128 kbps (PS) scenario.

		User Scenario		
		Pedestrian	**Vehicular**	**Indoor**
Number of added BSs		93	147	-
Number of added sectors 1		77	129	-
Number of added sectors 2		66	99	-
Number of added sectors 3		62	90	-
Uncovered area [%]		36.7	34.2	-
ξ **[km^{-2}]**		1.05	1.28	-
Equivalent uncovered traffic [%]	**VSS and SS**	4.8	6.0	-
	MS and LS	16.6	18.8	-
Area covered by 1 sector [%]		44.8	50.0	-
Area covered by 2 sectors [%]		17.2	15.3	-
Area covered by more than 2 sectors [%]		5.3	4.5	-

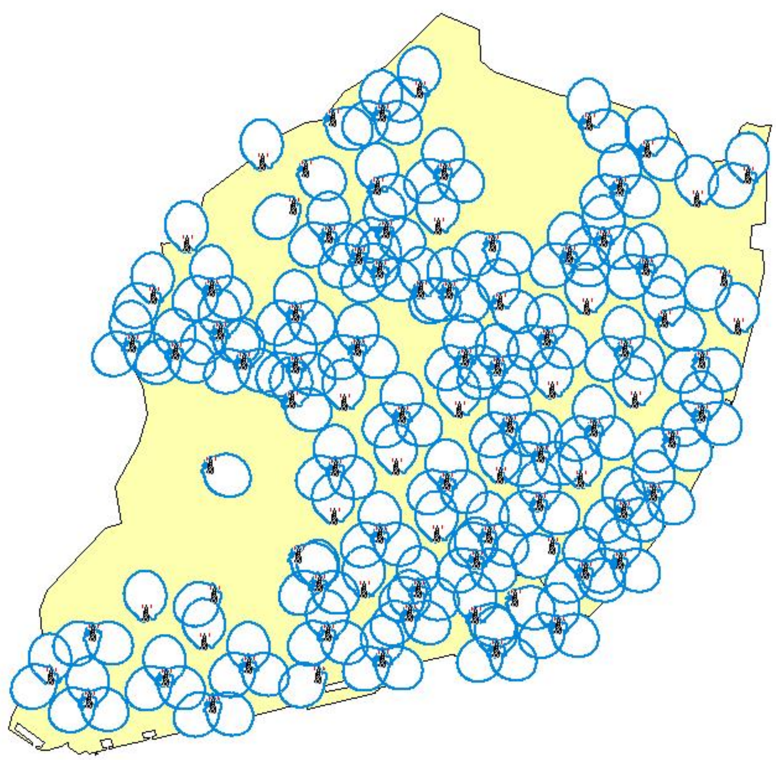


Figure H.7 – Coverage of the new network for no initial network and for a 128 kbps (PS) – pedestrian scenario.

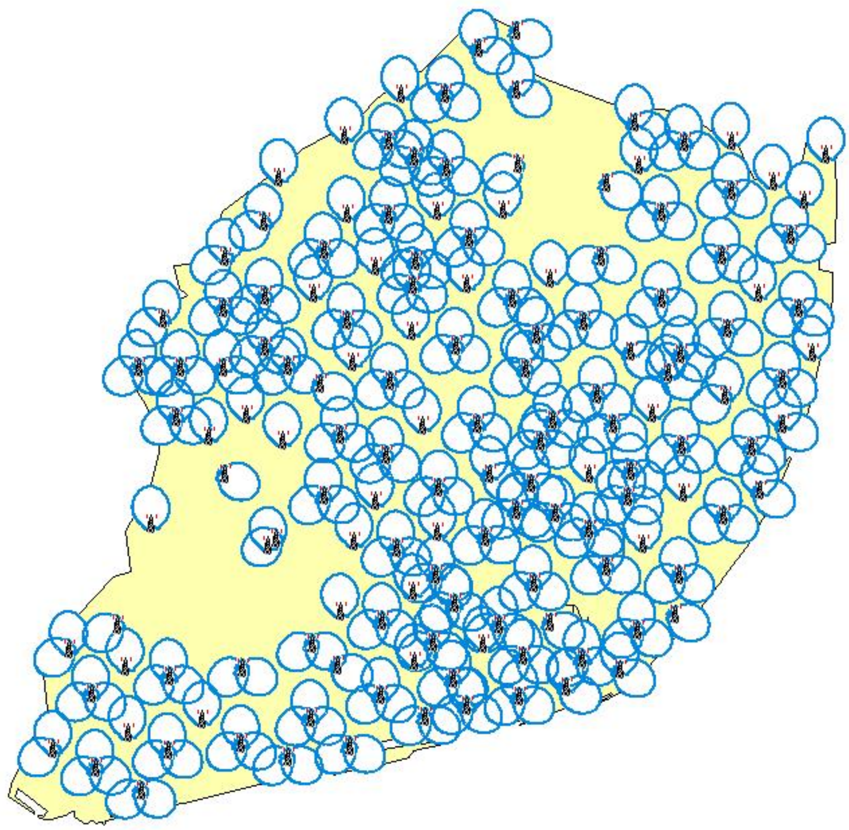


Figure H.8 – Coverage of the new network for no initial network and for a 128 kbps (PS) – vehicular scenario.

