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CERTIFICAN

Que la tesis **"Cost Based Optimization for Strategic Mobile Radio Access Network Planning using Metaheuristics"**, presentada por D. Juan Eulogio Sánchez García, realizada en el Departamento de Teoría de la Señal y Comunicaciones bajo nuestra dirección, reúne méritos suficientes para optar al grado de Doctor, por lo que puede procederse a su depósito y defensa.

Alcalá de Henares, 25 de Julio de 2013.

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D. Juan Eulogio Sánchez García ha realizado en el Departamento de Teoría de la Señal y Comunicaciones y bajo la dirección de los Doctores D. José Antonio Portilla Figueras y D. Sancho Salcedo Sanz, la tesis doctoral titulada **"Cost Based Optimization for Strategic Mobile Radio Access Network Planning using Metaheuristics"**, cumpliéndose todos los requisitos para la tramitación que conduce a su posterior lectura.

Alcalá de Henares, 25 de Julio de 2013.

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Universidad de Alcalá

Escuela Politécnica Superior

Departamento de Teoría de la Señal y Comunicaciones

Tesis Doctoral

Cost Based Optimization for Strategic Mobile Radio Access Network Planning using Metaheuristics

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Abstract

Mobile communication technologies have experimented a great evolution since their appearance in the early 90's. This evolution has been motivated by two main factors: the new applications and necessities demanded by the end-user, and the technology progress. Mobile services have evolved from the classical voice and short message services (SMS), to more attractive and therefore better accepted services such as video-telephony, video-streaming, online gaming, and the mobile broadband access service (MBAS), which provides internet access on global mobility. All this improvements are a reality due to the appearance of new channel access methods, modulation and coding schemes, application of multiple input multiple output (MIMO) transmission and reception techniques, etc.

The liberalization of the sector has also played an important role in the evolution and current situation of mobile communications. Before this liberalization process, mobile communications' market presented a monopolistic scheme, based on public network infrastructure. However, liberalization caused the appearance of multiple companies providing services, with the necessity of new network infrastructure deployment. This new liberalized framework makes necessary the existence of a National Regulatory Authority (NRA) to establish a fair competitive market situation. One of the main objectives of the NRA is to determine the interconnection costs. Interconnection makes possible the communication between users from different mobile operators, as well as the access to the whole set of services. Few mobile operators make use of network of a third partner to provide a specific service to the end-user.

The goal of this Ph. D. Thesis is to minimize the investment cost associated to the network equipment. The interconnection charges determined by the NRA depends, to some extent, on this invested cost, as we show in the different chapters of this work. To achieve this objective, the thesis is divided into two main parts: first, a set of network dimensioning algorithms is developed. The second part is focused on the design and implementation of metaheuristic optimization algorithms to solve the optimal service distribution over the considered technologies problem (OSDP).

The planning and dimensioning module is based on four different algorithms. These algorithms are able to perform the dimensioning and planning process of a mobile radio access network (RAN), in a multi-technology (second (2G), third (3G) and fourth (4G) generations are considered), multi-user profile, based on the existence of three different type of users (customer, business and premium users), and multi-service environment (covering from the classical voice and SMS services, low binary rate data services (64-144 Kbps) to the mobile broadband access service).

The second part of this thesis is focused on solving the OSDP. The goal of this part is to distribute the traffic demand over the different technologies to be deployed. To achieve this objective, an efficient use of the technologies considered to reduce the investment costs incurred on network equipment, is needed. This is due to the technical features of each specific mobile generation systems, i.e., second generation systems are mainly focused on the provision of voice service and SMS, while third generation systems are data-oriented networks. Finally, the enhancement of the third generation system, known as High Speed Data Access (HSPA), together with 4G systems are focused on the provision of high speed data services such as the MBAS.

We have tested the proposed algorithms for solving the OSDP in a set of different scenarios. The results provided by these algorithms have been used to carry out techno-economical studies such as the performance analysis of the HSPA and 4G systems providing the MBAS, the LTE deployment simulation in the 800 MHz frequency band, this study is based on two real scenarios reproducing the coverage and capacity conditions of the two largest mobile operators in Spain, Movistar and Vodafone. Moreover, a study simulating the deployment of a LTE network with different spectrum allocation in the 800 MHz, 1800 MHz, and 2600 MHz has been carried out. Improvements, in terms of investment cost and therefore a reduction on services provision costs, have been observed for all the simulated cases.

The experiments performed in this thesis are focused on the spanish case. However, the algorithms implemented can be easily adopted to carry out similar studies in any other european country. In fact, the dimensioning algorithms of the first part of this thesis have been successfully applied to several international regulatory projects.

Resumen

La evolución experimentada por las comunicaciones móviles a lo largo de las últimas décadas ha sido motivada por dos factores principales: el surgimiento de nuevas aplicaciones y necesidades por parte del usuario, así como los avances tecnológicos. Los servicios ofrecidos para términales móviles han evolucionado desde el clásico servicio de voz y mensajes cortos (SMS), a servicios más atractivos y por lo tanto con una rápida aceptación por parte de usuario final como, *video telephony, video streaming, online gaming, and the internet broadband access* (MBAS). Todos estos nuevos servicios se han convertido en una realidad gracias a los avances técnologicos, avances tales como nuevas técnicas de acceso al medio compartido, nuevos esquemas de codificiación y modulación de la información intercambiada, sistemas de transmisión y recepción basados en múltiples antenas (MIMO), etc.

Un aspecto importante en esta evolución fue la liberación del sector a principios de los años 90, donde la función reguladora llevado a cabo por las autoridades regulatorias nacionales (NRA) se ha antojado fundamental. Uno de los principales problemas tratados por la NRA espcífica de cada nación es la determinación de los costes por servicios mayoristas, esto es los servicios entre operadores de servicios móvilles, entre los que cabe destacar el coste por terminación de llamada o de inteconexión. El servicio de interconexión hace posible la comunicación de usuarios de diferente operadores, así como el acceso a la totalidad de servicios, incluso a aquellos no prestados por un operador en concreto gracias al uso de una red perteneciente a otro operador, por parte de todos los usuarios.

El objetivo principal de esta tesis es la minimización de los costes de inversión en equipamiento de red, lo cual repercute en el establecimiento de las tarifas de interconexión como se verá a lo largo de este trabajo. La consecución de dicho objetivo se divide en dos partes: en primer lugar, el desarrollo de un conjunto de algoritmos para el dimesionado óptimo de una red de acceso radio (RAN) para un sistema de comunicaciones móvilles. En segundo lugar, el diseño y aplicación de algoritmos de optimización para la distribución óptima de los servicios sobre el conjunto de tecnologías móviles existentes (OSDP).

El modulo de diseño de red proporciona cuatro algoritmos diferenciados encargados del dimensionado y planificación de la red de acceso móvil. Estos algoritmos se aplican en un entorno multi-tecnología, considerando sistemas de segunda (2G), tercera (3G) y cuarta (4G) generación, multi-usuario, teniendo en cuenta diferentes perfiles de usuarios con su respectiva carga de tráfico, y multo-servicio, incluyendo voz, servicios de datos de baja velocidad (64-144 Kbps), y acceso a internet de banda ancha

móvil.

La segunda parte de la tesis se encarga de distribuir de una manera óptima el conjunto de servicios sobre las tecnologías a desplegar. El objetivo de esta parte es hacer un uso eficiente de las tecnologías existentes reduciendo los costes de inversión en equipamiento de red. Esto es posible gracias a las diferencias tecnológicas existente entre los diferentes sistemas móviles, que hacen que los sistemas de segunda generación sean adecuados para proporcionar el servicio de voz y mensajería corta, mientras que redes de tercera generación muestran un mejor rendimiento en la transmisión de servicios de datos. Por último, el servicio de banda ancha móvil es nativo de redes de última generadón, como High Speed Data Acces (HSPA) y 4G.

Ambos módulos han sido aplicados a un extenso conjunto de experimentos para el desarrollo de análisis tecno-económicos tales como el estudio del rendimiento de las tecnologías de HSPA y 4G para la prestación del servicio de banda ancha móvil, así como el análisis de escenarios reales de despliegue para redes 4G que tendrán lugar a partir del próximo año coinicidiendo con la licitación de las frecuencias en la banda de 800 MHz. Así mismo, se ha llevado a cabo un estudio sobre el despliegue de redes de 4G en las bandas de 800 MHz, 1800 MHz y 2600 MHz, comparando los costes de inversión obtenidos tras la optimización. En todos los casos se ha demostrado la mejora, en términos de costes de inversión, obtenida tras la aplicación de ambos módulos, posibilitando una reducción en la determinación de los costes de provisión de servicios.

Los estudios realizados en esta tesis se centran en la nación de España, sin embargo todos los algoritmos implementados son aplicables a cualquier otro país europeo, prueba de ello es que los algoritmos de diseño de red han sido utilizados en diversos proyectos de regulación.

To my parents, Eulogio and Josefa,
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If you always put limits on everything you do, physical or anything else.
It will spread into your work and into your life. There are no limits.
There are only plateaus, and you must not stay there,
you must go beyond them.

- Bruce Lee -

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Introduction

1.1 Cellular Mobile Communications History

Mobile communication has experimented a phenomenal growth since their first appearance in the 80's of the past century. Different factors have influenced this growth, such as the use of digital technology instead of analog one, the employment of different medium access techniques, several modulation and coding schemes, etc. All these changes have been collected in the different mobile communication standards by international organizations like the Thrid Generation Partnership Project (3GPP).

1.1.1 First Generation Networks

The first generation (1G) systems in mobile communications dates from the 80's. Several mobile radio networks existed before these 1G systems but they were not cellular systems. The first cellular system was developed by Nippon Telephone and Telegraph company in 1979. Several first generation cellular systems were introduced in Europe few years later. Nordic Mobile Telephone and Total Access Communication System developed the two most important networks in Europe in 1981. These systems were voice-oriented networks, based on analog transmission techniques, handover and roaming were also offered by this kind of systems, however interoperation between different countries was not possible.

In USA the Advanced Mobile Phone System was launched in 1982. The system was allocated a 40MHz bandwidth in the 800MHz, mobile terminal to base station communication, DL, and in the 900MHz frequency band, base station to mobile terminal link, UL. In 1988 an additional 10MHz bandwidth was allocated. Initially deployed with omnidirectional antennas in Chicago for a coverage surface of 2100 square miles, it consisted of 832 channels offering a data transfer rate of 10Kbps. Later on, directional antennas were used to improve the frequency resources exploitation, which introduced the frequency reuse concept in cellular networks. Empirical experiments fixed the reuse pattern used in this networks to a value of 7 in order to fulfill the signal to interference ratio constraint of 18 dB. The AMPS used frequency modulation technique, FM, for speech signals transmission, control data information was transferred using frequency shift keying technique, FSK, and frequency division multiple access as the medium access technique, FDMA. Table 1.1 shows the main features of the first generation cellular systems.

Standard	DL freq. band (MHz)	UL freq. band (MHz)	Channel BW (KHz)	Modulation Technique	Multiple Access	Region
AMPS	869-894	824-849	30	FM	FDMA	USA
TACS	935-960	890-915	25			EU
E-TACS	917-950	872-905	25	FM	FDMA	UK
NMT 450	463-467.5	453-457.5	25			EU
NMT 900	935-960	890-915	12-5	FM	FDMA	EU
C-450	460-465.74	450-455.74	10			Germany Portugal
RMTS	460-465	450-455	25			Italy
Radiocom	169.8-173	165.2-168.4	12.5			France
2000	200.5-207.5	192.5-199.5				
	207.5-215.5	215.5-233.5				
	424.8-428	414.8-418				
NTT	915-918.5	860-863.5	6.25			Japan
	922-925	867-870	6.25			
	925-940	870-885	6.25/25			
JTACS/	898-901	843-846	12.5/25	FM	FDMA	Japan
NTACS	915-925	860-870	12.5/25			
	918-5-922	863.5-867	12.5			

Table 1.1: 1G cellular systems

1.1.2 Second Generation Networks

The second generation (2G) systems appeared ten years later. These systems were digital technology-based systems using two main different medium access techniques, time division multiple access, TDMA, and code division multiple access, CDMA. As a consequence of the use of digital technology, these second generation systems have a better spectral efficiency and an advanced roaming service. They also offer slow-rate data services and support a larger number of subscribers than 1G systems.

The major 2G standards are summarized into four FDD based systems: In North America the TDMA digital cellular system IS-54 were developed in 1991, and improved into the IS-136 in 1996. In 1993, the CDMA-One digital system IS-95 was developed. In Japan, it was defined the PDC standard, Personal Digital Communication, in 1990. In Europe, it was deployed the Global System for Mobile Communications, GSM, a TDMA based system supporting 8 subscribers (time slots) in a 200KHz channel, mainly operating in the 900MHz and 1800MHz frequency bands. Table 1.2 shows the main characteristics of the second generation standards

Standard	DL freq. band (MHz)	UL freq. band (MHz)	Channel BW (KHz)	Number of channels/carrier	Multiple Access
GSM	935 - 960	890 - 915	200	8	FDMA / TDMA
IS-54	869 - 894	824 - 849	30	3	FDMA / TDMA
IS-95	869 - 894	824 - 849	1250	N/A	FDMA / CDMA
PDC	810 - 826	940 - 956	25	3	FDMA / TDMA

Table 1.2: 2G cellular systems

GSM standard is efficient for voice service transmission. However, its performance related to data services transmission is poor, due to only very low data transfer rate is available. GSM technology has a bandwidth for data of 9.6 Kbps per time slot, 14.4 Kbps can be achieved by using more efficient modulation techniques. To increase the capacity bandwidth of the network, and to enable the provision of new services, 2G evolved standards, as high speed circuit switched data (HSCSD), general packet radio service (GPRS) and enhanced data rate for GSM evolution (EDGE), were defined. These new standards are add-ons to the 2G standards, mainly focus on deployment of efficient IP connectivity within the mobile networks, and are commonly known as 2G+ technologies or 2.5G.

HSCSD standard increase the available capacity at the end user employing several time slots for each subscriber. The maximum capacity that can be achieved is 38.4 Kbps or 57.6 Kbps in case 9.6 Kbps or 14.4 Kbps per time slot is used, respectively.

GPRS standard is a packet-switching oriented technology, optimized for IP traffic. Information (voice or data) to be sent in packet-switching networks is split into packets of a few Kbytes each, and routed according to the destination identifier contained in the header of each packet. GPRS provides flexible capacity per time slot depending on the deployed technology: CS1 offers a maximum capacity of 8 Kbps per time slot, CS2 increase this capacity to 12 Kbps, 14.4 Kbps for CS3 and 20 Kbps in case of using CS4 technology, all these transmission speeds are refereed to data, that is, packet overhead is not taken into consideration. Additionally, GPRS is charged by volume and not by time like in circuit-switching GSM networks. This implies an advantage for the end user, and from an operator point of view, GPRS enables a more efficient sharing of resources, since once one subscriber download the packets sent to it, e.g. webpage information, the resources allocated to that user are released and assigned to another user, and therefore the resources are not wasted by “idle” data calls.

EDGE increases the data transmission speed by means of introducing new modulation and coding schemes: 8 Phase Shift Keying, 8PSK. This standard is also known as Enhanced GPRS, EGPRS. The main advantage of EGPRS over GPRS and GSM is the use of 8PSK modulation, that enables to send 3 bits per transmission step. In GSM and/or GPRS, only 1 bit is transmitted in each step, and therefore the transmission speed is 3 times lower than in EGPRS. Another advantage of EGPRS over GPRS is the definition of 9 different modulation and coding schemes, MCS, enabling transmission speeds per time slot from 8.8 Kbps, in case of MCS-1 is defined, to 59.2 Kbps for MCS-9. Overhead is not considered, as it was not in GPRS case.

1.1.3 Third Generation Networks

Third generation (3G) networks supposed a radical improvement in data transfer rates. The main enhancement of these systems was the use of a new access technique known as Wideband Code Division Multiple Access (WCDMA). 3GPP defined the first 3G cellular system in the Release 99 specification, Universal Mobile Telecommunication System (UMTS). The introduction of UMTS began in 2001 when the first UMTS commercial network was deployed in Japan by NTT DoCoMo’s, few years later a worldwide 3G deployment started.

The establishment of 3G networks was not easy at the beginning: the use of different frequency bands in comparison to the ones used by the 2G and 2G+ systems forced the operators to pay high fees for new licenses, and in addition, 3G networks needed a high investment due to the installation of a complete new network equipment in the RAN and the updating of existing equipment in the core network. Despite these problems, 3G systems were widely accepted and grew up, even, in a faster way than GSM did it. In 2006, about 140 WCDMA commercial networks in 50 countries were estimated to be in operation, with 100 millions of subscribers (40 millions in Europe). This fast growth is due to the fact that 3G systems offered a wider range of advanced services to the end user, such as voice telephony, video calls and wireless broadband access, a higher network capacity due to an improved spectral efficiency and the use of wider bandwidth, and improved coverage. Additionally, another reason that made possible this acceptance was the intensive marketing campaign carried out by operators.

By using WCDMA medium access technique, 3G systems' subscribers are no longer separated by timeslots or frequencies but by a unique code that is allocated to each user. This new technique implies that the carrier bandwidth is larger than the carrier in GSM systems, and therefore it enables a faster transfer data rate, e.g. Release 99 UTRAN allowed to send data, theoretically, up to 2 Mbps in downlink (DL) direction and 384 Kbps in the uplink (UL) direction, as well.

Further 3GPP work concluded in the definition of several enhancements to the UMTS systems. The major enhancement specified within Release 4 is a concept called the Bearer-Independent Core Network (BICN), voice traffic is carried inside IP packets instead of using circuit-switched 64 Kbps timeslots. Release 5 was the precursor of a new data transmission scheme, High Speed Downlink Packet Access (HSDPA). This new scheme increases the data transfer rate available in the DL direction, from base station to the subscriber. HSDPA peak data rates are not fixed, and depend on several factors:

- Terminal category or throughput capability of the handset.
- Capability of the network.
- Maximum interference level allowed in the cell. It depends on the number of users in the cell downloading data at the same time, and interference from neighboring cells.
- Bandwidth of the backhaul links.
- The quality of the radio channel.

In case that an ideal radio environment occurs, the maximum peak rate defined in HSDPA standard is 14.4 Mbps. This transfer speed decreases as the number of users downloading data at the same time in the cell increases or as the distance between the user and the base station increases. Nevertheless, even in not so favorable radio conditions, HSDPA offers data transfer rates of several Mbps.

Release 6 introduces a new scheme in UL data transmission: High Speed Uplink Packet Access (HSUPA). The objective of this scheme is to increase the data transfer rate between the handset and the base station. Peak data rates, as in HSDPA, are variable, under ideal radio conditions a maximum theoretical 5.76 Mbps for a single user is achieved. In real world, data transmission rates in HSUPA are not so high, but it offers higher data rates than UMTS and GSM. Additionally, HSUPA increases the maximum number of active connections sending data to the network, reducing the investment cost of the network. Both, Release 5 and 6, schemes are generally known as High Speed Packet Access (HSPA).

An increasing necessity of rising the data transfer rate made possible the definition of the Release 7. The main enhancements in Release 7 were an increase of the transmission speed in both, DL and UL, directions. In the DL direction this speed increase is achieved by the use of a new modulation scheme, 64 Quadrature Amplitude Modulation (64QAM) and the use of several antennas, Multiple Input Multiple Output (MIMO) transmission schemes. In the case of UL direction, a new modulation scheme 16 Quadrature Amplitude Modulation (16QAM) is applied, making possible transmission speeds up to 11.5 Mbps.

The introduction of networks based on HSDPA and HSUPA schemes was carried out much faster way than the transition from GSM to UMTS networks [1]. Evolution from UMTS to HSPA implies slight changes in the software of the installed network equipment, what explains that HSPA systems established in such a short period of time. In November 2008, about 230 HSDPA commercial networks in 100 different countries were already deployed. In the case of HSUPA, in 2008, 55 mobile operators deployed HSUPA networks to increase uploading data transmission speeds from 0.4 Mbps to 1.4 Mbps.

1.1.4 Fourth Generation Networks

3GPP continued its work on defining new evolved mobile standards to fulfill the growth of data traffic. In 2005, 3GPP defined the requirements of a new technology for mobile communications. This requirements were:

- Packet-switched domain.
- Capabilities uplink/downlink up to 50/100 Mbps.
- Higher capacity in comparison with HSPA, three or four times HSDPA capacity in case of DL direction, and two to three times in the UL case.
- Reduce the round-trip time and access time, 30 ms and 300 ms, respectively.
- Improved mobility and security.
- Flexible allocation of frequency resources.