Table H.4 – Results for no initial network and for a 384 kbps (PS) reference service bearer.

		User Scenario		
		Pedestrian	**Vehicular**	**Indoor**
Number of added BSs		117	-	-
Number of added sectors 1		105	-	-
Number of added sectors 2		89	-	-
Number of added sectors 3		73	-	-
Uncovered area [%]		29.7	-	-
ξ **[km^{-2}]**		1.17	-	-
Equivalent uncovered traffic [%]	**VSS and SS**	6.4	-	-
	MS and LS	14.4	-	-
Area covered by 1 sector [%]		49.7	-	-
Area covered by 2 sectors [%]		20.1	-	-
Area covered by more than 2 sectors [%]		5.0	-	-

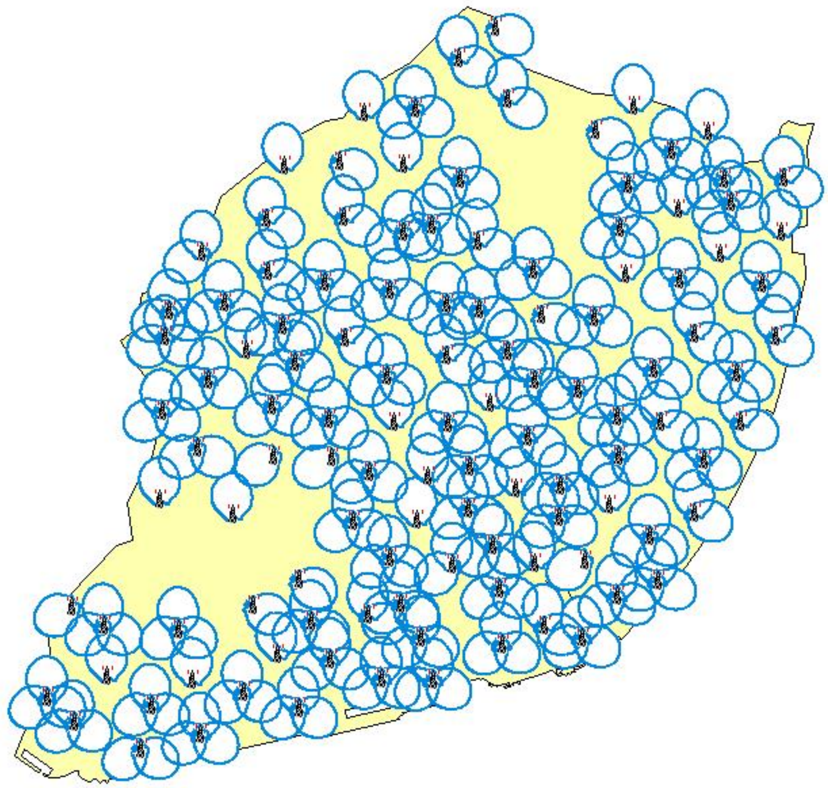


Figure H.9 – Coverage of the new network for no initial network and for a 384 kbps (PS) – pedestrian scenario.

Table H.5 – Results for a 384 kbps (PS) – pedestrian scenario for several ζ , and for no initial network.

		ζ [km^{-2}]	
		30	**90**
Number of added BSs		118	117
Number of added sectors 1		113	101
Number of added sectors 2		88	86
Number of added sectors 3		78	70
Uncovered area [%]		27.2	34.6
ξ **[km^{-2}]**		1.10	1.09
Equivalent uncovered traffic [%]	**VSS and SS**	8.9	7.0
	MS and LS	11.3	15.3
Area covered by 1 sector [%]		51.3	46.7
Area covered by 2 sectors [%]		20.7	17.5
Area covered by more than 2 sectors [%]		6.5	4.7

Table H.6 – Results for a 384 kbps (PS) – pedestrian scenario for several $\gamma_{hotspot}$, and for no initial network.

		$\gamma_{hotspot}$ [%]	
		30	**100**
Number of added BSs		140	108
Number of added sectors 1		128	96
Number of added sectors 2		112	80
Number of added sectors 3		96	64
Uncovered area [%]		21.8	33.7
ξ **[km^{-2}]**		0.94	1.39
Equivalent uncovered traffic [%]	**VSS and SS**	9.8	3.4
	MS and LS	6.8	20.6
Area covered by 1 sector [%]		47.3	48.9
Area covered by 2 sectors [%]		27.8	16.8
Area covered by more than 2 sectors [%]		9.3	3.9

Table H.7 – Results for a 384 kbps (PS) – pedestrian scenario for several P_{sup}, and for no initial network.