This work concluded on the definition of Long-Term Evolution (LTE) in Release 8. LTE is known as the combination of the Evolved UMTS Terrestrial Radio Access Network (eUTRAN) and the Evolved Packet Core (EPC). The main improvement of LTE in comparison with the previous HSPA standard is the use of new access methods for both, DL and UL, directions in such a way that the capacity requirements defined are fulfilled [2]. LTE uses Orthogonal Frequency Division Multiple Access (OFDMA) in DL. Its main advantage is the possibility of dividing the available bandwidth into multiple orthogonal modulated sub-carriers, a different modulation scheme can be applied to each of them. In UL direction, Single Carrier Frequency Division Multiple Access (SC-FDMA) is used.

Nowadays, LTE commercial networks are in development in many countries worldwide. It is estimated, as shown in Figure 1.1, that the current number of LTE commercial networks is about 145 networks in 66 different countries. A report about the evolution and growth of LTE forecasts that 234 commercial networks in 83 countries will be working by the end of 2013 [3].

1.1.5 Fifth Generation Networks

The previous commented mobile technologies are already deployed (2G and 3G systems) or are currently being deployed, such as fourth generation systems. However, the evolution of mobile

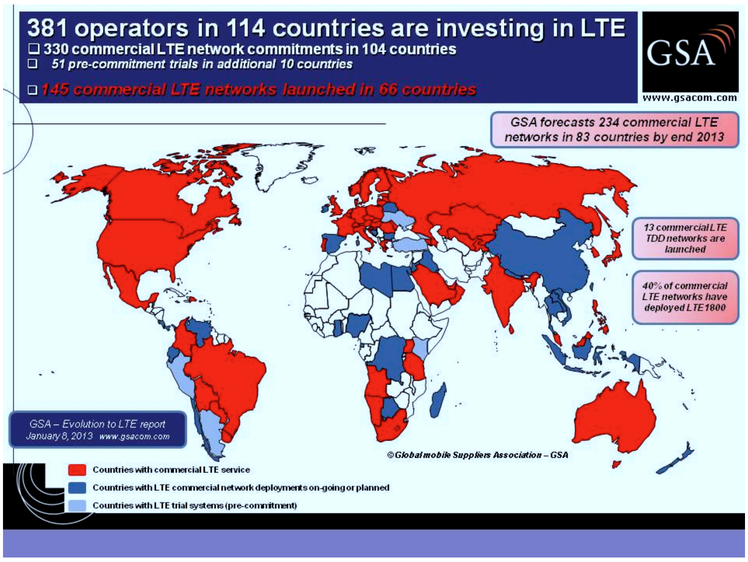


Figure 1.1: Worldwide LTE commercial network.

Source: GSA. Evolution to LTE Report. http://www.gsacom.com/downloads/pdf/GSA_Evolution_to_LTE_report_080113.php4

technologies is still on going: the fifth generation (5G) system is considered to be the evolution of the LTE and LTE Advanced technologies achieving minimum binary rates of 1Gbps. This new generation is not standardized by any standardization body such as 3GPP or ITU-R. We will give a short description of 5G systems and its mains features in this section.

The idea of the 5G systems is an all-IP platform, allowing the interconnection between most of the already existing communication infrastructures. Moreover, the user of the 5G technology is supposed to be capable of accessing to all possible applications by means of an universal device. Both ideas, force to deal with a set of exciting challenges:

- New ways of using spectrum: A new mobile technology involves the use of new licensed frequency bands or the reutilization of part of the already allocated spectrum. An alternative to this methodology is the used of unlicensed spectrum, that is broadcast spectrum that is not used, also known as *white spectrum*, as a complement to the licensed spectrum. This concept is related to the concept of cognitive radio. Cognitive radio technology allows different radio technologies to share the same spectrum, it is able to detect the unused spectrum and adapt the transmission schemes to the requirements of that spectrum. However, this technique is completely new in mobile communications and required an extensive study of the feasibility and impact of its application.

- Software Defined Radio (SDR): It allows to adapt the air interface to the available radio access technology via software, this is done, nowadays, by the network infrastructure. In 5G systems is done by a software that can be downloaded on the run.

- Reconfigurable Interoperability between several types of wireless access network: According to the access methods, up to now, each mobile technology has its own features and are not compatible with other standard. This point is solved in 5G network by allowing a complete interconnection between several access networks. It allows a most efficient exploitation of the network resources, exploring the availability of access resources and the specific services requirements. It is possible to balance the load of the service between the different access networks allowing to make the most of the spectrum and network resources exploitation.

- Nanotechnology: Defined as the "*The design, characterization, production, and application of structures, devices, and systems by controlled manipulation of size and shape at the nanometer scale (atomic, molecular, and macromolecular scale) that produces structures, devices, and systems with at least one novel/superior characteristic or property*" [4]. New 5G applications will required a larger memory and computing power to offer higher binary rates. The application of nanotechnology will make possible to provide solution for power efficient computing, sensing, memory enlargement, and human-machine interaction.

- All-IP Network: It is the key aspect of 5G systems, it allows the complete interconnection between all possible types of radio access, and therefore it makes possible to fulfill the increasing demand.

- Cloud computing: It is defined as "*a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction*", [5]. In 5G systems, cloud computing is applied to have a central remote server to provide contents, and it also allows to the end-user to access to their personal files at any computer with an internet connection and access to applications without installation, reducing the memory requirements in the terminals, and therefore reducing the power consumption and the computing power requirements.

Summarizing the network architecture of 5G systems is based on a mobile terminal, together with a set of independent and autonomous radio access technologies (RAT). The access to the services and applications is based on Cloud Computing Resources (CCR), that links the Reconfigurable Multi Technology Core (RMTC) that allows different radio access technologies to be configured in the network by means of the information given remotely by a Remote Reconfiguration Database (RRD), which information is based on a set of Reconfiguration Data models (RCM). All these elements enable the interconnection between different radio access technologies and spread the applications and services than can be offered to the end-user, [6], [7].

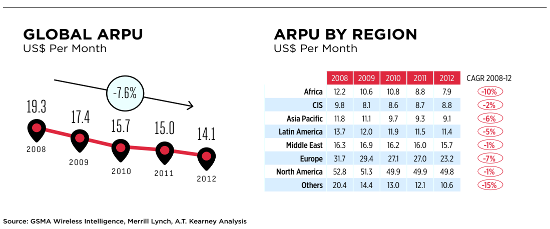
1.2 Market and Regulation

1.2.1 Worldwide Mobile Market Framework

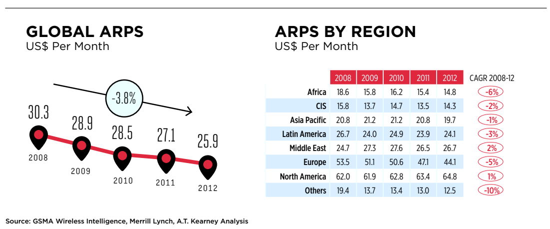
Mobile communications market has undergone significant changes the last 5-10 years. Mobile operators have made possible this evolution by means of capital investment in network infrastructure to provide new services to the end user. This fact makes possible the growth of mobile market and the appearance of new technologies and services such as video-calls, streaming, mobile TV, mobile broadband, etc. In this section, the growth of the mobile market is analyzed from different points of view: subscribers, connections, data growth and revenues.

First, from a social point of view, the number of subscribers accessing to mobile services has increased a 8.3% in the last four years, 2008-20012, and it is estimated to grew another 4.2% in the period from 2012 to 2017 [8]. Nowadays, the number of connections are higher than the number of subscribers, since each subscriber may have more than one handset or mobile device with multiple Subscriber Identity Module (SIM) cards. This makes that the growth, in terms of connections, is even higher, 13.2% and 7.6%, respectively [8]. The main drivers of this growth are the emerging markets, the developing countries. It is estimated that Asia Pacific region is responsible of 57% of connections growth from 2008 and 2012, and an additional 20% is caused by African and Latin-American countries. The investment in new network infrastructure made by operators in developing countries, explains the growth in these regions, making possible that more people own and use mobile technology, specially in rural areas. In developed regions such as Europe or North America, this growth will be about 1%, however the connections growth is supposed to be higher in these regions than in developing regions, since the increase of machine to machine (M2M) connections.

Moreover, the reduction in the prices of accessing to mobile services promotes this growth too. This eases the access to mobile services to a wider range of people, and turn the mobile market into a main pillar of accessibility and equality among the actual worldwide population. The global average revenue per unit rate (ARPU) fell from US$19 to US$14 per month. The average revenue per subscriber (ARPS), that excludes the multi-SIM and M2M effects, also shows a decline in prices. Figure 1.2 shows the evolution of ARPS and ARPU in the period from 2008 to 2012.



(a)



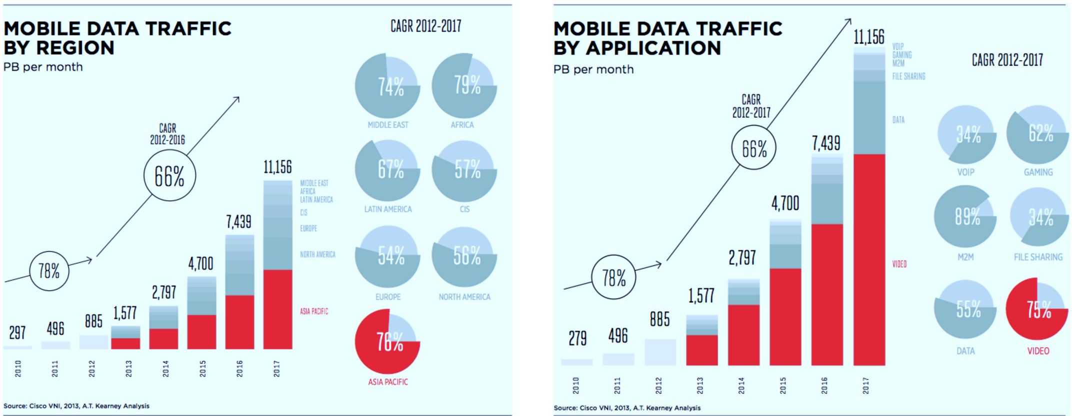
(b)

Figure 1.2: Average Revenue (a) by unit; (b) by subscriber

Source: The mobile economy 2013. `http://www.atkearney.com/documents/10192/760890/The_Mobile_Economy_2013.pdf/6ac11770-5a26-4fef-80bd-870ab83222f0`

Second, from a technical point of view, the evolution experimented by mobile markets and the offer of new advanced services such as mobile internet make the data traffic to increase even faster than the number of connections and/or subscribers does. Cisco, in their recent Visual Network Index (VNI) report [9], indicates a worldwide exponential data traffic growth, reaching 1.577 Petabytes per month in 2013, and is forecast to reach 11.156 Petabytes by 2017, see Figure 1.3. As it happened with the connections, Asia Pacific is the leader region of the data traffic growth.

The key engine of the data traffic growth is the introduction of the mobile broadband access service (MBAS). MBAS gives the possibility of accessing internet everywhere with a high download speed of contents, even it is supposed to be the substitute of the fixed line internet service in future. The number of connections related to the MBAS have grown 7 times since 2008, and it is expected to grow at 26% in 2017. The investment made by operators to improve the performance of their networks, in terms of download speed, constitutes the second factor of



(a) (b)

Figure 1.3: Mobile Data Traffic Growth (a) by region; (b) by application

Source: The mobile economy 2013. http://www.atkearney.com/documents/10192/760890/The_Mobile_Economy_2013.pdf/6ac11770-5a26-4fef-80bd-870ab83222f0

this data traffic growth. Average download binary rates have been doubled in the last two years, and it is estimated to increase seven times by 2017, reaching 4 Mbps.

The constant evolution of mobile technologies has turn this market into a major factor in worldwide economies. Mobile market's influence in global economy is shown in different ways: operators direct revenues, investment, employment generation and productivity improvement. Global revenues of mobile operators have increased their contribution to the global gross domestic product (GDP). The global growth corresponds to 4% from 2008 to 2012 and it is expected to continue growing at a lower rate of 2.3% through 2017, [8]. In 2012, revenues of mobile operators contributed US$1 trillion (1.4% world's GDP), the impact that the growth of mobile operator's revenues has in the GDP depends on the region considered.

Asia Pacific and Africa are the regions where this growth has influenced in a more significant way. Africa shows the highest rate of increase, and will lead, annually, the mobile operator revenue increase by 25% in the period 2012 and 2017. However, Eurozone is going through a serious period of crisis that, in addition to the strict regulatory processes carried out by the governmental institutions and the fierce competition existing, makes mobile revenues to tip into a deep recession period, e.g. global european revenues decreased from US$248 billion to US$216 billion in the last four years, and it is expected to continue decreasing by 2% until 2017.

In order to solve this situation, alternatives such as the investment in LTE technology deployments to offer better quality services and higher data transfer rates to the user, as well as different ways of charge's estimation related to the use of the network are proposed. As an example, in Switzerland, Swisscom operator bases its LTE traffics on the contracted download speed, independently on the volume of traffic downloaded. In addition, in developed regions, future revenues will depend on the adoption of higher rates of smartphone, growth in M2M connections, the establishment of new mobile devices such as tablets, and the appearance of new applications. Figure 1.4 shows the trend in mobile network revenues in the last four years and its forecasting until year 2017.

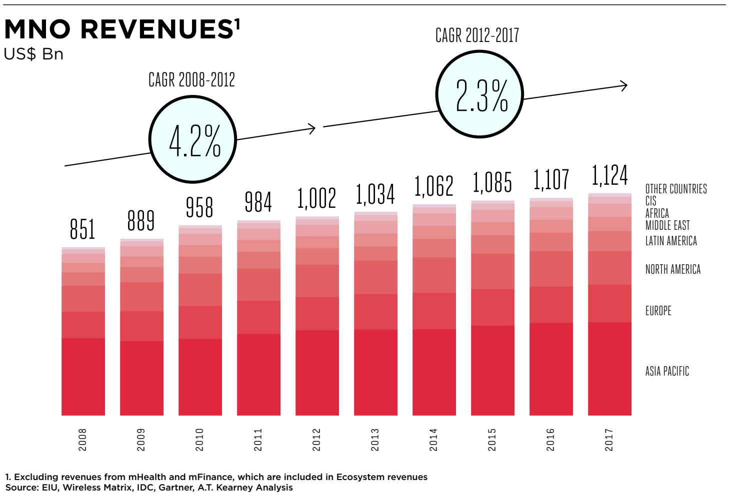


Figure 1.4: Mobile Network Operator Revenues.

Source: The mobile economy 2013. http://www.atkearney.com/documents/10192/760890/The_Mobile_Economy_2013.pdf/6ac11770-5a26-4fef-80bd-870ab83222f0

Mobile operators are constantly investing in updating existing or installing new network infrastructure and fees to fulfill the requirements of new services and technologies. The appearance of LTE technology and other Next Generation Networks (NGN) forces the operators to make heavy investments in new equipment and new spectrum. Mobile communications is, currently, the third industry in terms of investment costs, only behind electrical and maritime industries. After recovery from the economic crisis, during 2009 and 2010, it is expected that mobile CAPEX grows at almost 4% globally. Figure 1.5 shows the CAPEX as a percentage of revenues in 2012.

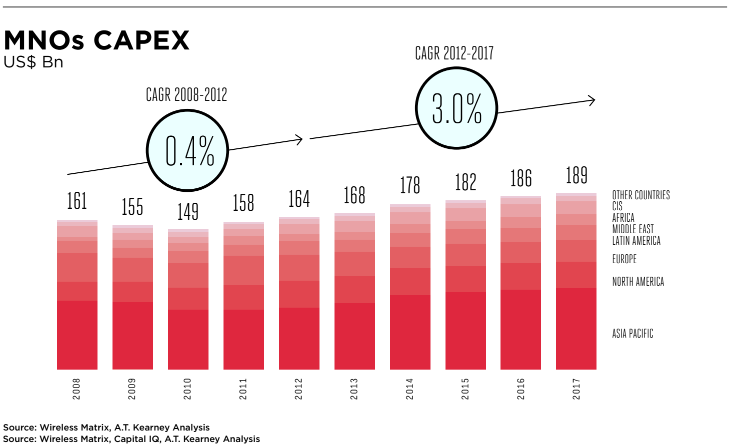


Figure 1.5: CAPEX Investment

Source: The mobile economy 2013. http://www.atkearney.com/documents/10192/760890/The_Mobile_Economy_2013.pdf/6ac11770-5a26-4fef-80bd-870ab83222f0

Employment generation constitutes the third important socio-economic aspect of mobile communications environment. In 2012, almost 9 million people were occupying a mobile communications related employment (18% of growth related to 2008), and it is forecast to reach almost 10.3 millions in 2017. While Asia Pacific is the region that contributes the highest growth index with almost 5%, Europe mobile environment employment is decreasing due to the economical situation. Mobile industry employments are defined in several fields, direct employment such as operator's employees, applications programmers and marketing sector. Development and marketing of contents sector is experimenting a fast growth since the appearance of smartphones, Android platform, and devices such as the iPhone and the iPad. These new intelligent devices contribute to new content development, mainly online content, e.g., according to a study carried out by TechNet, the "app economy" creates over 466000 jobs in the US since 2007 (first iPhone model introduction to the market). Figure 1.6 shows the mobile industry related employment evolution.

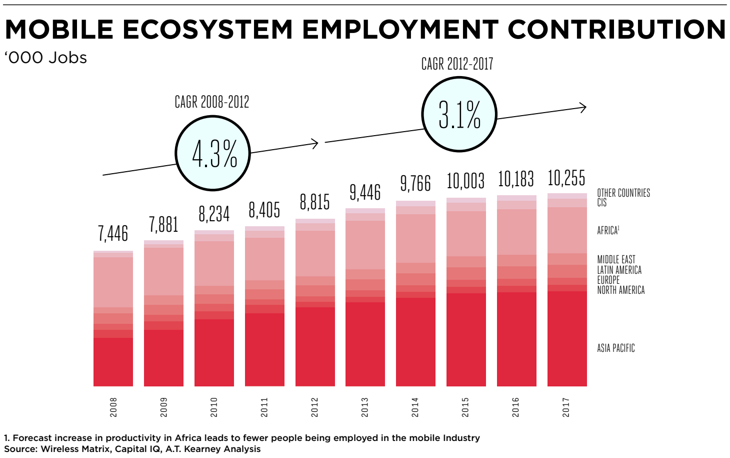


Figure 1.6: Mobile Industry related employment contribution

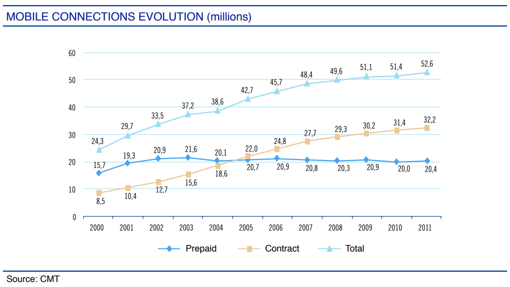
Source: The mobile economy 2013. http://www.atkearney.com/documents/10192/760890/The_Mobile_Economy_2013.pdf/6ac11770-5a26-4fef-80bd-870ab83222f0

Moreover, mobile industry development contributes in an indirect way to improve other sectors productivity, such as education, retail and entertainment. There are several sectors that shows a major improvement due to the evolution of mobile technologies, health is one of those sectors. Other sectors such as fishing and agriculture are improved by the use of mobile technology, e.g., in Brazil, operator Vivo in partnership with ZTE and Qualcomm introduced 3G technology to aid *fishermen92*, this application make easier the process of finding buyers, send information about the weather and updates market prices, what finally leads to a better decision choices and increase productivity. In Africa similar applications are applied to the farming sector.

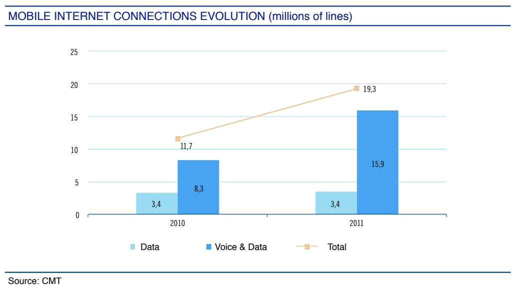
1.2.2 Spanish Mobile Market Framework

In this subsection we focus on the current situation of the mobile technology sector in Spain. A description about the evolution of subscribers and connections, investment, revenues and traffic is given, all the data is referred in [10].

The total number of connections is rising since the last ten years, doubling the number of lines. The number of voice connections reached 52.6 millions (114 lines per 100 inhabitants), that means that new 1.2 millions of connections were contracted in 2011. Machine associated lines, tele control and telemetry grew up to 2.5 millions of lines, implying an increasing of 18.1% in relation to 2010. Mobile internet experimented a very important growth in 2011, 19.3 millions of people (41.8 connections per 100 inhabitants) accessed to the Internet through a mobile device, this represents a 65.1% higher than in 2010. Data connections are based on two different types, voice and data subscriptions (mobile devices and smartphones) that represents 15.9 millions of connections (91.3% higher than connections in 2010), and exclusive data connections such as USB modems, with 3.4 millions of connections in 2011. Figure 1.7 shows the evolution for both main type of services, voice and mobile internet services.