		P_{sup} [%]		
		10	**50**	**100**
Number of added BSs		98	122	124
Number of added sectors 1		83	111	111
Number of added sectors 2		76	108	115
Number of added sectors 3		65	80	114
Uncovered area [%]		38.4	25.1	20.9
ξ **[km^{-2}]**		1.59	0.61	0.35
Equivalent uncovered traffic [%]	**VSS and SS**	2.6	9.8	8.1
	MS and LS	27.6	5.2	2.3
Area covered by 1 sector [%]		47.0	48.5	44.5
Area covered by 2 sectors [%]		14.5	24.4	29.3
Area covered by more than 2 sectors [%]		3.9	6.6	10.0

Table H.8 – Results for the initial network for a 128 kbps – pedestrian scenario.

		Initial network
Number of BSs		194
Number of sectors 1		194
Number of sectors 2		194
Number of sectors 3		194
Uncovered area [%]		12.5
ξ **[km^{-2}]**		0.36
Equivalent uncovered traffic [%]	**VSS and SS**	1.4
	MS and LS	1.7
Area covered by 1 sector [%]		28.7
Area covered by 2 sectors [%]		22.1
Area covered by more than 2 sectors [%]		47.3
C_{unc}^{BH} **[MB/h]**		3 477

Table H.9 – Results for the initial network for a 128 kbps – vehicular scenario.

		Initial network
Number of BSs		194
Number of sectors 1		194
Number of sectors 2		194
Number of sectors 3		194
Uncovered area [%]		28.1
ξ **[km^{-2}]**		0.75
Equivalent uncovered traffic [%]	**VSS and SS**	2.7
	MS and LS	8.8
Area covered by 1 sector [%]		34.2
Area covered by 2 sectors [%]		21.6
Area covered by more than 2 sectors [%]		21.0
C_{unc}^{BH} **[MB/h]**		13 278

Table H.10 – Results for the initial network for a 384 kbps – pedestrian scenario.

		Initial network
Number of BSs		194
Number of sectors 1		194
Number of sectors 2		194
Number of sectors 3		194
Uncovered area [%]		18.2
ξ [km^{-2}]		0.51
Equivalent uncovered traffic [%]	VSS and SS	1.9
	MS and LS	3.7
Area covered by 1 sector [%]		31.1
Area covered by 2 sectors [%]		23.3
Area covered by more than 2 sectors [%]		35.2

Table H.11 – Results for a 12.2 kbps (CS) scenario, with the initial network.

		User Scenario		
		Pedestrian	Vehicular	Indoor
Number of added BSs		0	1	-
Number of added sectors 1		0	1	-
Number of added sectors 2		0	0	-
Number of added sectors 3		0	1	-
Uncovered area [%]		2.2	7.9	-
ξ [km^{-2}]		0.00	0.18	-
Equivalent uncovered traffic [%]	VSS and SS	0.4	1.2	-
	MS and LS	0.0	0.4	-
Area covered by 1 sector [%]		22.1	27.3	-
Area covered by 2 sectors [%]		17.7	20.3	-
Area covered by more than 2 sectors [%]		82.0	58.5	-