(a)



(b)

Figure 1.7: Mobile Connections Evolution (a) Voice; (b) Mobile Internet

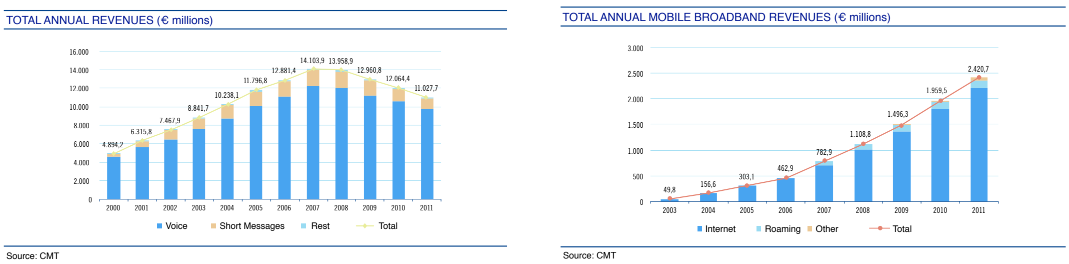
Source: Comisión del Mercado de las Telecomunicaciones. Informe Económico Sectorial, 2011.

In the same way the number of connections increased, the total average volume of traffic reached higher values in relation to 2010. The total volume of traffic of the voice service was of 72500 millions of minutes. While minutes corresponding to international calls were those who increased their value the highest, the part of the traffic corresponding to mobile-to-fixed network decreased by a value of 5.4% with respect to 2010. Traffic between mobile networks kept almost constant. Users destination of calls has changed since the last 10 years, calls generated in a mobile network may end into the same mobile network, on-net, a different mobile network, off-net, fixed network or into international networks. While in 2002, traffic from national mobile networks to national fixed networks did represent a 20.7% of the total traffic generated by mobile subscribers, ten year laters, this part of the traffic has been reduced to the 8.5% of total traffic. By contrast, voice traffic between mobile networks has increased 3.5 times its value with respect to 2002, representing the 84% of the total, on-net (48.9%) and off-net (35%), voice traffic. International calls and roaming also increased, with respect to 2010, by 31% and 10.9% respectively.

Short messages (SMS) and/or multimedia messages (MMS) services have reduced their impact in the total mobile traffic figure. The introduction of new internet messaging applications such as Facebook, Whatsapp, Line, Twitter, etc., allowing the user to send messages without additional cost, flat data rate associated, made almost unnecessary the use of this kind of services. This is reflected in a reduction by 35.5% from 2004 to 2011. Finally, as it was explained above, the access to mobile internet has increased in the last years, and so does the amount of traffic related to mobile broadband service (MBAS). 90500 Terabytes of internet data traffic were carried in 2011, rising its value by 40.7% in relation to 2010.

However, this growth in the number of connections has not been reflected in a revenue increase. The economic situation of Spain made impossible to turn the higher number of connections into a growth of mobile operator's revenues. In 2011, incomes corresponding to final services (voice, short messages, registration fee and other services such as tele control, telemetry, trunking, etc.) reached 11027.7 € millions, what implies a 8.6% reduction with respect to 2010.

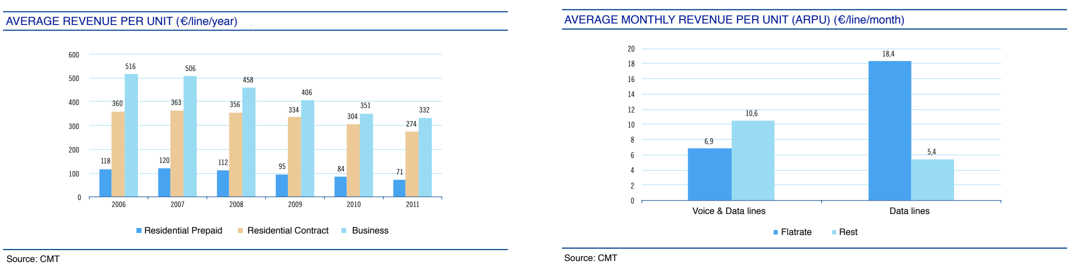
On the one hand, voice and short messages were the services with the highest reduction in revenues, 8.3% and 10.2% respectively. On the other hand, mobile broadband contributed with a income increase of 23.5%, for a total amount of 2420.7 € millions. Most of these revenues are related to monthly mobile internet flat data rates (91.1%). The average revenue per unit (ARPU) is affected by this general revenue reduction. Prepaid residential ARPU, in 2011, corresponds to 71 € per connection, it decreased a 15.6% its value in relation to 2010. Following the same trend, the postpaid residential ARPU decreased by a factor of 10% in relation to 2010. Referring to the business ARPU, it also reduced its incomes per connection by a 5.4% in relation to 2010. Figures 1.8 and 1.9 show the evolution of the different type of services revenues and ARPU.



(a) (b)

Figure 1.8: Spanish Mobile Revenues due to: (a) Final Services; (b) Mobile Broadband

Source: Comisión del Mercado de las Telecomunicaciones. Informe Económico Sectorial, 2011.



(a) (b)

Figure 1.9: Average Revenue per Unit due to: (a) Final Services; (b) Mobile Broadband

Source: Comisión del Mercado de las Telecomunicaciones. Informe Económico Sectorial, 2011.

Finally, ITC sector has influence in areas such as employment and investment. In 2010, the total amount of generated capital by ITC companies was of 104373 € millions, this value is based on 64586 € millions corresponding to IT and contents provider companies and 39787 € millions corresponding to telecommunications companies. ITC companies contributed with 459165 employees in 2010, 77839 of them due to telecommunications companies. In addition, ITC and specially telecommunication companies play an important role in the amount of capital invested in research and investigation, development of new technologies, improvement of the offered services, etc., in 2010 the total investment was of 16681 € millions, from which telecommunication companies contributed with 4480 € millions.

1.2.3 Regulation Framework

The current framework of the mobile communications' market has not been possible until the liberalization process occurred at the beginning of the 90's of the last century. This process implied an increase in competence, a wider offer of services and providers and a reduction in prices. Until then, telecommunication services were provided by public institutions under monopoly conditions, and therefore no regulatory organizations were needed.

The liberalization process followed three main phases, each of them making necessary improvements on the regularization scheme.The first two phases are privatization and partial competition. The privatization concept is the mechanism that transfers the ownership of the business from public sector to private sector. The partial competition phase is based on allowing the entry of new service providers, which sometimes occurs simultaneously with the privatization phase. The main objective of these initial phases is to open the market to the entry of new providers and the creation of a competitive market. However, most of the new private operators, approximately 7 out of 10 of major operators in the world [11], came from a monopolistic situation, and therefore, initially, the status of the private companies keeps as monopolistic, with a significant share and power on the market. In addition, as private companies, their operations are focused on maximizing their profits. These both phases make necessary the concept of a regulatory institution to prevent the operator on falling into unfair market practices, generally know as abuse of market power [12], based on:

- Predatory pricing: Selling a product below its true cost.
- Margin squeeze: Offering a high priced wholesale input to a company with which it also competes in the provision of the corresponding end user retail service, e.g. interconnection and call termination rates.
- Discrimination: Selling the same product to different companies with different prices without economic justification.
- Exclusive dealing arrangements with equipment, service or content providers.
- Cross-Subsidy: The dominant company plays in different markets (fixed, mobile, internet access), and it uses its integration to be profitable even though suffering losses in a specific market.
- Intellectual property and information sharing: Dominant companies are not willing to disclose their technical and commercial background, due to the fact this may difficult the interconnection with other operators.

The third phase of liberalization occurs when the dominant operator's exclusivity period ends and full competition is allowed. In this phase, the regulatory authority plays an important role implementing rules to foster and sustain the transition from the former monopoly / partial competition status to effective competition. The main objectives of regulation processes in this phase are to guarantee a widespread access, effective competition and customer protection. The main rules that must be implemented to make possible this transition are summarized as follows [13]:

- Creation of functional regulators to oversee the introduction of competition.
- Preparing the dominant operator to face competition, e.g. deadlines for market exclusivities.
- Allocation and management of resources in a non-discriminatory way.
- Expand and enhance access to telecommunications and ICT networks and services.
- Promote and protect costumer interests, including universal access and privacy.

As described, the aim of a regulator is to guarantee the correct working of the sector, i.e., to protect and ease the access to the services from the end-user point of view, and to make possible the entry of new providers into the market in a fair and balanced way. To achieve this, a regulator must be structurally and financial independent. Moreover, the real effectiveness of achieving the objective depends on how the operator develops its functionality in an independent and autonomous way. In addition, other features such as accountability, transparency and predictability should be demonstrated.

The achievement of these characteristics requires countries to establish a structurally independent regulator that separates the telecommunications regulation function from the supplying services function, this reduces the possibility of political or industry capture.

From a financial point of view, independence is related to the funding sources origin, a regulator which funding sources came from multiple origins and not only from government, services providers excluded. Regulatory bodies fulfilling this requirement increase their effectiveness and have a higher grade of freedom from possible governmental influences. Finally, meeting both structural and financial independence criteria, countries must guarantee that a regulatory authority functions in an effective way. This functional effectiveness is a combination of different features such as well defined functions and responsibilities, definition of procedures to ensure transparency and public participation in the regulatory process.

One of the most important issues a regulator has to face is the interconnection problem. The World Trade Organization defines the interconnection concept as: *Linking with suppliers providing public telecommunications transport network or services in order to allow the users of one supplier to communicate with users of another supplier and to access services provided by another supplier, where specific commitments are undertaken* [14].

Based on the above definition, several interconnection possibilities can be defined, traditional wireline networks interconnection, wireline to wireless networks interconnection, emergent to dominant operators interconnection, IP interconnection that happens when a wireline or wireless operator offers internet access to its subscribers using an internet service provider that compete with it, VoIP service providers to traditional public switching telephone network (PSTN) providers interconnection. All these interconnection mechanisms have three main advantages:

- Provide a service that is not feasible, from an economical point of view, without interconnection, e.g., calls to customers on another operator's network.
- Increase the profitability. Interconnection increase the value of telecommunications services and the range of services operators can offer.
- Expand and improve valuable services to the end user.

However, interconnection can also limit competition of an operator with significant market power (SMP), e.g., in case of a potential competitor of the dominant operator needs to access to the dominant operator's network. In these cases, the incumbent operator may fall into the temptation of blocking interconnection by means of refusing it or allowing it at prohibitive prices or providing lower quality interconnection services in comparison to the quality offered to its own customers. These reasons make necessary a national regulatory authority (NRA) that guarantees the fulfillment of the following obligations [14]:

- Interconnection must be provided
  - **on non-discriminatory** terms, conditions and rates, and of a quality no less favorable than that provided to its own like services, or for its affiliates, or for like services of other non-affiliated suppliers,
  - **in a timely fashion on terms**, conditions and cost-oriented rates that are transparent, reasonable, having regard to economic feasibility, and sufficiently unbundled so that the supplier need not to pay for network equipment that it does not require for the service provided, and
  - **upon request**, at points in addition to the network termination points offered to the majority of users, subject to charges that reflect the cost of construction of necessary additional facilities.
- Public availability of the procedures for interconnection negotiations.
- Transparency of interconnection arrangements, to avoid anti-competitive behavior in the market.
- An interconnecting service supplier must have recourse to an independent domestic body, NRA, to resolve disputes regarding appropriate terms, conditions, and rates for interconnection within a period of reasonable time.

1.2.3.1 Termination Charges in European Countries

Once the fundamentals of interconnection have been explained, this subsection presents a set of decisions and processes performed by different national regulatory authorities (NRA) in Spain, Germany and UK.

The goal of every regulatory process is to adequate the termination charges that one operator has to pay for terminating a voice call making use of network resources owned by other operator. This charge is estimated based on the cost that operators incurred on providing the mobile termination access service (MTAS). The reduction of these mobile termination rates (MTR) is performed following a specific calendar of reduced prices, the glide path.

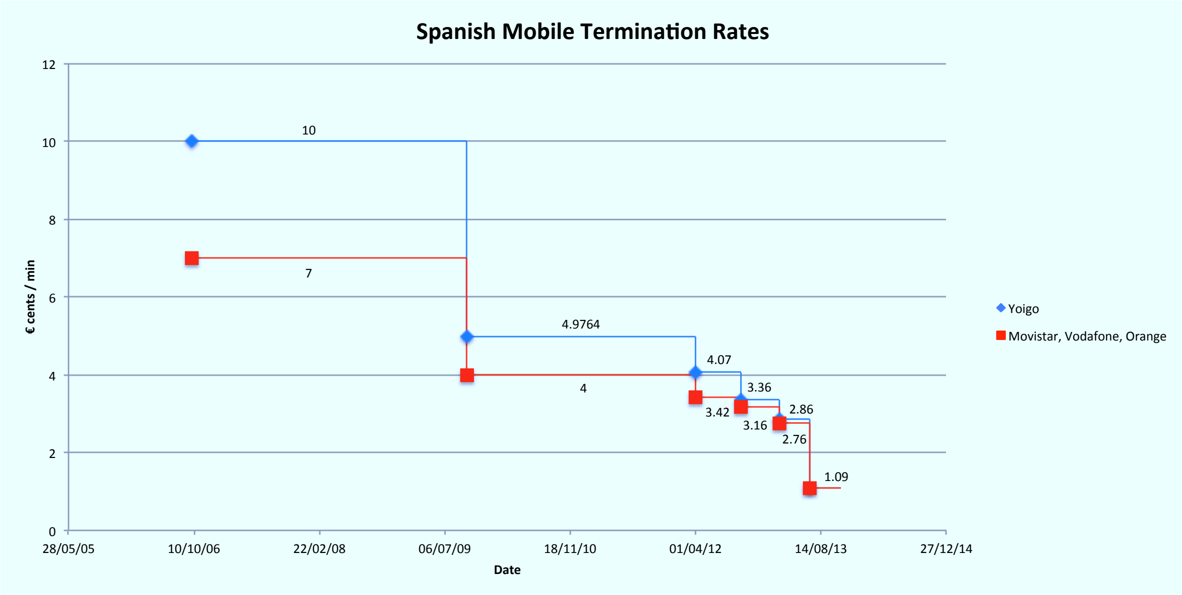


Figure 1.10: MTR's Evolution in Spain.

In Spain, the Telecommunications Market Commission is the organization in charge of regulating mobile services' prices. Three different glide paths were defined, the first one went from October 2006 to September 2009. Before this first regulatory process, each operator fixed its own termination charges, the aim of this process was to equalize the termination charges between operators. This goal was achieved by means of lowering termination charges until a common price of 0.07 €/min for Telefónica Móviles, Vodafone and Orange. This implied an average reduction in the termination fees between a 41% and 47%. Yoigo's glide path was different due to its late market's entrance, fixing a termination charge of 0.10 €/minute

The second glide path was performed from October 2009 to April 2012, and it involved an average decreasing of the termination fees between a 40% and 50%. The resulting average price was set to 0.04 €/minute for Movistar, Vodafone and Orange, and as it happened in the first glide path, the price applied to Yoigo was slightly higher, 0.049764 €/min.

Finally, the third glide path went from April 2012 to July 2013. The estimated termination charge was set to 0.0109 €/min, what implied a reduction of a 75% for Movistar, Vodafone and Orange, and a 80% for Yoigo. Figure 1.10 shows the evolution of the mobile termination rates through the last 8 years in Spain.

Ofcom is the United Kingdom's NRA. The model chosen by Ofcom to perform the corresponding regulatory projects is the well-known Long Rung Incremental Cost Model (LRIC), see Section 1.3.1 for details. The last decision on mobile termination charges in the UK is divided into six different periods of time, going from April 2011 to March 2015, and forces british mobile operators to reduce their interconnection fees from £0.0418 (0.0489 €) per minute to £0.0067 (0.0078 €) per minute [15].

The Federal Network Agency (FNA), also known as Bundesnetzagentur or BNetzA, is the

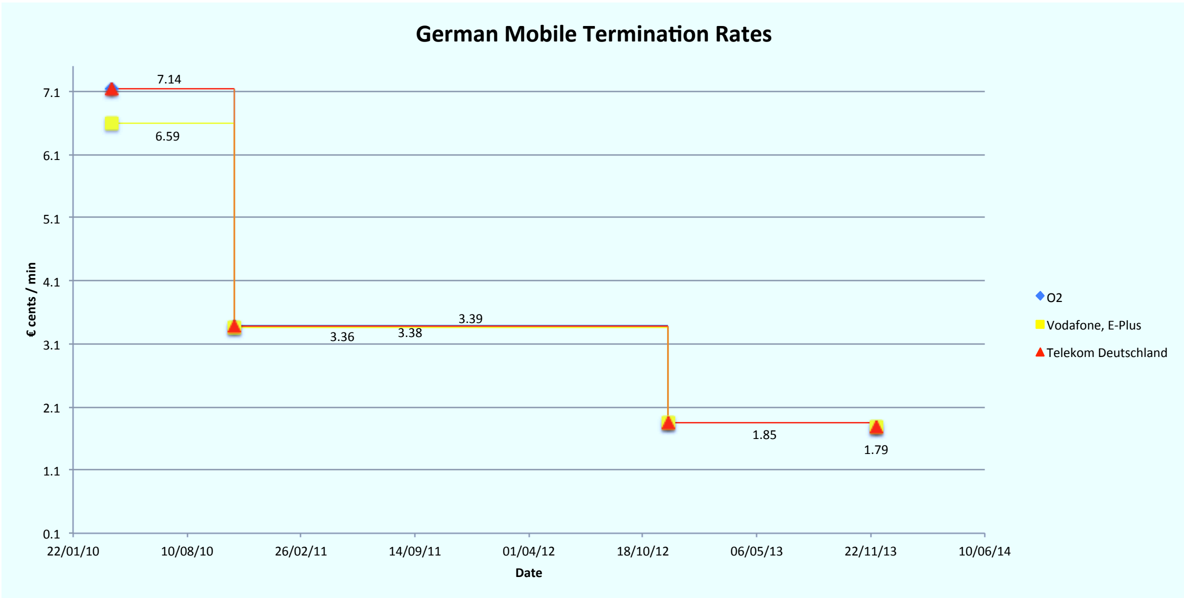


Figure 1.11: MTR's Evolution in Germany.

corresponding NRA in Germany. MTRs in Germany, based on the LRIC Bottom Up model, have been reduced by a factor of 74.93% in the last four years. Before the approval of the regulatory decision of November 2010, MTRs were in the range from 0.0659 to 0.0714 €/minute. From December 2010 to November 2012, a reduction of the termination charges were performed, setting them to 0.0336 for Vodafone and E-Plus, 0.038 for Telekom Deutschland and 0.039 for Telefónica O2, which implies a reduction of a 45.38% in comparison to previous fees [16]. Finally, in 2012 a new regulatory process established a reduction of charges of a 54.1%, setting a unique termination rate for all mobile operators in Germany. The final rate was set to 0.0179 €/min, achieved in two steps, from December 2012 to November 2013 a MTR of 0.0185 €/min is set, and the final 0.0179 €/min is valid starting on December 2013 [17]. Figure 1.11 shows the evolution of the mobile termination rates through the last 3 years in Germany.

1.3 ICT Regulation Toolkit

In the previous section, the current regulatory framework of the main european countries has been described. Moreover, one of the key aspects in regulatory processes, the necessity of the MTAS rate estimation, has been introduced. There are three main forms of mobile interconnection: fixed-to-mobile interconnection happens when a mobile network terminates a call from a fixed network, mobile-to-fixed interconnection occurs when a mobile operator interconnects with a fixed network in order to complete calls originated by the mobile operator's users, and mobile-to-mobile interconnection that happens when two different mobile operators interconnect with each other. For all cases, MTAS rates must be estimated according to cost-oriented and/or non cost-oriented methodologies. The most common non cost-oriented methodologies are forbearance, prices for termination are set based on commercial negotiations; international benchmarking, applied in the absence of cost based data, regulators rely on international benchmarking to set termination charges in their countries; and Bill and Keep (BAK) where no termination charge is defined, both operators find an agreement to eliminate it.

These non cost-oriented mechanisms present a set of drawbacks, e.g., in the forbearance case both operators need to reach an agreement to fix the termination charge, and in case of benchmarking, termination rate from foreign countries depends on their own market and framework, which differ dramatically from one country to another. The BAK methodology is an alternative to cost-oriented mechanism, it reduces administrative costs, increases productive efficiency because each operator has to support its own traffic and other operator's traffic without additional incomes and therefore operator focuses its efforts on reducing costs, and remove the strategic role played by termination rates. However, BAK has remarkable drawbacks: operators try to reduce the network usage by competitors, offering a lower quality or establishing lower prices for the off-net calls [18], [19]. In addition, it is an inefficient system due to the fact that operators tend to reduce the investment on network's capacity and updating.

Due to all these drawbacks, the European Commission and most of NRAs are adopting cost-oriented methodologies to calculate the termination rates [20], [21], [22]. Fixing fair interconnection prices pursues one main goal, economic efficiency. Economic efficiency is achieved from three different aspects such as: allocative efficiency requiring that resources, products and services are allocated to those who value them the most, implying end-users have to pay prices according to the cost of those products or service provision; productive efficiency, use of scare resources, such as spectrum, as productively as possible; and dynamic efficiency. Every operator should invest in improving, updating and turning their own networks into more technological efficient networks in order to reduce costs or to expand products offerings. In addition, promoting competition and achieving universal service are also defined as two important goals of regulation.

Setting fair interconnection prices should be based on the additional cost to the incumbent from providing interconnection services. However, the cost incurred for the provision of a service is based on two main factors, direct and indirect costs. Direct costs are related to the cost incurred for that specific service (fixed and volume-sensitive costs), indirect costs are defined as costs related to the production of a set of services and it is not easy to allocate these costs to a specific service. Indirect costs are classified into two different categories, joint costs in case costs caused by a set of services and common costs that are related to the general functioning of the operator. Operation and maintenance costs (OPEX), as well as capital expeditures (CAPEX, e.g., cost of network and office equipment [23]) also have to be taken into account.

Indirect costs, such as network equipment costs, represent a large fraction of the overall costs, and therefore, they are relevant in the termination rates estimation process. However, network equipment is used for the provision of several services at the same time, this is the reason why allocating indirect costs to a specific service is not an easy task. Solving this allocating indirect costs problem is addressed based on different cost accounting methodologies:

- Historical versus Current Cost Accounting: Historical costs (HCA) are based on the costs paid for the element when it was bought, that can differ from the value when the cost study is developed. To solve this problem, a depreciation factor is applied to estimate the current value of the element. This historical approach has three main drawbacks:
  - The evolution of the acquisition costs of assets is not taken into account.
  - Historical accounts cannot incorporate the impact of continuously evolving technologies or ensure that costs are those of an operator employing modern technologies.

  - It reflects all inefficiencies that results of past decisions of the operator [24].

Current cost accounting (CCA) takes into account current prices of the required elements to deploy the network, in case of any element no longer exists, the concept of *modern equivalent asset* is applied, that is the price of an equivalent existing element to the required one is considered. The impact of new technologies in network operations is simulated in the CCA methodology by the use of efficiency factors. This CCA scheme leads into lower rates than HCA.

- Top-down vs. bottom-up approach: The top-down approach starts from operators financial data and accounting systems, and uses this information to allocate costs to the services by means of cost allocation factors. On the other hand, the bottom-down approach starts from no existing financial data, it is based on user demand and subscribers input data to calculate an optimized and efficient network to allocate the cost of the production of services. Both approaches should lead to similar results, however the different initial assumptions considered in the process make difficult to achieve this aim. Several efforts has been made to meet a trade-off solution [25], [26], in fact both of them can be used as a cross-validation method to check the results given by the other approach. A more detailed information about these two approaches is given in the cost standards explanation.

- Cost standards: Based on the scope and type of costs considered in the accounting costs process, different methods for assessing the cost of individual services are defined. The most common standards [27], [28] are: Fully Distributed Cost (FDC), Activity-based Costing (AC) and Long Run Incremental Cost (LRIC).

  - **Fully Distributed Cost:** This approach is also know as *fully allocated cost* (FAC). It is based on the allocation of the overall costs of the network, volume-sensitive costs, direct fixed costs and a share of the joint and common costs, to the provision of each service defined in the profile. The proportion of joint and common costs allocated to each service implies the definition of different common cost pools and assignment factors. The assignment factor is defined as the contribution to the common costs of each service. This allocation follows an arbitrary process, and therefore it constitutes the main drawback of this scheme. Prices obtained using FDC could be non-optimized and non-stable prices, and reflect inefficiencies of the operator's network.
  - **Activity-based Costing:** Improved FDC cost model. Up to four different levels to allocate costs are defined, reducing, in this way, the arbitrariness caused by the FDC model. The first level corresponds to the indirect costs such as staff salaries, depreciation of network elements, etc. A second level corresponding to costs related to the activities required to generate services is defined. Network equipment costs are also considered in a third level definition, this costs are based on activity costs related to operation, organization, administration and maintenance. Finally, the fourth level corresponds to the services and is based on costs from the second level not allocated to network equipment costs and costs from level three. The relation between the levels is based on a set of different assignment factors. This method reduces the arbitrary process of allocation costs present in FDC model. However, it does not allow to estimate the incremental cost of a service, that is, it is no possible to figure out the reduction, in terms of costs, caused by not offering a specific service, due to the fact that FDC nor AC methodologies are able to distinguish between fixed and variable costs. This constitutes the main drawback of the AC method.

– **Long Run Incremental Cost:** It associates a long term horizon to incremental costs. These incremental costs measurement is directly related to the increasing or decreasing of the production output by a substantial and discrete increment. Due to the increment is substantial, capital and fixed costs, as well as volume-sensitive and directly attributable costs, are taken into consideration. All costs are considered as variables and the production capacity can be increased to satisfy the increased demand. An enhancement of this model is known under the name Forward Looking Long Run Incremental Cost, FL-LRIC, where the concept of forward looking stress the fact that we consider not just the current service demand but also its future development.

LRIC model presents a set of advantages in comparison to the FDC or AC models. Some of these advantages are: the investment in network equipment updating as the unique mechanism to increase the operator's revenue, the establishment of market competitiveness due to the use of current costs, and the allowance for unbundling operations, e.g., the separate provision of the individual components of a service instead of the provision of an integrated package. These advantages make the LRIC model to be the preferred one to be applied on regulatory process by most NRA [20], [21]. However, it has two main drawbacks, it does not take into account common costs, and traditional counting systems do not provide the information required by the LRIC model.

The European Commission, in its Recommendation 98/195/EC article 3 for interconnection costs, has recommended the use of LRIC. Two main approaches are defined in LRIC modeling, *bottom-up* and *top-down*.

Bottom-up Approach

Bottom-Up LRIC could be defined as the incurred cost associated to an hypothetic new operator to be able to supply the set of services defined in the profile of an already existing operator, applying the best available technologies.

The associated cost to each service is calculated from an optimized efficient network, this cost is the sum of the cost contribution of the network elements each service uses. Therefore, Bottom-Up LRIC implies difficulties related to the optimized design of the network, mainly in the radio access network structure where the most part of the investment in infrastructure is done in case of deploying a mobile network. To solve this problem, it is required designing network tools , that may turn, in some cases, into complete cost models [29]. Bottom-Up modeling has the following steps:

1. Services definition, number and location of customers, as well as user demand.
2. Design of the network facilities required to provide the services defined.
3. Estimation of the amount of each type of equipment required to deploy the network.
4. Cost estimation of each type of elements. Using the cost per type of unit to be installed, total cost associate to each type of network element is calculated.
5. Calculation of the annual amount of cost associated to each network element.
6. Annual operation and maintenance costs estimation.

7. Calculation of total costs for each network element as the sum of the amounts obtained in steps 5 and 6.
8. Divide the total cost estimated by a relevant cost-driver, e.g., number of minutes, to obtain a unit costs.

Top-down Approach

In this case, a designing network tool is not necessary. Top-down LRIC modeling starts from the operator's actual cost of the network, already deployed. This method does not require any network designing tool to estimate the cost of the services. The top-down LRIC estimation separates the operator's assets and costs into different service groups, and adds the costs associated to interconnection service. The process is summarized as follows:

1. Service identification and separation from interconnection service.
2. Assets and costs identification and separation based on operator's accounts.
3. In case a cost element or asset is associated to only one service, allocate it to that service.
4. Allocation of shared and common costs between services based on allocation rules.
5. Calculate LRIC for each service by adding the costs allocated to that services. An appropriate return on those assets allocated to the service has to be included.

Top-down LRIC model results might be inefficient, due to its starting point is an existing non-optimized network configuration and costs. Moreover, it is based on actual operating costs and historic capital costs, that are not forward-looking costs and therefore it is more difficult to take into account future changes in costs than in the bottom-up model.

1.3.1 LRIC Bottom-Up Approach

The long rung incremental cost model is the one defined by the European Commission as the most suitable cost model to apply in regulatory process [30]. In this section a mathematical description on the LRIC Bottom-Up (LRIC-BU) cost model is introduced.

A LRIC-BU model is based on the determination of the annualized capital expenditure on network equipment and facilities (CAPEX), and the operation and maintenance costs (OPEX). The first step is to estimate the annualized CAPEX, for this purpose the economic lifetime of the installed equipment is considered. Additional factors such as depreciation, together with the return of invested capital by the investors should be covered. Therefore the goal is to obtain annual amounts of amortization, or recovery of the invested capital, according to what is know as economic depreciation. This first approach to estimate annualized CAPEX is show in Equation 1.1.

$$I = A \cdot \left(\frac{1}{1+WACC} + \frac{1}{(1+WACC)^2} + \frac{1}{(1+WACC)^3} + \cdots + \frac{1}{(1+WACC)^n} \right) \tag{1.1}$$

where:

- I is the total investment in year 0.

- A is the annual amount of amortization.
- n is the number of years considered in the economic lifetime of the network element.

The return of the invested capital on equipment over their lifetime consists on the return on equity and the return on debt capital, therefore it is based on a wighted average of both factors, that is known as the "Weighted Average Cost of Capital" (WACC), see Equation 1.2.

$$WACC = \left(r_e \cdot \frac{E}{D+E}\right) + \left(r_d \cdot \frac{D}{D+E}\right) \tag{1.2}$$

The return on equity is estimated by means of the capital asset pricing model (CAPM) as indicated in Equation 1.3.

$$r_e = r_f + \beta \cdot (r_m - r_f) \tag{1.3}$$

where:

- r_f is the risk free interest rate, that is, the rate corresponding to $\beta = 0$.
- r_m is the equity market return, that is, the rate corresponding to $\beta = 1$.
- β is the company's equity beta.
- E is the equity capital.
- D is the debt capital.

Debt is commonly obtained through credits from banks, having a specific interest rate that has to be returned, this is known as return on debt, C_d. However, part of this interest rate can be deducted in many countries, this is defined by a tax-rate, T.

$$r_d = C_d \cdot (1 - T) \tag{1.4}$$

However, this method does not consider two important aspects on the economic lifetime of an asset, the growth in the equipment utilization and the variations in the asset's price. First, network equipment's grade of use depends directly on the volume of services, therefore for a partial period of time, network equipment is underutilized, making the most of the equipment as service volumes grow. Second, throughout the economic lifetime of the equipment, its price is subject to changes. Both variations have influence on future pricing estimations, and have to be taken into account in this study. These aspects are defined in Equation 1.5 by the average impact of the projected growth of services, g, and the average rate of variation of the price of the equipment during its lifetime, Δp.

$$\begin{aligned} I \;=\; & A \cdot \left(\frac{1}{1+WACC} + \frac{(1+\Delta p)\cdot(1+g)}{(1+WACC)^2} + \frac{((1+\Delta p)\cdot(1+g))^2}{(1+WACC)^3} + \cdots + \right. \\ & \left. \frac{((1+\Delta p)\cdot(1+g))^{n-1}}{(1+WACC)^n} \right) \end{aligned} \tag{1.5}$$

Based on Equation 1.5, the annual amortization is estimated as indicated in Equation 1.6.

$$\begin{aligned} A \;=\; & I \cdot \left[\left(\frac{1}{1+WACC} + \frac{(1+\Delta p)\cdot(1+g)}{(1+WACC)^2} + \frac{((1+\Delta p)\cdot(1+g))^2}{(1+WACC)^3} + \cdots + \right.\right. \\ & \left.\left. \frac{((1+\Delta p)\cdot(1+g))^{n-1}}{(1+WACC)^n} \right) \right]^{-1} \end{aligned} \tag{1.6}$$

The second step is to determine the value corresponding to OPEX. In LRIC-BU, it is common to estimate these costs as a percentage mark-up of the investment value of the network elements expressed in current prices.

The total cost of providing the services considered and running the whole network is obtained by means of adding up the CAPEX and OPEX values, together with a set of parameters indicating the intensity of use of each network element, known as routing factors. The routing factors indicates the number of times each network element is used when providing a specific service. Dividing the cost derived of providing the service by the number of units delivered, e.g., minutes of calling, kbps, etc., the unitary cost of the service is estimated. LRIC-BU models, as explained in the previous section, do not consider the common organizational costs, this can be defined as mark-up of the total cost, and added to the process.

One of the objectives of the NRAs is the establishment of a competitive market and to adequate the mobile charges. Special attention is required to the interconnection between operators or termination charges (MTAS). Interconnection is focused on off-net calls, there are two main possibilities when an off-net call occurs. On the one hand, the call is delivered to the MSC to which the BTS serving the user that receives the call, it corresponds to the termination option B in Figure 1.12. In this case, the network elements are: BTS, link between BTS and BSC, BSC, link between the BSC and MSC, the MSC and the Home Location Register (HLR) is used once. On the other hand, the call is delivered to a different MSC to that serving the user that receives the call, termination option A in Figure 1.12. In this case, apart from the network elements considered in the previous case, it is necessary to consider the cost of the second MSC and the link between both MSCs. The cost estimated to each case is then weighted based on the probability of happening of each case, obtaining a unique MTAS cost.

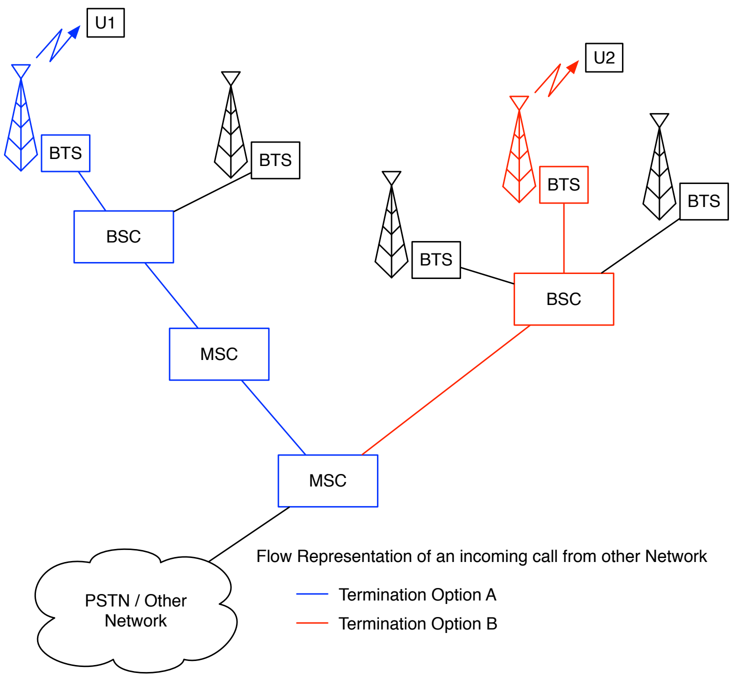


Figure 1.12: Network equipment utilization for terminating a call into other operator's network.

Chapter 2

State of the art, materials and methods

In this chapter, several studies and previous works that have motivated the present doctoral thesis are described. It is divided into four different sections: an introduction of several strategic and operational tools based on simulators carrying out capacity and coverage analysis is given in the first section. The second section describes the multiple propagation and capacity models that can be used by a network dimensioning process, together with the definition of the services and their characteristic parameters. A description of the evolutionary computation methods, together with their application to telecommunications, is found in the third section. Finally, the objectives and the structure of the rest of the work is presented at the end of the chapter.

2.1 Strategic and Operational Software Tools

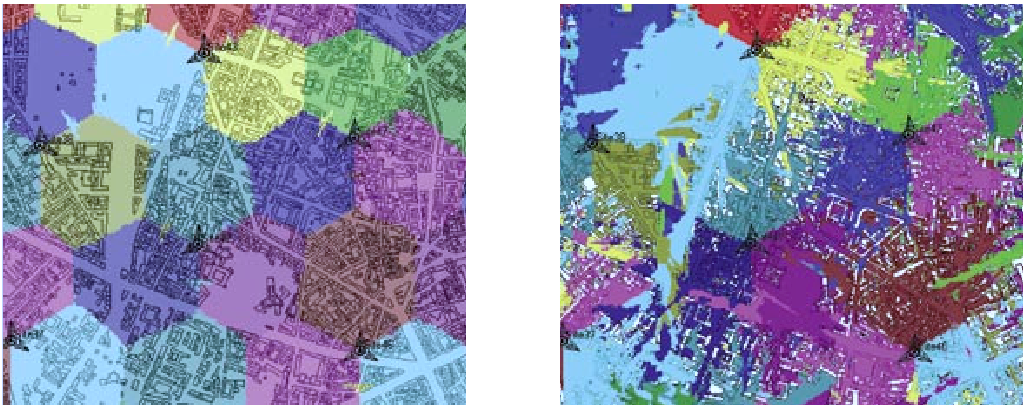
Strategic planning is one of the key factors to ensure the correct function and the success of a mobile communication network. The strategic planning process is divided into there main phases:

- Strategic network dimensioning and design.
- Detailed planning and implementation.
- Network operation and optimization.

The network deployment process is the first step that operators have to face when supplying a set of services to their customers. An optimal network deployment, fulfilling the real world constraints, determines the success of each network operator in the market. Strategic and operative software tools for designing, planning, and optimizing wireless access networks provide capabilities to save time and money during the network deployment phase, and can be used in all phases of a radio network's lifecycle.

The detailed planning phase is the most critical phase of a network deployment, due to it is based on propagation and capacity studies. One of the problems of the propagation part is that it requires the employment of complex and precise propagation methods. These methods are based on ray tracing and diffraction theory. To solve this point, software tools such as Wavesight by Wavecall Corportation are considered [31]. Wavesight is based on propagation studies carried out in the Laussanne Technological Institute, and collaborations in projects with companies such as Swisscom, KPN and Bell Laboratories.

Wavesight tool provides coverage analysis, giving information about the total received power for every point in the area under study. Figure 2.1 shows the different results obtained by the application of a classical model and the results provided by the UTD (Unified Theory of Diffraction) ray tracing and 3D building databases of Wavesight. The application of the Wavesight tool provides more precise network coverage information for macro and micro-cell layers than the empirical models, due to it allows to simulate propagation effects such as canyon effects and shadowing areas.



(a) (b)

Figure 2.1: Wavesight propagation results provide by: (a) Classical model; (b) UTD ray tracing

Source: Wavecall Corporation. http://www.wavecall.com/accurate.php

However, these type of diffraction and ray modeling methods require a large set of input data. In [32], a relation between the number of input data and the accuracy of the model is shown. These methods' performance depends on the accuracy of the geographical data base, registers included in the data base must contain information about the location, width and height of the buildings, together with information about the materials of the buildings affecting to the ray refractions. One example of this dependance on the accuracy of the data is the fact that a deviation below 1 meter in the position of the 95% of the buildings implies a 1 $d\beta$ error in the results.

Alternatives to solve this problem are given by simulation software tools. Simulations tools have been applied to the detailed planning, the network operation and the optimization phases. These tools are classified in two different categories:

- Dynamic Simulators. These kind of simulators analyze the temporal evolution of the system.

- Static Simulators. Analyze a specific temporal point of the system. Carrying out analysis of multiple temporal points of the system, stats related to the performance of the system are obtained. Monte Carlo models are one example of these kind of simulators.

In [33], a dynamic simulator capable of managing hierarchical cell structures is introduced. In this case, there are two different layers of cells, macro-cell and micro-cell layers, and traffic overflowing between them is allowed. This simulator provides information about blocking and dropping probabilities, as well as the handoff rate and total capacity of the system. Input data related to the handset such as call rate, average connection time, probability of active connection, as well as base station related data, e.g., location, transmission power and distance between base stations are considered to obtain the results. It is observed that the use of a hierarchical cell structure improves the performance of the network in comparison to traditional network structures, however the study is performed on a single service profile, only voice is considered.

NetSim [34] is a second example of simulators applied to cellular planning. This simulator has been developed in the Technological University of Helsinki. It provides information related to network control (handover, power control, admission control), coverage and capacity of the system. NetSim's main objective is to establish a relationship between link layer simulators such as COSSAP, that analyze signal processing aspects, and high-level network simulators analyzing the whole system, like OPNET and BONES. NetSim uses a deterministic propagation model for microcellular urban environment based on ray tracing methods. The main blocks of NetSim can be logicaly divided into four main models:

- Reference scenario. It provides information about the location of the mobile stations, velocity and activated service type data. It is compounded by users and teletraffic models.
  - Users model. It generates information about users' location and velocities.
  - Teletraffic model. Related to voice service simulation control and traffic channels behavior taking into account voice activity detection. An Internet data transmission model is also provided.
- Propagation module. Based on the ray tracing model, it estimates the received signal of every mobile station in the system.
- Signal Processing module. It provides information related to the post-processing signal to interference ratio, SIR, for each link. It is compounded by:
  - Antenna model. It is in charge of simulating different antenna configurations such as omnidirectional antennas, distributed antennas, switched beam systems, etc.
  - RAKE receiver and interference model. It estimates the SIR after despreading and combining all received signals. Combining can be done either by maximal ratio combining or selection combining.
- Radio Network Control module. It is in charge of power control, admission and handover control algorithms.