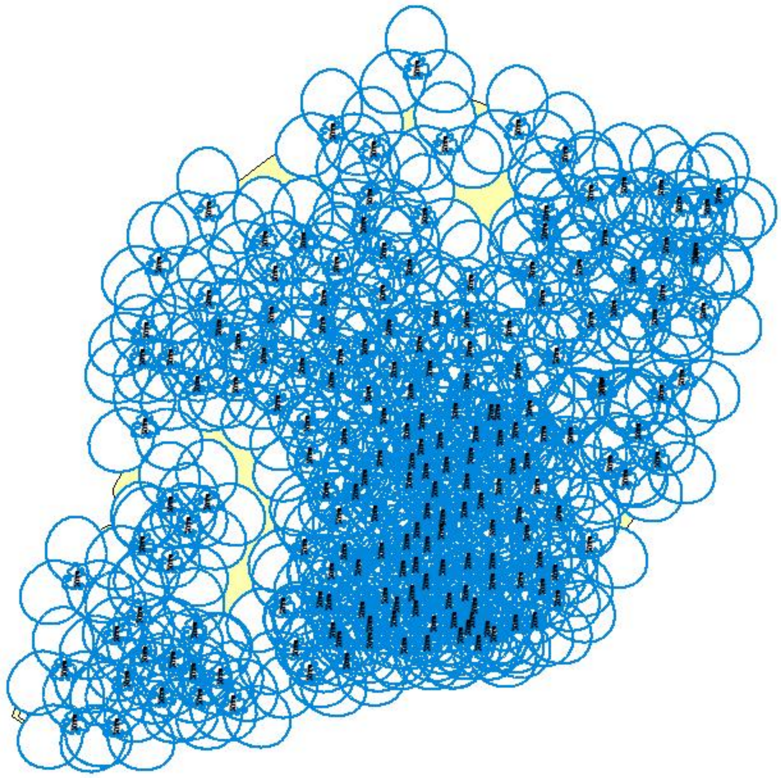


Figure H.10 – Coverage of the new network with initial network and for a 12.2 kbps (CS) – pedestrian scenario.

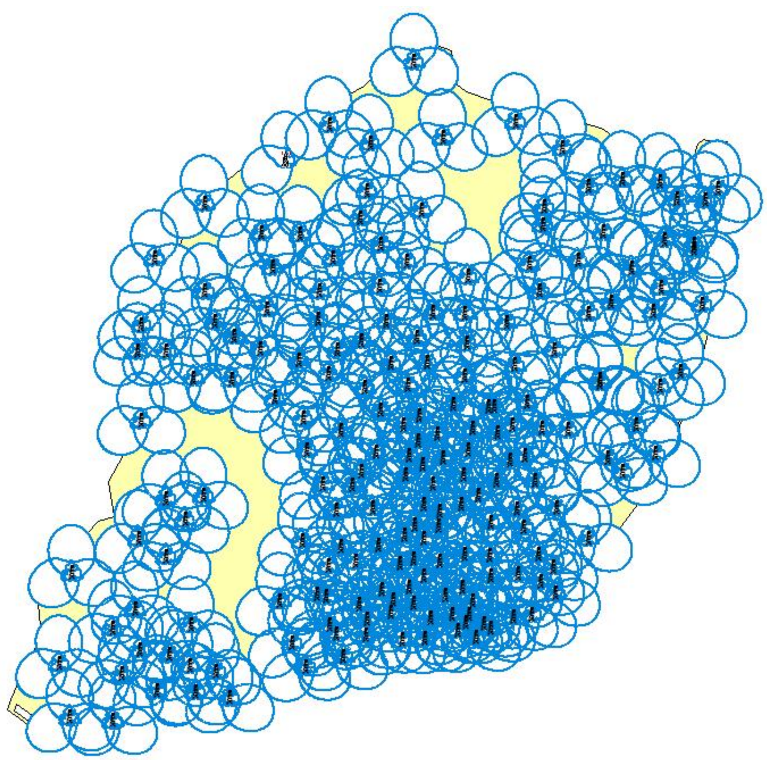


Figure H.11 – Coverage of the new network with initial network and for a 12.2 kbps (CS) – vehicular scenario.

Table H.12 – Results for a 64 kbps (PS) scenario, with the initial network.

		User Scenario		
		Pedestrian	**Vehicular**	**Indoor**
Number of added BSs		0	8	-
Number of added sectors 1		0	7	-
Number of added sectors 2		0	4	-
Number of added sectors 3		0	5	-
Uncovered area [%]		6.1	13.6	-
ξ **[km^{-2}]**		0.17	0.32	-
Equivalent uncovered traffic [%]	**VSS and SS**	0.9	1.6	-
	MS and LS	0.2	1.7	-
Area covered by 1 sector [%]		25.4	31.8	-
Area covered by 2 sectors [%]		18.4	24.1	-
Area covered by more than 2 sectors [%]		66.7	39.4	-

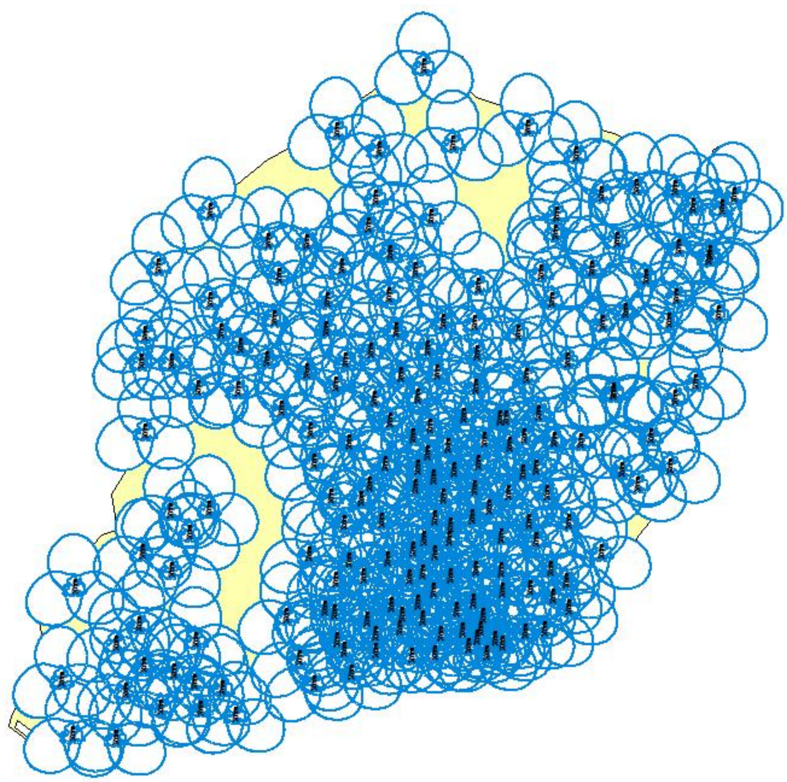


Figure H.12 – Coverage of the new network with initial network and for a 64 kbps (PS) – pedestrian scenario.

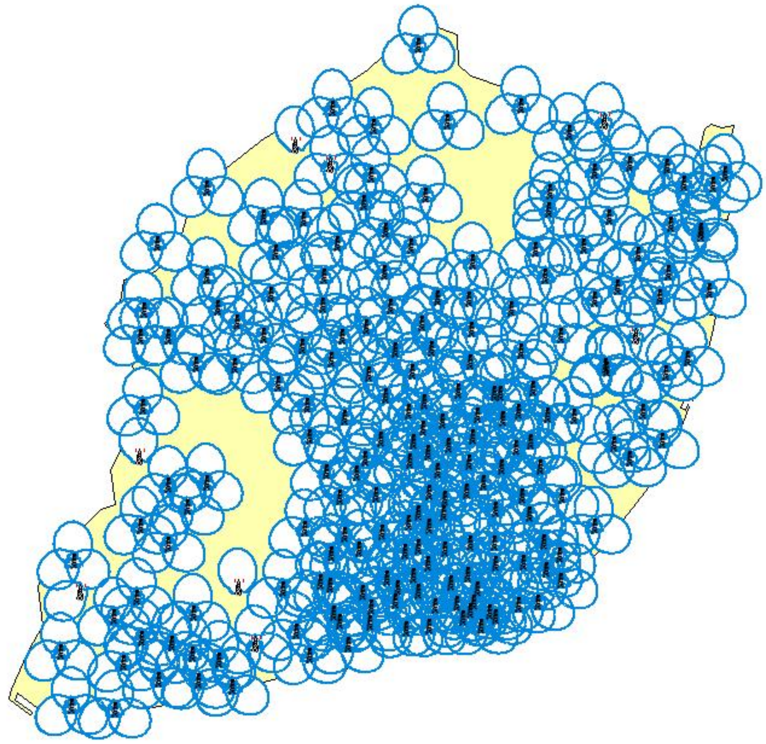


Figure H.13 – Coverage of the new network with initial network and for a 64 kbps (PS) – vehicular scenario.

Table H.13 – Results for a 128 kbps (PS) scenario, with the initial network.

		User Scenario		
		Pedestrian	**Vehicular**	**Indoor**
Number of added BSs		3	15	-
Number of added sectors 1		2	9	-
Number of added sectors 2		1	8	-
Number of added sectors 3		2	6	-
Uncovered area [%]		11.2	21.4	-
ξ **[km^{-2}]**		0.28	0.62	-
Equivalent uncovered traffic [%]	**VSS and SS**	1.4	2.0	-
	MS and LS	1.1	5.4	-
Area covered by 1 sector [%]		29.0	36.6	-
Area covered by 2 sectors [%]		22.7	23.7	-
Area covered by more than 2 sectors [%]		47.9	24.4	-
C_{unc}^{BH} **[MB/h]**		2 766	8 453	-