Simulations developed in the article provides details about the number of handsets and call attempts, obtaining the number of blocked and discarded connections due to low quality signal. NetSim result provides information about the maximum cell range based on the capacity of the system and the coverage analysis, which is based on the ray-tracing propagation model. However, NetSim requires a large set of input data to provide the results, and it is based on a single service scenario, only voice is considered, although it is supposed to manage a multi-service profile in future.

A static simulator is developed in [35]. Authors of this simulator are worldwide known due to their large research experience, see [36] and [2], and their professional careers in Nokia. It is a MATLAB based static simulator capable of performing coverage and capacity analysis, as well as quality of service related issuers. It consists of four main parts:

- Initialization. Simulation parameters are configured in this phase. It is split into two process, the first one reads the input data such as handset information parameters, base station parameters, traffic distribution and geographical area where the network deployment is going to be performed, etc. The second process estimates the link budget for every position considered in the area under study. Okumura-Hata model is the one selected in the article, but it allows the application of any kind of propagation model imported from other tools.

- Uplink processing. Estimation of the handset transmission power that fulfills the cell interference and base station sensitivity requirements. Parameters such as soft handover gain, power control checking and service characteristics are taken into account when carrying out the transmission power that meets the E_b/N_0 requirements. Once the transmission power is calculated, handsets are allocated to the base station based on a best server process, that is, the handset is allocated to the base station that minimizes the handset transmission power.

- Downlink processing. Estimation of the base station transmission power for each of the handsets in a way that meets the carrier to interference (C/I) ratio. Parameters such as soft-handover gain, service data rate and orthogonality factor are taken into account.

- Postprocessing. Results generation providing best server maps for the downlink and uplink directions, traffic load in the uplink, soft-handover areas and other results. All the results are also expressed in tables and histograms, the simulator also provides uplink coverage of a specific handset.

A study on a 57 homogeneous distributed cells network is carried out in the article to show the perform of the simulator. Up to 1500 voice user, as well as 30 data users (144 Kbps) hot spots are considered. Finally, and in order to compare the performance of this static simulator and a dynamic simulator, both of them are applied to the area of Helsinki. Similar results in terms of coverage area, power distribution, cell load factor and number of links, are obtained and therefore the static simulator is accepted as a feasible solution to carry out the network planning.

Verification of the static simulator is carried out comparing its results to a dynamic simulator results in [37]. It is based on simulations in the area of Helsinki, call generation is based on a Poisson process. Total cell loading, transmission power distribution in the uplink and downlink, coverage area for each cell, soft handover areas, soft handover probabilities, blocking and dropping calls are the main results to compare between the dynamic and the static simulators. The conclusion of the study is that the results for both dynamic and static simulators are quite similar, mainly results related to uplink and downlink power distributions, cell loading levels and supported links per cell. Despite the fact that the static simulator is considered a valid approach to perform the planning of the network, the dynamic simulator however is suitable for benchmarking of radio resources management algorithms and for analyzing dynamic features in the networks and not for planning.

In line with the simulators explained previously, it is found [38]. This PhD. Thesis received the Nokia Award to the best Phd. Thesis in Mobile Internet and 3^{rd} generation mobile systems in 2002. The main contributions of this thesis are:

- Urban environment fading model proposal.

- Definition of a traffic model based on tele services and bearer services for both circuit and packet switching.
- WCDMA power control capacity model. Development of algorithms which perform the uplink and downlink power control. Additionally, a description about power control equations in multiple service environments is introduced.
- Development of an algorithm for solving the user allocation problem, and its corresponding transmission power, within a cell.
- Static simulator definition to perform WCDMA capacity analysis. It is described as a static simulator using as input data the obtained results from the 3GPP link level simulations.

Simulations carried out in [38] are based on degradation probability. A large set of possible static configurations of the system based on the E_b/N_0 of every service considered is generated. The algorithms check the existence of a feasible solution for the users allocation to each base station, estimating the corresponding transmission power. The key point is the system degradation, that is, to meet the QoS requirements of all users in the system. In case no combination of transmission power is feasible, the system is supposed to be momentary blocked. Due to it is a static simulator, a large set of simulations has to be done to obtain relevant results. The set of parameters that makes the system degradation to be below a specific threshold is defined as the capacity region. This threshold is defined in such a way that every user QoS is fulfilled, and therefore it establishes the capacity of the system.

Simulation results provide also the transmission power, loading factors and handover user locations. These are useful parameters to study the performance of the network, it allows to determine the intercell distance where the system goes from being capacity driven to coverage driven.

Another contribution is found in [39] by S. Hurley, where a method to develop network planning in a specific area is introduced. The process followed to obtain the results is based on a square points network definition, named as test points, assigning to each of them a set of relevant information such as propagation loss, users traffic demand and QoS requirements. In addition, the model needs information about the candidate points to install the base stations, existing network structure information, and the definition of the available types of antenna with the radiation patterns. All this information is used as input data to a software tool, DESNET, that provides coverage geographical maps, as well as the total number and location of the base stations, services thresholds and capacity in Erlangs.

In line with this the work presented in [39], it is found the studies developed by Telefónica R+D in collaboration with Telefónica Spain. In [40], the structure and implementation of a software UMTS planning tool, UMTS Radio Access Network Optimization (URANO), is introduced. It has two main functions. First, it helps in network planning tasks, and second, it offers the possibility of optimizing existing networks. The process followed to perform the network planning is the following:

- Traffic demand estimation for each of the services defined, obtaining the corresponding traffic maps.
- Estimation of the number of required sites based on capacity and coverage studies.

- Location of the sites estimated, based on the cell range and additional factors such as street features and buildings.

- Coverage calculation. It make use of propagation models used in external applications such as DIRAC and MICENAS, the coverage of each cell, as well as the shadowing areas, are estimated.

- Monte Carlo simulations. The main objective of this last step is to evaluate the network performance.

The results provided by URANO are, among others, handset transmission power for each of the services, best server maps, that is, maps with the best base station available for users allocation in a specific area, handover maps, etc.

Apart from these tools and methods, there are four main commercial network planning tools. These commercial tools are mainly operational planning tools and are ASSET by Aircom, ATOLL by Forsk, PLANET by Mentum and WinProp by AWE Communications. In the following paragraphs a brief description about their features and methods is given.

WinProp is a wireless propagation and radio network planning software developed by AWE Communications [41]. It provides tools to simulate and plan 2.5G, 3G and beyond 3G networks, static network planning modules, as well as dynamic network simulators to help engineers to perform their daily work of designing and optimizing wireless networks, are provided. WinProp defines multiple propagation scenarios, urban, suburban, rural, indoor and tunnel, that are applied to either empirical propagation models or ray-optical/deterministic models. The Dominant Path Model and the fast 3D Ray Tracing models (IRT) are also available.

On the one hand, from a network planning point of view, coverage plots, best server predictions, reception probability and SINR maps, mobile station and base station transmission power estimations, neighbor cell list as well as the capacity are determined. Additionally, the electromagnetic compatibility such as environmental aspects and health issues, due to the superposition of multiple carriers can be analyzed. On the other hand, WinProp offers dynamic system simulators for 3G, including HSDPA, cellular networks. These simulators provides algorithms to analyze the QoS, blocking and dropping probability for packet switched services, as well as different radio resource management algorithms.

ASSET is a planning and operational software tool developed by Aircom company [42]. It provides multiple modules to plan and optimize multi-technology networks such as GSM/EDGE, AMPS, TDMA, TACS, PCS, UMTS, HSDPA, HSUPA, HSPA+, LTE, etc. The tool includes a geographic information system, GIS, providing a comprehensive set of display and layering functionality including the ability to display Web Maps and to edit cell parameters directly from the GIS. It performs capacity analysis based on traffic forecasting and includes a set of empirical and deterministic propagation models, as well as the option to add 3^{rd} party propagation models form providers such as Siradel, Wavecall and AWE Communications. Additionally, multiple productivity packs, such as an automatic cell planning module, ACP, a propagation model valid for all type of cells from micro to macro-cells, type of environments, technologies and a frequency range from 400 MHz to 5 GHz, MYRIAD, an automatic frequency planner to perform interference analysis, a financial analysis module, etc., are implemented to enhance the performance of the tool.

ATOLL is a multi-technology planning and optimization platform which includes GSM/UMTS/LTE and CDMA/LTE traffic models, Monte Carlo simulators and an ACP module. It allows to model traffic-related aspects of multi-technology networks and dynamically spread and offload traffic between them. It is a GIS oriented tool providing a high-performance built-in geographic information system designed for radio network planning and optimization, it supports GIS tools such as MapInfo, ArcView, Google Earth, as well as Web Map Services and online maps, e.g., Google, Bing, etc. It is composed by different modules, one per mobile generation.

- Second generation module is in charge of performing the modeling of GSM, GPRS and EDGE, it supports dual-band and hierarchical cell structure (HCS), frequency hopping, discontinuous transmission (DTX) and adaptive multi-rate (AMR). It performs uplink and downlink coverage analysis, interference, handover and QoS analysis, as well as neighboring planning. In terms of traffic analysis, it allows to spread traffic between cell layers with traffic overflow modeling, cell dimensioning for mixed voice and data traffic and timeslot configurations.

- Third generation, UMTS and HSPA, module supports multiple carriers and frequency bands, advanced bearer and service modeling, HSPA and HSPA+ modeling, multi-carrier and dual-band HSPA planning, as well as VoIP. It also allows traffic modeling, including user equipment, user profiles and environment types.

- Finally, LTE module supports multiple input multiple output, MIMO, antenna configurations, modeling of voice and data service with different channel quality indicators, CQIs, and different user equipment categories. Simulation and analysis are based on a LTE Monte Carlo simulator including power control and advanced radio resources management and scheduling algorithms.

Mentum Planet is a multiRAN planning, operational and optimization wireless network tool. It supports most of the commercially deployed wireless standards, GSM, GRPS, EDGE, WCDMA, HSPA, HSPA+, LTE, Wi-Fi, WiMAX, etc. Advance GIS capabilities are also provided by the tool, it includes the MapInfo Professiona GIS desktop system, offering the possibility of producing professional-grade maps as layered PDFs. The main functionalities of the tool are strategic network planning, wireless network design, network optimization and network management. It contains multiple technology modules, GSM/GPRS/EDGE, WCDMA/HSPA and LTE modules are among them.

- Second generation technology module offers the possibility of planning, designing and optimizing GSM/GPRS/EDGE networks, it supports voice and data services, multi-band and multi-technology deployment. it provides methods to plan and design GSM network expansion for coverage and capacity, deploy GPRS/EDGE and manage network capacity for voice and data services, frequency planning, and refarming activities for the deployment of 3G/4G networks.

- WCDMA/HSPA technology module offers operators a solution to roll out a new 3G network or migrating its existing 2G to a 3G network. It supports also third generation enhancement technologies, HSDPA (3GPP Release 5), HSPA (3GPP Release 6), and HSPA+ (3GPP Release 7 and 8). It provides methods to plan and design 3G networks analyzing coverage and capacity, deploy mobile broadband service using HSPA/HSPA+, manage spectrum refarming, optimize network capacity, coverage and quality.

- LTE technology module provides methods to overlay 4G LTE network on an existing 2G and 3G network, evaluate LTE capacity by means of a Monte Carlo simulator based on throughput and data rate negotiation according to QoS classes and priorities, coverage analysis, spectrum refarming, evaluate several strategic options such as MIMO configurations, multi-band and multi-carrier deployment. It supports LTE (3GPP Release 8 to 10).

Mentum Company provides another wireless network designing tool, it is called Mentum CellPlanner [43], also know as TEMS. It is developed in close collaboration with Ericsson, and it offers complete planning and optimization capabilities. It contains methods for network dimensioning, traffic planning, site configuration, frequency and code planning, and automatic cell planning (ACP). It is compatible with the traffic and network configuration data, and it provides several propagation models, slope-based models such as 9999 model, COST-231 Walfisch-Ikegami RF model, Okumura-Hata model, etc., and traffic management capabilities based on bearers, services and terminals traffic definition and demographic data as input to traffic maps.

The objective of the different software tool and methods detailed previously is to perform the network planning, optimization and maintenance tasks. The main advantage of these methods is they provide accurate results in terms of coverage areas and cell loading or capacity. However, all of them need a large data base containing precise data information about aspects such as topography, demography, type of environment where the study is going to be performed, location and type of obstacles including the type of material, the height of the obstacle, streets width, etc. Moreover, the presented tools focus its studies on regional areas within a country, and it takes long computing time to obtain the results for a specific region. The main objective of the software tool developed in this thesis is to provide a nationwide mobile network dimensioning tool, based on the Cost231 propagation model and capacity models, with a shorter data base as compared with the existing tools, and to reduce the computing time to obtain precise results for the mobile radio access network dimensioning process.

2.2 Network Cellular Planning

As described, one of the main phases in mobile networks planning process corresponds to the strategic planning or network dimensioning process. This process encompasses several functions such as the technology selection, coverage strategies and requirements for every services considered, network configuration and dimensioning, and investment cost evaluation.

The starting point of the dimensioning process, is the technology selection. Later on, the type of area, urban, suburban or rural, where the network is going to be deployed, the type of subscribers, the offered services, as well as the temporal framework of the technology, that is, deploying a mature or novel technology, and its possibilities of updating and evolving to future networks, constitutes a critical point in the strategic planning process.

The next phase is the configuration and dimension of the network. Independently of the technology selected in the previous phase of the process, this point is based on two main aspects, coverage and capacity analysis.

2.2.1 Coverage planning

The coverage analysis, that is, the estimation of the cell range due to the propagation constraints of the environment, is tackled by the use of several propagation models. A simple classification of models is done based on the features of each model. Propagation models based on measurements are classified as empirical models, e.g., Okumura's and Hata's model. A second group of models are those based on physical laws, in which it is necessary to distinguish between models with and without empirical corrections, semi-empirical models and deterministic models, respectively. Walfisch and Ikegami model is classified as a semi-empirical model, and Friss model is a deterministic model.

Okumura-Hata model is based on an extensive series of measurements made in the city of Tokyo, measurements were made in the frequency range from 200 MHz to 2 GHz. Initially, the model is only valid for a frequency range from 200 MHz to 1500 MHz, M. Hata developed, see [44], the first extension of the model. Okumura-Hata's predictions are collected in a set of graphical results, the most important of which have been mathematically approximated by [44]. It is the most widely used propagation model, and in occasions used to cross check the results of new propagation models. Urban values in the model have been standardized for international use in [45]. The method distinguishes between a series of clutter and terrain categories, urban, suburban and open areas. Urban category is taken as reference, suburban and open areas results are obtained by mean of applying correction factors to the reference urban equations. Okumura-Hata model has the following constraints, frequency range from 150 MHz to 1500 MHz, base station height, defined as the height above ground level in the range 3-10 Km from the base station, between 30 and 200 meters, mobile station height shorter than 10 meters. Later on, the model is extended by the COST 231 project to cover the frequency range from 1500 MHz to 2000 MHz, see [46], [47].

Okumura model and its extensions is not the only model available to carry out coverage analysis. An additional model is the developed by Walfisch and Bertoni, see [48], [49], [50]. It is a more sophisticated model and takes into account additional factors in comparison to the Hata model, such as the height of the buildings and the influence of the building roofs. Losses are calculated like the product of isotropic antenna free space losses, noise factor due to the buildings and the existing losses between the building roof and the street, this model is based on the diffraction theory. Topography is also considered, however the type of terrain is not taken into consideration.

Ikegami model attempts to predict field strengths at specific points [51]. This model is based on rays geometric theory, it takes into account parameters such as building heights, shapes and positions. Based on these factors, ray paths between the transmitter and the receiver are estimated, considering only single reflections from walls. Diffraction is calculated using a single edge approximation at the nearest building to the mobile device. Note that this model considers that the wall reflection loss is constant.

The last two models have been combined into one model know as COST 231 Walfisch-Ikegami model [47]. It mixes the estimation of the settled field of Walfisch-Bertoni model with the estimation of diffraction down to street level of Ikegami model, and includes a set of empirical corrections factors. The model takes into account the width of the streets and their orientation. It is applicable for 800 MHz to 2000 MHz, heights of base stations between 4 and 50 meters, and mobile stations heights shorter than 3 meters.

Longley-Rice propagation model is also valid for developing coverage analysis. This method is applicable for the frequency range 20 MHz - 40 GHz, antenna heights in the range 0.5 - 3000 meters and for distances up to 2000 Km. The median loss is calculated based on two-ray theory and extrapolated diffraction attenuation for radio line-of-sight paths. For trans-horizon systems either diffraction or forward scatter attenuation is used. Longley-Rice model does not consider any correction factor to take into account building losses, weather conditions or multi path propagation, see [52], [53].

In addition to these models, there are various studies solving the problem of carrying out the attenuation exponent related to the distance. Most of these studies are based on measurements at specific frequency carriers and indoor or urban areas, and therefore their application is restricted to this propagation environments. The macrocell's PCS model, [54], attempts to figure out the attenuation factor based on measurements for 1900 MHz, and assuming omnidirectional antennas. Two possible cases are considered, line of sight case (LOS) when no obstacles are present between the transmitter and receiver, in this case the two ray model is used to estimate the attenuation factor, and obstructed case (OBS) where obstacles are in the path, the logarithmic model is used. In [55], a wide study on different indoor propagation models, as well as the attenuation factor estimation process is explained.

2.2.2 Capacity planning

The second step of the network dimensioning process is the capacity estimation of the system. The process followed to obtain the capacity depends on the type of technology considered. However, one parameter that is used in every technology is the offered traffic, that is, the traffic generated by the subscribers. The main difference is found in the type of system under study, on the one hand, hard-blocking systems are those whose capacity depends directly on the amount of hardware installed in the base station, such as GSM. On the other hand, there are systems whose capacity depends on the interference generated by the users in the own cell and in neighboring cells, these systems are known as soft-blocking systems, an example of this kind of systems is W-CDMA systems such as UMTS or HSPA.

Second generation TDMA based networks, such as GSM, are hard-blocking systems, that is, the capacity of the system depends directly on the amount of hardware installed, and therefore the coverage influence in the final solution is higher than the capacity influence. Due to this fact, 2G system planning processes are mainly focused on the coverage analysis, setting aside the capacity study. However, the capacity study is also needed, specially in urban areas where cells are, normally, capacity driven due to the high number of subscribers and therefore a large amount of traffic demand. Capacity estimation in these kind of systems is based on the employment of the first Erlang equation, also know as Erlang-B equation. Parameters such as user demand, number of connections, blocking probability or grade of service (GoS), are taken into consideration when developing capacity studies related to 2G systems. The number of connections depends on the bandwidth available and on the reuse pattern concept.

However, in 3G systems, such as UMTS or HSPA, capacity importance increases due to the interrelation existing between coverage and capacity in the final cell range estimation. Soft-blocking systems, the final cell range is determined not only by the amount of hardware installed in the base station but by the maximum interference level allowed in a cell. A wide set of studies about capacity estimation in these kind of systems have been developed to improve the planning network process.

A first approach is found in [56], where the direct sequence wideband spectrum modulation fundamentals are detailed. The article settles the principles on:

- Single CDMA cell capacity estimation. System capacity equations, as well as a mathematical expression for estimating the maximum number of users inside a cell are defined.
- Sectoring and voice activity factor. In this part of the article sectoring and voice activity factor detection are described as two methods to improve the cell capacity. Sectoring increases the capacity of the cell almost as many times as sectors have the base station. The second option to increase capacity is the detection of the voice activity factor, in the article this parameter is defined as 0.375, and it duplicates the system capacity.
- Power checking. Power checking is one of the most relevant factors affecting capacity in WCDMA systems. The article provides detailed equations to calculate the power limits and the way it affects the capacity for both, uplink and downlink, directions in multicellular environments.

Finally, a comparison between CDMA and FDMA is made. IS-95 system with a bandwidth of 1.25 MHz and voice service at 8 Kbps is used. In case of the FDMA system and a reuse factor of 1/7, the maximum number of users per cell is 6, and for the CDMA system is 108 users. In case of TDMA, standardized 30 KHz channels are used, the gain is 6 times the number of users.

Capacity analysis are commonly focused on the downlink, uplink is generally limited by propagation constraints, due to the low transmission power of mobile devices. In the downlink, the transmission power is shared among all the users inside a cell, and this power limitation could cause a reduction in the capacity of the cell due to the interrelation between capacity and coverage. In [57] and [58], downlink load equations are detailed.

In [59], the downlink capacity problem in a multi service environment is analyzed. The article establishes a relation between the cell to interference ratio, C/I, received in the handset, and the base station transmitted power. The total cell capacity, in Kbps, is estimated considering the maximum number of allowed users for each of the services defined in each of the combination of services. The scenario defined for the experiments is based on four services, voice and long constrained data at 64, 144 and 384 Kbps. The different combinations of these services lead to a variable throughput in the range from 557 Kbps to 1104 Kbps. A Okumura-Hata based propagation model is also described in this article.

All the methods commented are valid for a one-cell system, however it is interesting to study the behavior of the capacity in a multicellular system, close to real world configuration networks. There are few studies focused on multicellular systems. Multicellular systems capacity is affected by the inter-cell interference concept, that constitute one of the key factors in WCDMA networks dimensioning. While intra-cell interference is caused by the traffic distribution inside the own cell, inter-cell interference is caused by neighboring cells and it affects directly to the total capacity of the cell and therefore to the coverage area. It depends on the propagation environment, the base station's location and the traffic distribution. Inter-cell interference is a complex determination parameter, and average values (0.6 - 0.75) are applied to the cell capacity dimensioning process.

However, there are several researching works on intercell interference that attempts to obtain an analytical estimation of this parameter. A first approach is developed in [60], in this study a reuse frequency model is applied to urban square cellular structures. The application of this model to WCDMA system is explained in [61] and [62]. Interference study in these articles is based on a four steps process: traffic redistribution, traffic decomposition, partial evaluation and final evaluation. The frequency reuse efficiency is defined as the capacity reduction of a multiple cell system as compared to a one-cell system, and can be estimated for a given cell. The starting point is a concentric cells structure from a specific cell j, traffic of cells in tiers surrounding cell j, is redistributed around this cell within the corresponding tier, in such a way that j cell becomes the central cell of the system. There is an additional constraint, the total sum of traffic of each tier must keep constant. Later on, a traffic decomposition process, where traffic density for each cell is estimated, is carried out. The partial evaluation process is in charge of carrying out the partial frequency reuse efficiencies for cell j, due to each cell in surrounding tiers. Finally, the final evaluation process estimates the final reuse efficiency of cell j as a function of the partial intercell interference values calculated in the previous step.

The main constraint of these studies is the two dimensions estimation process. In [63], an enhancement method is introduced. In this article, a way to reduce the two dimensional process to only one dimension is detailed, it approximates each of the tiers surrounding the central cell to an equivalent cell. This way makes the model easier to implement.

Another enhancement of the model is introduced in [64], where any traffic distribution is allowed and the location of the cells is not restricted to the typical concentric structure, in this case cells can be located anywhere, overlapping is also considered. This last enhancement approximates the model to real world conditions.

3G WCDMA capacity cell planning studies are also carried in [65]. In this work, a set of linear equations to analyze multicellular systems, including power control checking, is presented. One of the remarkable conclusions of the article is the estimation of the number of necessary cells to analyze the system interference based on the total cell loading factor. Results are valid for an omnidirectional antenna and voice service oriented scenario.

HSPA is the first technology thought to provide mobile broadband access service, mainly internet based applications such as video streaming, online gaming, etc., are offered to the end user. This kind of applications generate an asymmetric traffic distribution, the uplink traffic volume is shorter, in a factor of 0.3 [66], than the traffic volume in the downlink. Due to this reason, most of the efforts related to HSPA capacity dimensioning process are focused on the downlink. In [67] an analytical method for the HSDPA dimensioning is introduced. The method presented in this work is a statistical based method, it determines the maximum cell range in such a way that the probability of outage at the worst location of the cell is below a threshold. The probability of outage is based on the signal to interference plus noise ratio, therefore the cell range is set by the minimum SINR value required by a user in the word location of the cell.

In [68], HSPA capacity, as well as coverage, dimensioning is studied. In this case a C++ simulator is implemented to analyze downlink and uplink capacity for HSPA technology. Single and multiple user scenarios are considered. The capacity simulation process is based on coverage results. A set of different services is defined, each of them characterized by specific throughputs, minimum and maximum throughput per service. Coverage area of a cell is calculated after Cost231 Walfisch propagation model, and the number of potential users within the cell is estimated. The simulator evaluates the maximum throughput that can be offered to any of the users within the cell, depending on its location and the SINR parameter. Only those users whose demanded throughput for each of the services considered is below the throughput offered by the base station depending on its location are accepted. Once the set of users accepted is obtained, the cell range is estimated as the average distance to the base station of the users, and the total throughput per base station is calculated. Three different reduction methods, in case the maximum throughput of the cell is shorter than the demanded throughput by the subscribers, are implemented.

LTE capacity dimensioning process is based on two different approaches, a traffic volume based dimensioning method, and a data rate based dimensioning method. In both cases, the cell capacity is the key factor when obtaining the total number of subscribers. In [69] the description about the process of both approaches is given.

- The traffic volume based method obtains the cell capacity based on the spectral efficiency of LTE technology and the available bandwidth. Later on, the total capacity per month of the site under study, depending on the number of sectors, on the busy hour average loading and on the days per month taken into account, is calculated. Finally, the total number of subscribers is estimated according to the total capacity per month and the traffic per user in bytes.
- The data rate based method, estimates the number of subscribers according to the minimum or guaranteed required user data rate. The cell capacity in Mbps is obtained based on simulation results, and making use of these both values, cell capacity and required user data rate at the cell edge, as well as the number of sectors and a new factor known as overbooking factor, it reduces the number of subscribers downloading data at the same time, the total number of subscribers is estimated.

However, there are additional approaches to estimates the network capacity of a LTE system. In [70], LTE capacity planning is based on the coverage analysis, once the cell size and site count is obtained from propagation studies, a verification process is performed. The verification process is based on checking whether with the given site density, the system is capable to carry the total traffic load defined as input. In case the system has not enough capacity, additional base stations are added until fulfill the previous condition. In order to carry out this verification, the average cell throughput is obtained by means of simulations. In this work capacity estimation is done from the following simulations results:

- Average SINR distribution table (system level result).
- Average throughput or spectral efficiency versus average SINR table (link level results).

In this thesis, capacity planning is done separately for each of the areas within a district (urban, suburban and rural), due to the different values taken by multiple propagation and capacity input parameters. The corresponding traffic in the busy hour, that is the most restrictive case, is considered to carry out the dimensioning process, together with the percentage channel loading and an additional parameter, known as overbooking factor (OBF).

2.2.3 Service Description

In this section a service description is introduced. Two approaches for defining the services is given, the first one describes the services categories, traffic class with the corresponding QoS, and the second one gives information about second generation and third generation bearer services and their correlation with the service categories.

2.2.3.1 Service category description

Services can be described at different levels: a high level description and a low level description. The high level description corresponds to the end user service concept as the final application, these applications are grouped into multiple categories. The low level description is related to the physical categories, from which the network dimensioning is performed. In this section a description about the high level description of the services considered is introduced.

The services defined in this thesis are in line with the results of the studies developed by the UMTS-Forum. Table 2.1 shows the services categories defined by the UMTS-Forum.

Service Category	Service Description (Original text from the study)	Market Segment
Mobile Intranet / Extranet Access	A business 3G service that provides secure mobile access to corporate Local Area Networks (LANs), Virtual Private Networkds (VPNs), and the Internet	Business
Customized Infotainment	A consumer 3G service that provides device-independent access to personalized content anywhere, anytime via structured-access mechanisms based on mobile portals	Consumer
Multimedia Messaging Service (MMS)	A consumer or business 3G service that offers non-real-time, multimedia messaging with always-on-capabilities allowing the provision of instant messaging. Targeted at closed user groups that can be services provider- or user-defined. MMS also includes machine-to-machine telemetry services	Consumer
Mobile Internet Access	A 3G service that offers mobile access to full fixed ISP services with near-wireline transmission quality and functionality. It includes full Web access to the Internet as well as file transfer, email, and streaming video/audio capability	Consumer
Simple Voice and Rich Voice	A 3G service that is real-time and two-way. Simple Voice provides traditional voice services including mobile voice features (such as operator services, directory assistance and roaming). Rich Voice provides advanced voice capabilities (such as voice over IP (VoIP), voice-activated net access, Web-initiated voice calls, mobile videophone and voice enriched with multimedia communications	Consumer and Business

Table 2.1: Service categories description in the UMTS-Forum study

The UMTS-Forum service study, for each of the service categories in Table 2.1, defines the following characteristics:

- Monthly number of connections per service.
- Source and destination contribution per service: mobile-to-mobile (M2M), mobile-to-fixed (M2F), and fixed-to-mobile (F2M).
- Uplink-downlink ratio.
- File size (Kbytes) for both, uplink and downlink.

- Busy hour traffic percentage.

This UMTS-Forum services description is taken as the starting point by the network deployment module implemented in this thesis. However, few modifications in order to make this classification compatible to the actual applications, as well as a traffic classes to QoS mapping, is done. Table 2.2 shows an alternative service classification, grouping different type of services according to common QoS characteristics.

Service Category	Service Description
Real Time Voice	Two way voice service communication
Other Real Time	Aggregated traffic from other real time services, such as rich voice, videoconference, multimedia and real time gaming
VoIP (packet-switched)	Two way communication by means of a virtual connection
Streaming	Video Streaming, typically from servers located in external networks
Business Data	Data communication with high QoS requirements (delay, jitter and PER), such as VPN, intranet connections between mobile users or mobile devices such as M2M or machine-to-machine communication
Best Effort Mobile	Data communication with low QoS requirements, access to services across mobile portals, data services between mobile users, such as intra-P2P, and external services such as Web Services, shopping, external e-mail, and extra-P2P.
SMS; MMS	Short Message Service and Multimedia Message Service
Mobile Broadband	Multimedia and data communication with large bandwidths requirements

Table 2.2: Service categories description applied to the model

In addition, for each of the service categories defined, the following characteristics are considered in the model:

- Average bandwidth uplink (MBU) and downlink (MBD).
- Average packet length for both, uplink (MLU) and downlink (MLD).
- Average duration of the connection per service.
- Source and destination relation with:
  - mobile to mobile (M2M)
  - mobile to fixed (M2F)
  - fixed to mobile (F2M)
  - mobile to server outside the considered network (M2ICP)
  - mobile to a server inside of the networks (M2MobServ)

  Mapping to corresponding traffic class for QoS differentiation.

Finally, the use of each service category must be associated to a user class. For this purpose, the model defines the following user classes:

- Business user.

- Premium user.
- Standard user.

This user classification is based on expected turnover volumes. The user demand contribution of each user class to the scenario is set by the user of the tool as an input data to the model, generating a traffic map. Table 2.3 shows an example of a possible distribution of the user demand in a hybrid GSM, UMTS, HSPA and LTE technology based scenario.

Service	User traffic distribution over:				Traffic Volume in Erlangs		
	GSM	UMTS	HSPA	LTE	Business	Premium	Standard
Voice	0.5	0.5	0	0	0.05	0.005	0.006
Video Telephony	0	1	0	0	0.01	0.0025	0
Streaming	0	0.5	0.3	0.2	0	0.005	0
Guaranteed Data	0	0.5	0.3	0.2	0.002	0	0
Best Effort	0	0.5	0.3	0.2	0.001	0.01	0.002
SMS	0.5	0.5	0	0	0.1	0.05	0.01
MMS	0	1	0	0	0.01	0.02	0
Mobile Broadband	0	0	0.8	0.2	0.01	0.005	0

Table 2.3: User demand distribution example

The distribution of each user type is a modeling parameter that is set by the user as input data, different distribution for each environment (urban, suburban and rural) is allowed. Table 2.4 shows an example of a possible user type distribution for each area within a district.

Type of user	Urban	Suburban	Rural
Business user	0.1	0.075	0.025
Premium user	0.2	0.1	0.050
Standard user	0.7	0.825	0.925

Table 2.4: User type distribution example

The differentiation of the user demand based on type of subscriber, region and technology, allows the model to perform a cell dimensioning process as close to reality as the definition of these parameters is. The level of detail these parameters are set with, depends on the data the user of the tool has, the more in detail this distribution is done, the more accurate results are going to be obtained.

2.2.3.2 Bearer service description

This section details the most relevant aspects considering the cell deployment of bearer services. Bearer services are those services that offer the capability of the transmission of data or signaling information between two different access points. They can be circuit or packet switched services, they concern only to the three lowest layers of the OSI model. A bearer service is defined by a set of characteristics that define such things as the traffic type, traffic characteristics, and the supported transfer rate, that is the quality of service (QoS).

On the one hand, bearer services are fixed in second generation systems, services are mapped into a specific number of slots as bearer. Data services are provided by means of circuit switched and packet switched technologies. Circuit switched technology is available in two different modes:

- Modem technology, single slot at 14.4 Kbps.
- High speed circuit switched data (HSCSD), multiple slots available from 1 to 4 and 14.4 Kbps. A maximum binary rate of 57.6 Kbps is achieved.

In case of packet switched technique, the following systems are considered:

- General Packet Radio System (GPRS). Upgrade of the GSM system, maximum uplink and downlink transfer rates depend on the code scheme (CS) and the multi-slot class (MS), as stated in Chapter 1. Maximum binary rate available in GPRS is achieved when using the highest code scheme (20 Kbps) and the multi-slot class number 10, meaning 4 slots in downlink and 1 slot in uplink, therefore a data rate of 80 Kbps (DL) and 20 Kbps (UL) is achieved.
- Enhanced Data Rate for GSM Evolution (EDGE). Increases the data transmission rate due to the appearance of new modulation and coding schemes (MCS). Maximum transfer rates depend, as it happens in GPRS, on the MCS selected. For the best of the cases, corresponding to the MCS-9 and multi-slot class 10, 4+1, the maximum binary rate achievable is 236.8 Kbps (DL) and 59.2 Kbps (UL).

Table 2.5 shows the characteristic values applied in case GPRS and EDGE technologies are deployed.

Service	Technology	Slots (DL / UL)	Transfer Rate (DL)	Transfer Rate (UL)
Real Time Voice	GSM	1	-	-
Other Real Time	GPRS	4 / 1	80	20
	EDGE	4 / 1	236.8	59.2
Streaming	GPRS	4 / 1	80	20
	EDGE	4 / 1	236.8	59.2
Guaranteed Data	GPRS	4 / 1	80	20
	EDGE	4 / !	236.8	59.2
Best Effort	GPRS	4 / 1	80	20
	EDGE	4 / 1	236.8	59.2
SMS / MMS	GPRS	1	20	20
HSCSD	GPRS	4	57.6	57.6
Modem	GPRS	1	14.4	14.4

Table 2.5: 2G Bearer Services definition

On the other hand, UMTS has the ability to negotiate the QoS parameters for a radio bearer. The parameters of a radio bearer define the QoS offered to an application. Four different classes are defined in UMTS:

- Conversational and real-time class: It is the most restrictive class in terms of QoS, almost constant and very short delay. Applications such as voice, video telephony and vide games are included in this class.
- Streaming class: Characterized by a very asymmetric data stream, although it allows larger delay and jitter than conversational services. Transferred data is processed as a continuous stream.

- Interactive class: It is used for upon-request data applications, such as web browsing, server access, M-comerce applications, online games, etc.
- Background class: It is the less restrictve class and it deals with delays of seconds or even minutes. Applications such as SMS, MMS and E-mail are included in this class.

Each of the services categories, defined above, is mapped into one of the corresponding values of the UMTS bearer levels, giving as a result the corresponding physical services. The most relevant characteristics in the definition of UMTS physical services are:

- Binary rate at the physical layer.
- Downlink and Uplink required E_b/N_0.
- Activity Factor.
- Blocking probability.

Based on the service categories and their corresponding parameters, as well as additional mobile network operator parameters, the model developed in this thesis transform the values of each service category into physical services in order to perform the network dimensioning. Table 2.6 shows the values for the bearer service in WCDMA for UMTS technology.

Service	UMTS Bearer Service	Peak Binary Rate (Kbps)	Profile	E_b/N_0 (UL)	E_b/N_0 (DL)	Activity Factor
Real Time Voice	Conversational, AMR Speech Voice (Circuit Switched)	12.2 12.2	Static Multipath	3.1 4.5	4.6 6.7	0.67 0.67
Other Real Time	Conversational (Circuit Switched and Packet Switched)	$<$ 128 $<$ 128	Static Multipath	0.3 1.5	2.7 5.3	1 1
Streaming	Streaming (Packet Switched)	$<$ 128 $<$ 128	Static Multipath	0.3 2	2.6 5.3	1 1
Guaranteed Data	Background (Packet Switched)	$<$ 384 $<$ 384	Static Multipath	0.3 3	2.3 5.2	1 1
Best Effort	Interactive or Background (Packet Switched)	$<$ 384 $<$ 384	Static Multipath	0.3 3	2.3 5.2	1 1
SMS / MMS	Interactive or Background (Packet Switched)	$<$ 384 $<$ 384	Static Multipath	0.3 2	2.6 5.3	1 1

Table 2.6: 3G UMTS Bearer Service definition

The new 3G-HSPA oriented high speed applications are defined by a different bearer service. The main objective of HSPA, containing both HSDPA and HSUPA, technology is the provision of broadband access in a similar way it is provided by xDSL or cable technology. This service can be provided through different technologies:

- High Speed Downlink Packet Access (HSDPA). It corresponds to Release 5 of the 3GPP specification. Transmission speeds achieving a maximum of 14.4 Mbps in the downlink, by means of the employment of 15 codes and a 16-QAM modulation technique. However, the maximum downlink speeds depends, directly, on the terminal category and the quality of the radio channel.

- High Speed Uplink Packet Access (HSUPA). Firstly defined in the Release 6 by the 3GPP, it implements maximum upload speeds of 5.7 Mbps, corresponding to category 6 user devices.

- Evolved High Speed Packet Access (HSPA+). Introduced in the Release 7 of the 3GPP. It increases the maximum transfer rates in the downlink and uplink by means of a new modulation technique, 64-QAM, and the application of multiple input and multiple output (MIMO) schemes. The maximum achievable transfer speeds are of 42 Mbps in downlink and 11.5 Mbps uplink.

The maximum binary rates expressed above are only achievable under specific conditions, limited number of users and in presence of an excellent channel quality. Real world conditions does not fulfill those requirements, and therefore the feasible transmission speeds are lower than the specified above. The main characteristic of this bearer service is the user guaranteed binary rate and the signal to interference and noise ratio. The higher the guaranteed binary rate is, the higher the SINR of the High Speed Downlink Shared Channel is.

LTE is focused on the provision of the mobile broadband access service as bearer service. LTE increases the binary rates offered by the HSPA technology by means of new modulation and coding schemes application. As it happened in the HSPA case, the most relevant characteristics are the user guaranteed binary rate and the SINR.

2.3 Genetic Algorithms

A genetic algorithm, GA, is a computational method inspired in natural selection and genetic fundamentals. John Holland, first adopted this terminology in his book *"Adaptation in Natural and Artificial Systems"* in 1975. There are other scientists that have collaborated in this field, and have developed similar ideas: Ingo Rechenberg [71] and Hans-Paul Schwefel [72] introduced the idea of the evolutive strategies (ES), and Lawrence Fogel [73], [74] defined the evolutionary programming (EP). Both ideas are based on the mutation and selection theory introduced by the Darwin's theory of evolution. Moreover, Bremermann, [75], and Freser [76] considered the use of recombination, this idea constitutes the heart of genetic algorithms.

Initially, genetic algorithms were not commonly accepted, the main reasons for this was the high computational complexity they required, even in case of simple problems, and the poor computational capacity of the machines in the 70's and 80's. However, once the technology took over these disadvantages, they are used in a large set of optimization process.

Darwin's theory of evolution is the start point of genetic algorithms. Darwin's theory defends that a living being experiments slightly genetic modifications based on the environment. Thaim of these modifications is to improve the grade of adaptability, generation after generation, of the individual to the environment where it lives. However, the genetic fundamentals explaining this modifications were discovered by Mendel, thirty years later. Based on this theory, a genetic algorithm offers the possibility of evolving an initial population of individuals, that represents the candidate solutions of a specific optimization problem, by means of the application of evolving methods in such a way that the new generated individuals are better suited to the environment than their predecessors. The grade of adaptability to the environment in GA's is measured by the fitness function. Summarizing, the key facts of a GA are:

- Individuals' encoding scheme: The aim of the encoding is mapping each candidate solution of the optimization problem to a unique binary or continuous value string. The external characteristics of a living organism are defined by its own genetic information, also know as genotype. Any genetic information caused by this genotype is code by the genes. The aggregation of specific number of genes forms a chromosome, each gene occupies a specific position within a chromosome and takes a different value, known as allele. From a mathematical point of view, this base implies the existence of a bijection between the set of candidate solutions, $\mathcal{F}$, and the set of chromosomes or individuals, $\mathcal{G}$, that code the solutions.
$$\zeta : \mathcal{F} \rightarrow \mathcal{G} \tag{2.1}$$

- Initial Population: The set of candidate solutions, individuals, to a specific optimization problem constitutes the initial population. The size of the initial population is the key aspect to figure out. On the one hand, a large size of the population increases the diversity of the solutions, increasing the exploration of the search space, however the convergence of the algorithm could be slow. On the other hand, a small sized population reduces the convergency time, but it reduces the exploration of the search space and it could obtain a local optima as solution of the optimization problem.