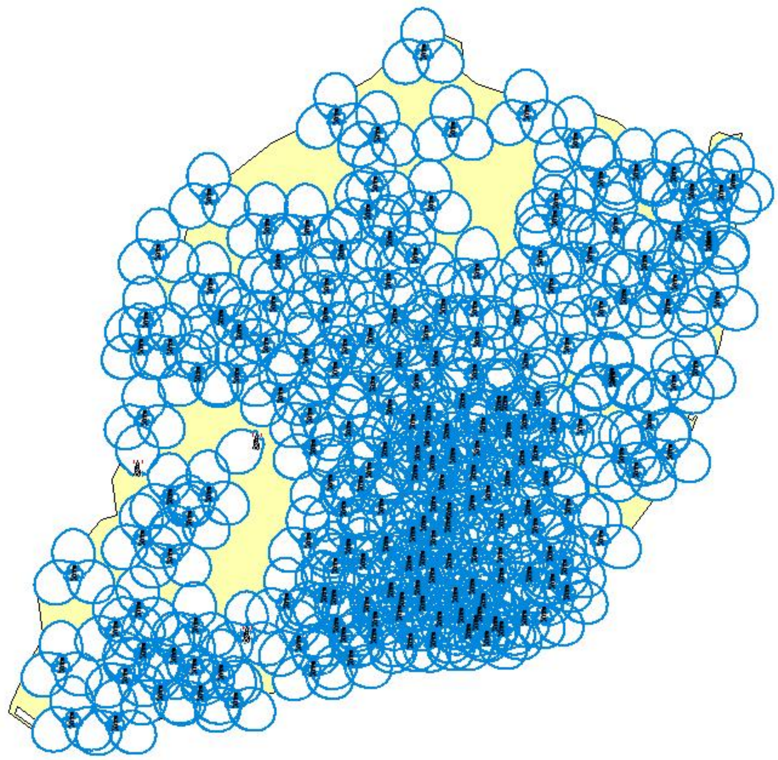


Figure H.14 – Coverage of the new network with initial network and for a 128 kbps (PS) – pedestrian scenario.

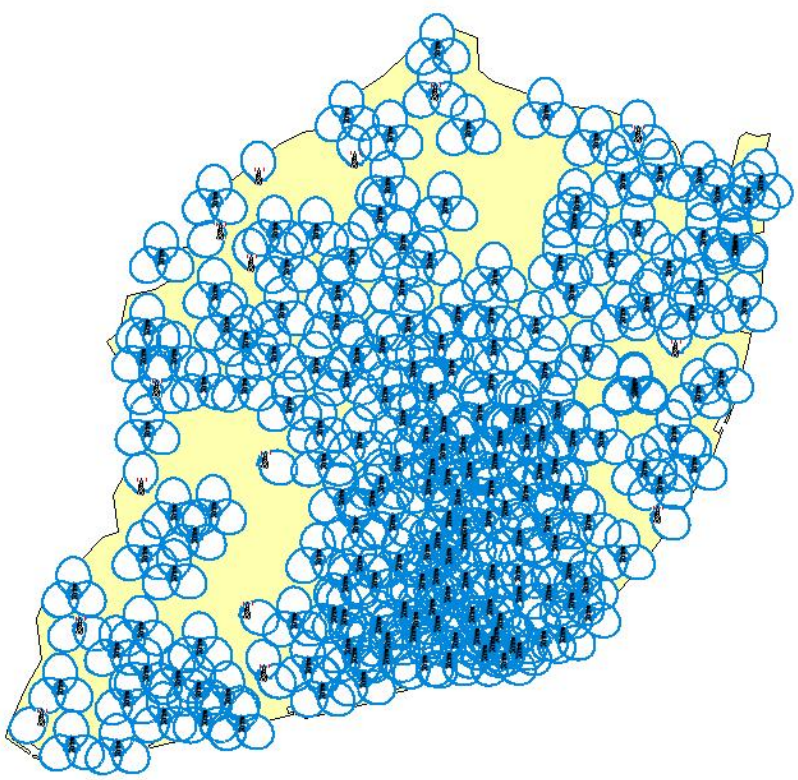


Figure H.15 – Coverage of the new network with initial network and for a 128 kbps (PS) – vehicular scenario.

Table H.14 – Results for a 384 kbps (PS) scenario, with the initial network.

		User Scenario		
		Pedestrian	**Vehicular**	**Indoor**
Number of added BSs		10	-	-
Number of added sectors 1		9	-	-
Number of added sectors 2		6	-	-
Number of added sectors 3		7	-	-
Uncovered area [%]		14.0	-	-
ξ **[km^{-2}]**		0.30	-	-
Equivalent uncovered traffic [%]	**VSS and SS**	1.9	-	-
	MS and LS	1.6	-	-
Area covered by 1 sector [%]		33.5	-	-
Area covered by 2 sectors [%]		24.9	-	-
Area covered by more than 2 sectors [%]		36.2	-	-