  Multiple studies attempting to estimate the optimal size of population based on the size of the individual have been performed. First, Goldberg obtains that the population size should increase as an exponential function of the individual size. Later studies concluded that the relation between the population size and the individual size can be linear [77]. However, the most widely used mechanism to determine the size of the population is the empirical methods, which suggest that a population size in a range from 20 to 100 individuals is adequate in most cases.

- Evolutionary mechanisms: The *survival of the fittest* theory rules in nature, it establishes that those individuals that are better suited to the environment where they live, have larger probability of surviving and therefore better chances to reproduce. New individuals' creation is based on the genetic combination of the parents (recombination), and external factors (mutation). New individuals have similar genetic characteristics comparing to their parents, but they are not genetically identical. These genetic differences make them to be more or less adaptable to the environment, in case the offspring is better adapted to the environment, it increases its probability of surviving and reproducing gradually, forming better suited to the environment individuals.

Therefore, a GA is based on the generation of an initial population, which is evolved by means of the application of evolutionary mechanisms implemented in a loop process. Every genetic algorithm is structured in three different phases, the initialization phase, the evolutionary phase and the stopping phase. The initialization phase generates the individuals and it estimates the grade of adaptability to the environment, that is, it calculates the fitness function value of each individual. Once the initialization phase ends, the process enters into the evolutionary loop, where the evolution operators are applied to the individuals in a iterative way until a stop condition is met. The stop condition is generally accepted to be either a number of evaluations or in case no improvements on the results are observed, that is, the fitness function of the best individual does not improve from one generation to the following one. The evolutionary operators in a GA are selection, crossover and mutation.

- Selection: The objective of this operator is to select those individuals that will be part of the next generation, this selection is made based on the fitness function's value of each individual. There are multiple selection mechanisms, the original scheme is known as the *roulette-wheel* method. The *roulett-wheel* uses a probability distribution in which the selection of each individual is proportional to its fitness function's value. An alternative method is the *ranking* scheme, where individuals are arranged as stated by their fitness function and only those k individuals with the best fitness function's value will be part of the next generation. Both schemes are fitness-proportional methods.

  There is a third common method, it is know as the *tournament selection* method, which represents an alternative to the fitness-proportional methods. In this case, a fraction of the total population is chosen and compared, each of the individuals is compared to the rest of the individuals in the selection, and those individuals having won the largest number of comparisons will be part of the next generation. This method is similar to the direct ranking scheme, however, due to only a fraction of the total population is compared, individuals having worse fitness increases their probability of living than in the ranking method where they have no chances of being part of the next generation.

- Crossover: The goal of this operator is generating new individuals from the existing ones. A classical implementation of the crossover operator consists on a random selection of two existing inhabitants to be crossed (by exchanging parts of their genetic information coded in the string) with a specific probability know as crossover probability, usually around the 60%. Each pair of parents generate a new pair of individuals, children, with different genetic information, these children replace their parents in case of improving their parent's fitness based on a selection criterion.

  There are multiple crossover schemes, one point, two points or multi-point depending on whether the parents are crossed by exchanging parts in one, two or multiple points of their coded strings. An alternative to these crossover operators is know as *k-bit-crossover* [78], where k individual's characteristics are randomly chosen and their values are swapped.

- Mutation: The aim of this operator is to increase the the diversity of the candidate solutions and the exploration of the search space. It is based on a slightly modification of a individual's specific characteristic, and it occurs with a very low probability, around the 1%. Due to the variation of the characteristic only affects to a specific chromosome, this operator does not imply the interaction of two different individuals as it happens in crossover and selection operators.

In few cases, an elitism operator is used in genetic algorithms. The goal of the genetic algorithm is to obtain the optimized solution to a problem, and its functioning is based on evolving an initial population obtaining better candidate solutions iteratively. An elitism operator guarantees that either the best individual, in terms of fitness function's value, at iteration k, or a new better individual will be part of the population at iteration $k+1$. In this way, the best solutions at each iteration are not discarded, possibility that exists if the tournament selection method is considered. However, depending on the type of problem and the way the elitism operator is implemented, it can cause a premature convergence to local optimal solutions.

2.3.1 Evolutionary computation applied to Telecommunications

Evolutionary computation is the general name under which a set of different metaheuristic nature-inspired algorithms are defined, for example genetic algorithms (GA), evolutionary programming (EP), evolution strategy (ES), together with swarm intelligence such as ant colony optimization, particle swarm optimization, teaching-learning-based optimization (TLBO), harmony search, etc. These methods are commonly applied to non-linear or restricted problems where classic linear optimization does not provide good solutions in terms of either efficiency or computing time. These new optimization mechanisms have been applied to a wide range of problems in multiple fields of science and engineering.

Telecommunications, more concretely mobile communications, problems are characterized by having the necessity of fulfilling a large set of constraints in terms of coverage, capacity, spectrum allocation, location of the nodes, distribution of the user demand over the links connecting the nodes, environmental constrictions in terms of maximum radiated power, minimum quality of service given to the end user, etc. Moreover, the planning and dimensioning process of a telecommunication network is a very cost process, in terms of computing time and complexity. The goal of any operator is to fulfill the quality constraints minimizing the invested capital in network equipment, operation and maintenance, and therefore evolutionary computation is presented as a suitable solution to solve this type of optimization problem taking into consideration all the constraints mentioned above.

Network planning problems have normally multiple objectives to optimize, and it happens when optimizing one of these objectives the rest or part of them worsen. In these cases, the solution is that which satisfies the opposing objectives to a certain degree. In [79], a multi-objective optimization problem is defined when planning a third generation network. It also introduces a theoretical way of parallelizing genetic algorithms, mainly focused on the evolution of the population and fitness evaluation.

One of the most common optimization problems is to figure out the location of the nodes of a network. Researches from the University of Rome, [80], apply genetic algorithms to the optimization of a UMTS network. The goal of this study is to estimate the optimal location of the nodes inside a specific area given as input to the algorithm. In this study, four different cases are considered:

- Case 1: No constraints considered.
- Case 2: A non-homogenous distributed traffic is assumed.
- Case 3: Limitation on the number of possible node's locations is considered.
- Case 4: Environmental constraint, limitation on the maximum radiated power allowed.

For all the cases, a genetic algorithm based on a roulette-wheel selection mechanism, a single-point crossover operator, and a mutation operator with a probability of occurrence between 0.01 and 0.1 is applied to a hypothetical suburban area of 9 square kilometers. The results show a reduction in the number of nodes required, and therefore a reduction in the investment costs, at the same time that an optimal service and specific coverage and capacity levels are guaranteed.

In [81], the base station's location problem is also studied. The goal of this study is to compare the performance of a genetic algorithm and a tabu search solving this optimization problem. It is divided into two main parts. First, the most relevant parameters for the genetic algorithm (population size and selection mechanism) and the tabu search (tabu tenure and candidate list size) are analyzed. Once these parameters are obtained, a comparison of the performance of both optimization mechanisms is done. The results of the study give information about the number of nodes required, together with the maximum, average and minimum investment costs, and the total covered area. For both mechanisms a reduction in the number of nodes, and therefore in the investment cost, is observed. A better performance of the genetic algorithm than the tabu search for increased randomness of mutation operators is observed.

The network elements' placement when planning a network, in this case for a Wireless Local Area Network (WLAN), is treated in [82]. In this work an evolutionary algorithm, HexagonGA, selecting the access point devices, locations, antennas, together with the access point's configuration parameters such as transmission power and frequency channel is introduced. The HexagonGA performed is tested on a WLAN planning simulation on Finland. Three different cases were considered, while the first case only uses capacity as a single optimization criteria, the second case considers both capacity and coverage as optimization criteria, and the third case adds the cost criteria to the optimization problem. A more efficient network is planned when the HexagonGA is applied than in the manual plan case, increasing the capacity of the system and minimizing the costs. Moreover, the algorithm presented also improves the computing time of the WLAN planning process.

In [83], a genetic algorithm is applied to solve the optimization problem of the base stations location in a 3G network, the goal of this work is to maximize the coverage area while minimizing the interference and costs. In the same line, Garber, in [84], applies classic and random weighted forms of a GA to solve the BS's placement problem, the goal is, once again, to maximize the coverage of the network. In this work, it is shown that a shorter number of BS and a higher coverage area is obtained after applying both GAs in comparison to an existing network for Cairo city. Other soft-computing techniques such as particle swarm optimization (PSO) have been applied to solve this optimization problem, in [85], a network planning scheme for high-speed railways based on PSO is proposed, the goal of this proposal is to reduce the number of logic cells based on a distributed antenna system, reducing the total system cost considering constraints of transmission rate, handoff time and antenna number requirements.

The management of scarce resources, such as the spectrum, is another problem where GAs are applied. Frequency channel assignment is studied from two different point of views, on the one hand the fixed channel assignment (FCA), where channels are permanently allocated to each cell and on the other hand, dynamic channel assignment (DCA), where all channels available are allocated upon request.

The FCA problem is studied in [86], where a modified genetic algorithm, called the genetic-fix algorithm, is proposed to solve the channel assignment problem satisfying both the traffic demand and the electromagnetic compatibility (cochannel, adjacent channel and cosite constraints). The genetic-fix algorithm is characterized by the generation and management of fixed size individuals, together with the use of minimum-separation encoding scheme, that reduces the number of required bits for representing the solution. The goal of this algorithm is to obtain a zero-conflicts channel allocation solution minimizing the number of channels used. Five different cases are considered in this work, depending on the number of cells, channels and electromagnetic constraints taken into consideration. For all the cases, the stating points are the compatibility matrix defining the interference conditions, and the demanded vector that indicates the number of channels required by each cell, that depends on the amount of traffic demanded within the cell. The performance of the GA is finally compared to the results obtained by a classic neural-network technique, achieving a 100%, 92%, 80% and 100% of convergence for four of the five cases considered, improving the results provided by the neural-network.

Based on the same fundamentals of [86], in [87] the use of GAs to solve the problem of assigning calls in a cellular network to frequency channels satisfying the user demand and minimizing the interference is treated. Three sets of experiments are considered, the first two cases are referred to small network cases, 4 and 5 cells are only considered. The second set of scenarios are based on the 21 hexagonal cells network used by Sivarajan et al. in [88]. Finally, the third set of scenarios are derived from the topographical data of a 24×21 km area around Helsinki, Finland, as used by Kunz in [89]. The performance of the GA is compared to other methods such as GAMS/MINOS-5, the heuristic steepest descent method (SD), stochastic simulated annealing (SSA), original Hopfield network (HN) and hill-climbing Hopfield network (HCHN), and the self-organizing neural network (SONN). The performance of the GA improves the results provided by the rest of the methods in all the scenarios considered.

Jaimes-Romero et al. proposed the use of two different genetic algorithms, a simple genetic algorithm (SGA) and a hybridized genetic algorithm (HGA), to solve the channel allocation problem in [90]. In the SGA the classical genetic operators, tournament selection, one-point crossover operator and uniform mutation, are applied to each individual based on a set of sub-strings or cells encoding the channels allocated to that specific cell. The HGA makes use of an alternative to the mutation operator, a local search algorithm is used instead of the uniform mutation, allowing the algorithm to explore globally and locally the solution space. Both algorithms are tested in four different scenarios where 1, 2, 3 and 4 channels per cell are required, and compared to the results obtained by a linear algorithm. First conclusion is that both GAs improves the results obtained by linear programming. Second, the performance tests show that while the SGA is able to converge to a zero-conflicts solution in case of 1, 2 and 3 channels per cell are required, the HGA is able to achieve a zero-conflict solution in case of 4 channels per cell too. Moreover, it is observed that the HGA converge to the solution faster than the SGA, two main reasons caused this effect, the first advantage is the encoding mechanism providing inherent information about the number of channels required per cell used by the HGA, the SGA does not take into consideration this information which leads it to evaluate a larger set of candidates until the solution is reached. The second advantage corresponds to the use of the local search algorithm implemented in the HGA, which allows the GA to explore a larger set of points in the solution space before the crossover operator is applied, reducing the number of generations to converge. This results are obtained in a reasonable time, which makes these proposed algorithms to be applied in DCA problems.

An alternative to solve the dynamic channel allocation problem is presented in [91]. In this work, a new heuristic algorithm to solve the DCA problem based on three stages, the regular interval assignment stage, the greedy region assignment stage and the genetic algorithm stage is introduced. The first stage assigns the channels to the cell that determines the lower bound, that is the most demanded cell. The second stage determines a greedy region of the network and assigns channels within the region. Finally, the third stage is applied to the remaining cells, the assignment of the channels is based on the use of a genetic algorithm to search for an optimal solution. The performance of this novel method is checked by its application to solve the Philadelphia problem, based on a regular hexagonal grid of 21 cells, where the lower-bound solution of the problem is fixed, see [88] for details. Results show that this three-stage heuristic method achieves the lower bound solution in 11 of 13 cases, showing a better performance that the method proposed in [88]. The final conclusion is that this method is an efficient an powerful tool for solving this DCA problem.

A Tabu Search algorithm is also proposed as a possible solution to the DCA problem. In [92], a Tabu Search algorithm and its application to a spectrum shared environment is studied. The goal of this algorithm is to increase the revenue obtained by an hypothetical operator providing packet-switched services, taking into consideration the cost of the leased spectrum and traffic heterogeneity. The performance of this proposal is compared to the fixed spectrum allocation (FSA), where the frequency resources are own by the operator. Results show a better performance of this new method than the FSA strategy networks with few cells, however it presents problem in case of networks having a large number of cells. To solve this problem, the application of the tabu search algorithm is done locally, focused on solving the channel allocation among a subset of cells or cluster.

Another constraint in telecommunication networks is the load balancing or routing problem. This routing problem has to be differently overcome based on the knowledge of the topology of the entire network. One approach to solve this problem is introduced in [93], in this work a hybrid genetic algorithm (HGA), based on classical genetic operators and a heuristic search that speed up the convergence of the algorithm, to optimize the link weights used for routing inside an autonomous system, considering the link utilization and weight reconfiguration is studied. Link weight changes are one of the most annoying factors that may happen in case of failures in an existing operational network, therefore the goal of this proposed algorithm is to minimized the weight changes. Results are compared to linear programming and a standard genetic algorithm results, observing a better performance of the HGA than the results obtained by the standard GA, and very close to the lower bound results provided by the linear programming results obtained by the generic routing protocol method.

Specially problematic is the routing problem in case the topology of the entire network is not known. Liu et al., [94], propose a routing algorithm for ad-hoc networks based on swarm intelligence, concretely based on ant colonies behavior. The goal of this algorithm is to adapt to changes of the network topology without invoking high routing overhead. Four different metrics are used to test the performance of the algorithm, the packet delivery ratio, the average end-to-end delay, path optimality and the transmission optimality. Two different set of experiments are defined, the first one is based on a 50 nodes network in a rectangular field of $1500 \times 300m^2$, and the second one contains 150 nodes in a rectangular area of $2000 \times 700m^2$. For both scenarios the network consists of 5, 10, 15 and 30 traffic flows. Results show a high delivery ratio for both cases, 97% for small networks and a 90% for bigger networks, showing slow delays in all cases. In order to evaluate the effectiveness of the routing algorithm the path optimality and the transmission optimality is explored. The path optimality measure the ability of the algorithm in discovering the shortest optimal route in comparison to the determined by a simulator, the results indicate a ratio between the average route length to the optimal one of 1.2 and 1.35 for both cases. The transmission optimality measures the total number of packet transmissions performed relative to the optimal number of transmissions for the packets sent in the simulation, showing a transmission of a 15% of routing overhead information in stationary and a worst case of 42% of routing overhead at the beginning of the simulation for the $1500 \times 300m^2$ case and an 8% larger routing overhead for the bigger network area.

2.4 Thesis Objectives and Structure

This thesis is focused on the development of a set of algorithms to deploy an optimized mobile radio access network, leading to a minimum investment network. This objective is divided into two parallel tasks. First, the necessity of a set of algorithms to estimate the required RAN equipment by means of carrying out coverage and capacity studies is tackled. In this thesis, the proposed algorithms to fulfill this necessity are:

- UMTS multi block algorithm: This algorithm allows to develop a third generation network, based on a multi service profile and different bandwidths and frequency bands.
- HSPA algorithm: It is compounded by two different algorithms. First, downlink communication studies are carried out by the HSDPA algorithm. Second, uplink studies are performed by the HSUPA algorithm. HSPA algorithms, as it happened in UTMS, allow a mono-block or multi-block in the same or different frequency bands deployment.
- LTE algorithm: Algorithm to perform the designing network part concerning to the LTE technology.

In a parallel way, it is required to implement a set of algorithms to solve the optimal service distribution problem (OSDP). The goal of these algorithms is to estimate the most efficient user demand distribution over the most suitable technology among the chosen one to be deployed. The following algorithms, based on evolutionary programming, are proposed in this thesis to solve this optimization problem.

- Evolutionary Algorithm Optimization (EA): Adaptation of well known general purpose algorithm.
- Coral-Reef Optimization (CRO): This algorithm is based on [95], and it simulates the coral reef behavior to solve our problem.
- Teaching-Learning Based Optimization (TLBO): Based on [96], pupils learning process is simulated with this algorithm.

Based on the above mentioned objectives, this document is structured as follows:

- **Part II. Proposed Contributions with Numerical Results:** This part of the thesis is focused on the description of the optimization and network deployment algorithms developed, description of the software tool and the results obtained by the testing processes of the tool.
  - Heuristic algorithms to perform the cellular dimensioning process. Mathematical and structural description of the algorithms that have been developed, used to obtain the optimal cell range, and therefore the optimal amount of equipment needed.

- Meta-heuristic algorithms applied to the optimal service distribution problem (OSDP). Description of the different developed optimization algorithms, based on the classical evolutive programming method, a coral-reef optimization algorithm and a teaching-learning based optimization algorithm.
- Planning software tool. Integration of the deployment and the optimization algorithms.
- Experiments and Results. In this chapter, several experiments have been carried out, taking into considerations real world constrains in terms of frequency resources, user demand and technologies available.

• **Part III. Conclusions and Future Work lines:** In this last part of the thesis, there different chapters are included.

- Conclusions of the work, where a general description of the research process and the obtained results is given.
- Future worklines describing the open points to be studied in future.
- The last chapter indicates the main contributions generated during the research process.

Part II

Proposed Contributions with Numerical Results

Chapter 3

Heuristic Algorithms for Cellular Network Dimensioning

One of the most relevant phases in the strategic planning of a cellular network is the cell dimensioning process. In this phase, studies on capacity and coverage to determine the maximum cell range, and therefore the required radio access network equipment, are carried out. The complexity of the process depends mainly on the type of technology to be deployed which determines possible interrelations between coverage and capacity, e.g. TDMA networks dimensioning process is easier to perform than the WCDMA based systems' process, such as UMTS or HSPA.

Coverage analysis in the cell dimensioning process needs complex propagation models to obtain the final cell range. In Chapter 2, several propagation models have been explained in detail. Optimization of the coverage leads to larger propagation cell ranges and therefore a reduction in the network elements and the investment costs in case of propagation driven cells. The complexity of the different propagation models depends, among other factors, on the input parameters considered to develop the analysis, parameters related to the handset and base station type such as transmission power, noise figure, antenna gains and losses in the handset or in the base station cables, together with free space losses and additional losses have to be taken into account. Regarding the complexity of the capacity analysis, it depends, as it happened in the coverage case, on the type of technology to be deployed. However, the two most important parameters when analyzing the capacity of a mobile network are the user demand and the interference constraints.

The implementation of software tools in charge of developing these coverage and capacity studies implies an optimization in time and costs for network operators to take decisions such as optimizing an existing network or migrating to a new technology. Regulatory authorities make use of these kind of tools to establish the cost per minute of service, the termination rates between operators, etc.

In this chapter, four algorithms, covering 2G-GSM, 3G-UMTS, 3G-HSPA and 4G-LTE technologies, to dimension a RA network are introduced.

3.1 Objective and scenario definition

The objective of the cell dimensioning process is to carry out an estimation of the total network equipment required to fulfill a set of capacity and coverage conditions. The starting point of the process is the definition of a scenario E that is composed by a large set of parameters, e.g., the set of cities and villages where the network is going to be deployed, frequency constraints, that is, available frequency bands (800 MHz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz), the bandwidth for each frequency band, operator's market share, a set of hardware available to deploy the network and its corresponding cost and propagation conditions such as terminal equipment losses, antenna gains and transmission power.