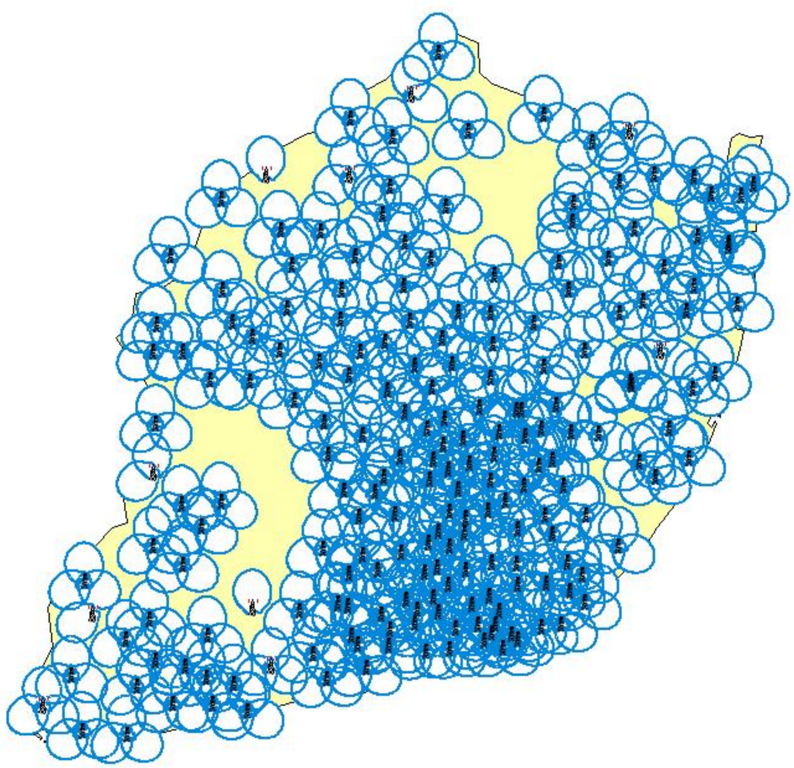


Figure H.16 – Coverage of the new network with initial network and for a 384 kbps (PS) – pedestrian scenario.

Table H.15 – Results for a 128 kbps (PS) – pedestrian scenario for several ζ , with the initial network.

		ζ [km^{-2}]	
		30	**70**
Number of added BSs		4	2
Number of added sectors 1		2	2
Number of added sectors 2		3	1
Number of added sectors 3		2	1
Uncovered area [%]		10.1	12.0
ξ **[km^{-2}]**		0.24	0.28
Equivalent uncovered traffic [%]	**VSS and SS**	1.6	1.6
	MS and LS	0.8	1.1
Area covered by 1 sector [%]		29.0	28.8
Area covered by 2 sectors [%]		22.8	22.8
Area covered by more than 2 sectors [%]		49.5	46.9

Table H.16 – Results for a 128 kbps (PS) – pedestrian scenario for several $\gamma_{hotspot}$, with the initial network.

		$\gamma_{hotspot}$ [%]	
		30	**100**
Number of added BSs		6	2
Number of added sectors 1		5	1
Number of added sectors 2		4	0
Number of added sectors 3		5	1
Uncovered area [%]		10.3	11.7
ξ **[km^{-2}]**		0.28	0.34
Equivalent uncovered traffic [%]	**VSS and SS**	1.1	1.2
	MS and LS	1.1	1.4
Area covered by 1 sector [%]		28.6	29.2
Area covered by 2 sectors [%]		23.8	22.3
Area covered by more than 2 sectors [%]		48.7	47.6

Table H.17 – Results for a 128 kbps (PS) – pedestrian scenario for several P_{sup}, with the initial network.

		P_{sup} [%]	
		10	**50**
Number of added BSs		1	5
Number of added sectors 1		1	3
Number of added sectors 2		1	2
Number of added sectors 3		1	2
Uncovered area [%]		11.9	10.6
ξ **[km^{-2}]**		0.30	0.28
Equivalent uncovered traffic [%]	**VSS and SS**	1.3	1.4
	MS and LS	1.3	1.0
Area covered by 1 sector [%]		28.5	29.2
Area covered by 2 sectors [%]		22.5	23.0
Area covered by more than 2 sectors [%]		47.8	47.9

Table H.18 – Results for a 128 kbps (PS) – vehicular scenario and P_{sup} = 100 %, with the initial network.

Number of added BSs		25
Number of added sectors 1		17
Number of added sectors 2		16
Number of added sectors 3		18
Uncovered area [%]		18.0
ξ **[km^{-2}]**		0.43
Equivalent uncovered traffic [%]	**VSS and SS**	3.3
	MS and LS	2.7
Area covered by 1 sector [%]		36.2
Area covered by 2 sectors [%]		26.6
Area covered by more than 2 sectors [%]		25.3

Table H.19 – Results for a 128 kbps (PS) – pedestrian scenario for different service bearer distributions, maintaining λ_{BHCA}, with the initial network

		Scenario 1	Scenario 2
Number of added BSs		3	3
Number of added sectors 1		2	2
Number of added sectors 2		1	1
Number of added sectors 3		2	2
Uncovered area [%]		11.2	11.2
ξ **[km^{-2}]**		0.28	0.26
Equivalent uncovered traffic [%]	**VSS and SS**	1.4	1.4
	MS and LS	1.1	1.1
Area covered by 1 sector [%]		29.0	29.0
Area covered by 2 sectors [%]		22.7	22.7
Area covered by more than 2 sectors [%]		47.9	47.9

Table H.20 – Results for a 128 kbps (PS) – pedestrian scenario for different service bearer distributions, increasing λ_{BHCA}, with the initial network

		Scenario 1	Scenario 2
Number of added BSs		3	3
Number of added sectors 1		2	2
Number of added sectors 2		1	2
Number of added sectors 3		2	2
Uncovered area [%]		11.2	11.1
ξ **[km^{-2}]**		0.30	0.32
Equivalent uncovered traffic [%]	**VSS and SS**	1.4	1.3
	MS and LS	1.1	1.0
Area covered by 1 sector [%]		29.0	29.0
Area covered by 2 sectors [%]		22.7	22.9
Area covered by more than 2 sectors [%]		47.9	47.9

Table H.21 – Performance analysis for the initial network for a 128 kbps (PS) – pedestrian scenario.

	Min.	Max.	Mean	Standard deviation
P_b [%]	0.38	1.29	0.807	0.321
P_d [%]	0.81	1.45	1.063	0.214
N_{unc}	2497	2651	2582.4	42.487
N_b	12	40	25	9.911
N_d	12	21	15.5	3.100
R_{global} [kbps]	346	362	354	4.972
Number of users	9.8	10.1	9.9	0.108

Table H.22 – Performance analysis for the initial network for a 128 kbps (PS) – pedestrian scenario.

	Min.	Max.	Mean
η_{DL} [%]	0	64.44	29.13
η_{UL} [%]	0	49.99	27.66
P_{Tx}^{BS} [dBm]	-82.15	23.26	12.31
Mean cell radius	0.70	0.72	0.72

Table H.23 – Performance analysis for the new network for a 128 kbps (PS) – pedestrian scenario.

	Min.	Max.	Mean	Standard deviation
P_b [%]	0.36	1.09	0.706	0.282
P_d [%]	0.55	1.44	0.939	0.266
N_{unc}	2478	2632	2563.7	42.750
N_b	11	34	22	8.819
N_d	8	21	13.8	3.882
R_{global} [kbps]	345	362	353	5.262
Number of users	9.68	10.01	9.83	0.099

Table H.24 – Performance analysis for the new network for a 128 kbps (PS) – pedestrian scenario.

	Min.	**Max.**	**Mean**
η_{DL} **[%]**	0.00	65.95	29.05
η_{UL} **[%]**	0.00	49.97	27.73
P_{Tx}^{BS} **[dBm]**	-82.15	22.10	12.33
Mean cell radius	0.00	0.72	0.72

Table H.25 – Results the new network for a 128 kbps (PS) – pedestrian scenario, using the simulator from [SeCa04].

		New network
Number of placed BSs		4
Number of placed sectors 1		4
Number of placed sectors 2		4
Number of placed sectors 3		4
Uncovered area [%]		7.6
ξ **[km^{-2}]**		0.39
Equivalent uncovered traffic [%]	**VSS and SS**	1.4
	MS and LS	0.9
Area covered by 1 sector [%]		29.5
Area covered by 2 sectors [%]		23.0
Area covered by more than 2 sectors [%]		51.6
C_{unc}^{BH} **[MB/h]**		2 649

Table H.26 – Results the new network for a 128 kbps (PS) – vehicular scenario, using the simulator from [SeCa04].

		New network
Number of placed BSs		21
Number of placed sectors 1		21
Number of placed sectors 2		21
Number of placed sectors 3		21
Uncovered area [%]		12.5
ξ **[km^{-2}]**		0.83
Equivalent uncovered traffic [%]	**VSS and SS**	4.6
	MS and LS	1.9
Area covered by 1 sector [%]		39.2
Area covered by 2 sectors [%]		27.4
Area covered by more than 2 sectors [%]		27.9
C_{unc}^{BH} **[MB/h]**		7 469

Table H.27 – Performance analysis for the new network for a 128 kbps (PS) – pedestrian scenario, using the simulator from [SeCa04].

	Min.	Max.	Mean	Standard deviation
P_b **[%]**	0.41	1.28	0.778	0.319
P_d **[%]**	0.75	1.37	1.010	0.188
N_{unc}	2488	2642	2572.7	42.991
N_b	13	40	24.2	9.964
N_d	11	20	14.8	2.700
R_{global} **[kbps]**	342	357	350	4.652
Number of users	9.58	9.87	9.75	0.098

Table H.28 – Performance analysis for the new network for a 128 kbps (PS) – pedestrian scenario, using the simulator from [SeCa04].

	Min.	**Max.**	**Mean**
η_{DL} [%]	0.00	61.89	28.86
η_{UL} [%]	0.00	49.99	27.50
P_{Tx}^{BS} [%]	-82.15	22.40	12.27
Mean cell radius	0.70	0.72	0.72

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