All the developed algorithms are capable of managing multi-service profiles, let us consider a set of services $\mathcal{S} = \{1 \leq i \leq |\mathcal{S}|\}$, such as voice, best effort data, guaranteed data, etc., each one defined by a set of parameters $\mathcal{P}_i^S$, $\mathcal{P}_i^S = \{1 \leq p \leq |\mathcal{P}|\}$, as the binary rate Rb_i^s, individual traffic per user, a_i^s, the required quality of service q_i^s and the grade of service (GoS) or blocking probability, Pb_i^s. Different technologies are considered, let us assume a set of available technologies $\mathcal{T} = \{1 \leq j \leq |\mathcal{T}|\}$, limited in our application to: 2G-GSM, 3G-UMTS, 3G-HSPA and 4G-LTE. A deployment function ψ which depends on the number and parameters of services and the distribution $\mathcal{D}$ of these services over the considered technologies. $\mathcal{D}$ stands for the part of the traffic of each specific service i that will be carried by the technology j, $(\mathcal{D}_{i,j})$, and it depends on the type of technology combination selected to deploy for each of the different cities or villages and the constraints of each of the services considered, e.g., voice service can only be carried either by a GSM network or by UMTS network, but it is not possible to provide this service over a HSPA or LTE network.

The deployment function ψ gives the number, location and type of the network resources, which are the base stations of the different technologies, for the selected scenario E. The dimensioning problem's objective is to minimize the cost of each technology network deployment $C_j(\psi)$ fulfilling the quality constraints of the set of services $\mathcal{S}$.

3.2 Second Generation Cellular Dimensioning Algorithms

The developed algorithm to carry out the estimation of the required second generation base stations (BTS) to fulfill the capacity and coverage constraints, is introduced in this section. Second generation systems are hard-blocking systems, which means that the capacity of the system depends on the amount of hardware installed in the base station, understanding hardware of the BTS as number of sectors and transceivers (TRX). Due to the fact of being a hard-blocking system, coverage and capacity analysis are carried out independently, there is not an explicit interrelation between the coverage and the capacity cell ranges.

The designing method implemented for second generation networks is capable of managing single and dual band deployments, generally thought to deploy in the 900 MHz and 1800 MHz frequency bands, but it also allows the use of different frequency bands. The structure of the network deployed for the second generation systems is based on a two layers configuration. The first layer corresponds to the umbrella cells layer, and the second one is the general layer where a single or a dual band deployment is performed.

Umbrella cells layer is commonly used to improve the coverage of the network, no capacity studies are carried out in this case. Umbrella cell configuration is based on the installation of a set of BTS above the average height of the surrounding buildings, BTSs installed in this layer are characterized by their high transmission power, which allows them to provide a large propagation cell range. Despite the fact of reducing the number of channels available for carrying traffic in the general layer due to its use in the umbrella cell layer, this configuration has important advantages. Let us suppose a highway inside a large city where the users are driving through at very high speeds, and let us assume that the general layer is the only one deployed, BTSs in the general layer has a shorter cell range and therefore it implies the number of handover between cells increases, this increase implies a very high load of signaling traffic and a degradation of the quality of signal offered to the end user. The second layer is necessary in order to meet the capacity requirements, specially in urban areas. Therefore, the combination of both layers, umbrella and general layer, is a feasible solution to provide good coverage and capacity to the system. Umbrella cells layer reduces the signaling load and improves the high speed users signal quality. while the general layer is in charge of carrying slow speed users traffic in high populated areas.

3.2.1 Coverage analysis

Coverage analysis is focused on the development of propagation methods to estimate the cell range due to the propagation environment conditions for both directions, uplink and downlink. In Chapter 2, several propagation methods were described, Cost231-Hata model is the propagation method implemented in this thesis. The application of this model implies two main phases:

- Estimation of the maximum allowed losses, L_c. It depends on several factors such as the transmission power, antenna gains, transmission and reception losses, as well as the receiver sensitivity.
- Cell range calculation by means of the application of Cost231 equations and L_c

The process described in this section is focused on the uplink. Uplink is the most restrictive direction according to the propagation cell range, due to the lower transmission power of the handset in comparison to the transmission power of the base station. However, the equations and process is valid for the downlink too.

The first step is the estimation of the maximum allowed cell loss, this parameter corresponds to the following equation:

$$L_c = L_p - M_{sf} - M_{ff} + G_{sh} \tag{3.1}$$

where:

- L_p: Maximum allowed path loss.
- M_{sf}: Slow fading margin.
- M_{ff}: Fast fading margin.
- G_{sh}: Soft handover gain.

The maximum allowed path loss is calculated as follows:

$$L_p = EIRP - S_{rx} + G_{rx} - L_{rx} \tag{3.2}$$

where:

- G_{rx}: Receiver antenna gain, in this cases base station antenna gain.
- L_{rx}: Built-in receiver losses, in this case it corresponds to the feeder and cable losses in the base station.

The $EIRP$ stands for the equivalent or effective isotropically radiated power concept. It is defined as the amount of power that an isotropic antenna would emit to transmit the same power measured in the maximum antenna gain direction of a non-isotropic antenna. The $EIRP$ depends on the transmission power of the antenna module for each connection of each service, the transmitter antenna gain, and the transmitter losses. Losses in the uplink direction are due to body losses and mismatch.

$$PIRE = P_{tx} + G_{tx} - L_{tx} \tag{3.3}$$

Receiver sensitivity, S_{rx}, is defined as the minimum signal power required, at the input of the receiver, to meet the quality requirement for the service. 3GPP defined the reference sensitivity levels for the handset and the base stations in [97]. Table 3.1 shows the sensitivity reference values accepted.

	Handset ($d\beta m$)	Macro-cell BTS ($d\beta m$)	Micro-cell BTS ($d\beta m$)	Pico-cell BTS (dBm)
900 MHz	-102	-104	-97	-88
1800 MHz	-102 / -100	-104	-92 / -102	-95

Table 3.1: 3GPP TS 05.05 Sensitivities for GSM

Once the value of the maximum allowed cell loss is calculated, the second step is the application of the Cost231-Hata equations to obtain the cell range due to propagation environment. Cost231 model distinguishes between different types of clutter or areas, urban, suburban and rural areas. Urban areas are considered as large and high populated cities with high office or residential buildings. Medium and low populated districts and industrial areas are considered as suburban areas in the model. Finally, villages and open areas are treated as rural areas. The general equation and its correction factors to estimate the cell range by propagation is shown in 3.4.

$$L_c = A + B \cdot \log(R_p) + C \tag{3.4}$$

where:

- A:

$$A = \begin{cases} 69.55 + 26.16 \cdot \log(f_c) - 13.82 \cdot \log(h_{bs}) - a(h_{ms}) & \text{if } f_c < 1500MHz \\ 46.3 + 33.9 \cdot \log(f_c) - 13.82 \cdot \log(h_{bs}) - a(h_{ms}) & \text{if } f_c > 1500MHz \end{cases} \tag{3.5}$$

- $B = 44.9 - 6.55 \cdot \log(h_{bs})$
- $a(h_{ms}) = (1.1 \cdot \log(f_c) - 0.7) \cdot h_{ms} - (1.56 \cdot \log(f_c - 0.8)$. Small and medium cities.
- C: Clutter correction factor

$$C = \begin{cases} 0 & \text{Urban areas} \\ -2 \cdot (\log(f_c/28))^2 - 5.4 & \text{Suburban areas} \\ -4.78 \cdot (\log(f_c))^2 + 18.33 \log(f_c) - 40.98 & \text{Rural areas} \end{cases} \tag{3.6}$$

- R_p: Propagation cell range [Km]

Finally, the cell rage due to propagation environment is obtained as follows:

$$R_p = 10^{\frac{L_c - A - C}{B}} \tag{3.7}$$

3.2.2 Capacity analysis

Capacity studies in GSM are based on two main parameters, the user demand and the type of base station considered. The algorithm is able to evaluate different types of base stations in terms of numbers of sectors and transceivers available. GSM is a hard-blocking system, previously explained, and a TDMA synchronous slotted system. Therefore the capacity required by any service can be expressed as multiple of the basic capacity unit, the slot of the TDMA frame.

First, the total user demand is calculated. For this purpose, all the services defined in the service profile are considered. The total amount of demand is calculated as the aggregation of the user demand for each of the services forming an unique service. GPRS and EDGE technologies impact is simulated by the number of slots, N_s, required per service. Individual user demand is expressed in Erlangs, E. The Erlang is a dimensionless unit, and it is defined as the use of one traffic resource during a time period of 60 minutes.

$$a = \sum_{i=1}^{|\mathbb{S}|} a_i^s \cdot D_{i,j} \cdot N_s \tag{3.8}$$

The second step is the evaluation and calculation of the traffic resources available for an specific type of base station. The capacity study is performed for a single sector, and then extended to the number of sectors available. Each sector has either one or more transceivers, every of them are time slotted, 8 different time slots per TRX. Depending on the configuration of the network, the number of time slots dedicated to carry data and voice traffic are 6 or 7. In this thesis, 6 slots are considered to be in charge of voice and data traffic transmission, 1 slot for signaling traffic, and 1 slot for handovers. The number of traffic channels, or time slots, available in one sector is calculated as follows:

$$N_{ts} = N_T \cdot N_t \tag{3.9}$$

where N_T is the number of TRX per sector, and N_t corresponds to the number of considered traffic time slots per transceiver.

Applying the first Erlang equation, commonly known as Erlang-B equation, to the value obtained in 3.9 and the most restrictive GoS among the services, the maximum amount of traffic that can be carried by a specific sector, A_s, is estimated.

$$A_s = E_B^{-1}(N_{ts}, min(Pb_i^s)) \tag{3.10}$$

Based on the single user demand, the maximum carried traffic per sector, the total number of simultaneous users in one sector, M, is estimated.

$$M = \frac{A_s}{a} \tag{3.11}$$

Finally, the cell range due to capacity constraints, R_t, is estimated considering the number of available sectors, N_S in the base station under study and the population density, ρ of the area, as indicated in 3.12

$$R_t = \sqrt{\frac{M \cdot N_S}{\pi \cdot \rho}} \tag{3.12}$$

3.2.3 Estimation of a single site cell range

The estimation of a single cell range is performed based on the coverage and capacity processes described above. The algorithm evaluates whether a single or dual band deployment is considered. In case of dual band, the lowest frequency band is selected for the umbrella cells layer and for the first frequency band general layer dimensioning process due to better propagation conditions. The second frequency band is used to reduce the traffic demand carried by the first frequency band, and therefore attempt to increase the final cell range, this is only possible in case of urban or high populated suburban areas where first frequency band cells are, generally, traffic driven cells, $R_t^1 < R_p^1$. Base stations in first and second frequency bands can be the same or different types, all possible base station model combinations are taken into account in this process.

Once both cell ranges, coverage and capacity, are calculated, the final cell range for that specific type of base station is estimated as the most restrictive first frequency band cell range, see Equation 3.13. The complete process is shown in Figure 3.1.

$$R_c = min(R_p^1, R_t^1) \tag{3.13}$$

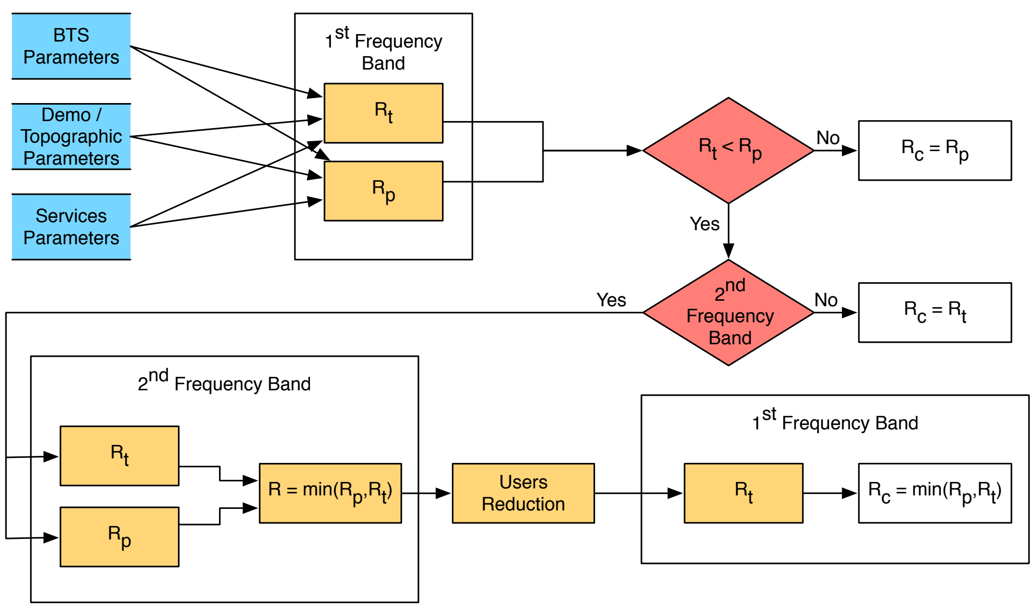


Figure 3.1: Dimensioning algorithm for GSM technology.

3.2.4 Estimation of the GSM Network Deployment

The algorithm shown in Figure 3.1 is executed for each possible type of base station for single band deployment, or every combination of base stations for first and second frequency band, if dual band deployment is available, $BTS = \{1 \leq k \leq |BTS|\}$. Each type of base station has an associated cost that is based on the type, macro, micro or pico, number of sectors and number of transceivers installed in the base station.

The cell range calculated for each base station or combination of base stations determines the number of sites required, N_{bs}. This value is calculated as shown in Equation 3.14.

$$N_{bs} = \left\lceil \frac{A}{A_{bs}} \right\rceil \tag{3.14}$$

where A stands for the surface of a specific area of a city, urban, suburban or rural, and A_{bs} is the surface of the base station.

Finally, the algorithm select the minimum cost combination among the possible solutions. The cost associated to each solution, $C^k_{2G}(\psi)$, is calculated as follows:

$$\begin{aligned} C^k_{2G}(\psi) &= N_{bs} \cdot (C_k + C_j) \\ C_{2G}(\psi) &= min\left(C^k_{2G}(\psi)\right) \qquad ,\{\forall k \in BTS\} \end{aligned} \tag{3.15}$$

where:

- C_k is the cost related to the first frequency band base station model in solution k, and
- C_j is the cost associated to the second frequency band base station type used in solution k. The type of base station used in the second band can be k or any other type of base station available for the area of the district, urban, suburban or rural, under study.

3.3 Third Generation Cellular Dimensioning Algorithms

In this section, the dimensioning algorithms for UMTS and HSPA technologies are described. Third generation systems are soft-blocking or interference limited systems, that is, the capacity of the system depends on the amount of interference in the system. Interference can be caused by two main factors, intra-cell interference produced by the users inside the own cell, and inter-cell interference that is the existing interference in a specific cell caused by neighboring cells. In addition, and due to the fact this systems are soft-blocking systems, there is an interrelation between capacity and coverage, and therefore the analysis cannot be performed independently as it happens in second generation systems.

3.3.1 UMTS Dimensioning Algorithm

UMTS dimensioning and optimization algorithm estimates the network equipment required by means of solving two different aspects:

- Outer Problem. It attempts to balance both cell ranges, capacity and coverage. The objective of this step is to obtain the largest final cell range maximizing the power transmission and capacity resources exploitation.

- Inner Problem. Capacity optimization process. The aim of this part of the algorithm is to balance cell ranges among the different services and to maximize the load factor of the cell. The maximum load factor of the cell depends on the amount of interference in the system, and that factor is defined in the algorithm as the interference margin parameter, IM.

UMTS dimensioning process it is divided into two different interrelated processes, the estimation of the coverage propagation cell range based on the Cost231 propagation model, and the estimation of the capacity cell range detailed below.

3.3.1.1 Coverage analysis

The coverage cell range estimation implies the employment of precise propagation models. Multiple propagation models were described in 2. The selected model to perform the coverage analysis is the Cost231 propagation model. A general description of this propagation model can be found in 3.2.1. Due to the different properties of the UMTS system in comparison to 2G systems, a description about the new considerations to take into account in the third generation systems coverage analysis is explained below.

The first step is the estimation of the maximum allowed cell loss, as indicated in 3.1, that implies the calculation of the maximum allowed path loss, 3.2. The receiver sensitivity, in this case, depends on the energy per bit over noise ratio, (E_b/N_0), the pre-processing gain, G_p, and the interfering power, P_{Irx}.

$$S_{rx} = \left(\frac{E_b}{N_0}\right)_i - G_{p_i} + P_{Irx} \tag{3.16}$$

Processing gain depends on the binary rate of each of the services considered, Rb_i^s, the bandwidth available, W, and the activity factor of each service, υ_i.

$$G_{p_i} = 10 \cdot \log\left(\frac{W}{Rb_i^s \cdot \upsilon_i}\right) \tag{3.17}$$

Total interfering power is defined as the aggregation of the receiver noise power, N_{rx}, and other users in the cell interference, IM. Receiver noise power depends on the noise density power, D_N, and the bandwidth of the interfering signal, Δ_{BW}, as indicated in 3.18.

$$\begin{aligned} P_{Irx} &= N_{rx} + IM \\ N_{rx} &= D_N \cdot \Delta_{BW} \end{aligned} \tag{3.18}$$

The noise density power is estimated as follows:

$$D_N[d\beta m/Hz] = 10 \cdot \log(\chi \cdot T) + 30 + N_f \tag{3.19}$$

where N_f stands for the receiver noise figure in $d\beta$, χ is the Boltzman constant, and T is the temperature in Kelvin degrees (290 °K).

Once the maximum allowed cell loss is estimated, the cell range due to propagation environment conditions is calculated be means of the use of the Cost231 equations and the cell loss value, equations can be found in 3.4. However in this case, the coverage analysis is performed for every service due to the different (E_b/N_0) values, which leads to different receiver sensitivities.

Two different arrays of cell ranges are obtained, one per direction, uplink ($\overline{R_{p_{UL}}}$) and downlink ($\overline{R_{p_{DL}}}$). The shortest value in those arrays is selected as the final coverage cell range.

$$R_p = min\left(\overline{R_{p_{UL}}}, \overline{R_{p_{DL}}}\right) \tag{3.20}$$

3.3.1.2 Capacity analysis

Capacity analysis is based on a large set of services parameters defined as input data. The most relevant parameters are:

- Binary rate of the service, Rb_i^s
- Bit energy to noise ratio for uplink, $\left(\frac{E_b}{N_o}\right)_i^{UL}$, and downlink, $\left(\frac{E_b}{N_o}\right)_i^{DL}$
- Average orthogonality factor, $\bar{\phi_i}$
- Activity factor, υ_i
- User demand, a_i^s
- Average connection duration, ts_i
- Blocking probability or GoS, Pb_i^s
- Service penetration, it indicates the ratio of subscribers that contract a specific service, p_i

Interference is the limiting factor in these kind of systems, and it is defined by the interference margin parameter, IM. The interference margin determines the maximum allowed load of the cell, that in third generation systems is, on average, in the range from 50% to 75%. Initial load factors per service are estimated based on the total load factor of the cell and the cell range obtained in the coverage analysis.

$$\begin{aligned}\overline{L_{DL}} &= \{L_{DL_i}, \forall i \in \mathcal{S}\} \\ \overline{L_{UL}} &= \{L_{UL_i}, \forall i \in \mathcal{S}\}\end{aligned} \tag{3.21}$$

The key factor of the capacity study is the interference margin parameter, it affects to the maximum load factor of the cell as indicated in the following equation:

$$1 > \eta_c = 1 - \frac{1}{10^{\left(\frac{IM}{10}\right)}} \tag{3.22}$$

In case of more than one frequency block is available, the algorithm makes use of as many blocks as necessary to maximize the cell range. The use of multiple blocks, N_b, affects directly to the maximum load factor of the cell:

$$\eta_c = N_b \cdot \left(1 - \frac{1}{10^{\left(\frac{IM}{10}\right)}}\right) \tag{3.23}$$

The initial aggregated traffic load of the services must to fulfill the following constraint:

$$\begin{aligned}\eta_c > \eta_{UL} &= \sum_{i=1}^{|\mathcal{S}|} L_{UL_i} \\ \eta_c > \eta_{DL} &= \sum_{i=1}^{|\mathcal{S}|} L_{DL_i}\end{aligned} \tag{3.24}$$

The load factor due to a single active connection, k, for each of the services defined is estimated as follows:

$$l_{UL_{i_k}} = \frac{1}{1 + \frac{1}{\frac{\left(\frac{E_b}{N_0}\right)_i^{UL} \cdot \nu_i \cdot R_b}{W}}}$$

$$l_{DL_{i_k}} = \frac{\left(\frac{E_b}{N_0}\right)_i^{UL} \cdot \nu_i}{\frac{W}{R_{b_i}}} \cdot [(1 - \bar{\phi}_i) + \bar{f}_{DL_i}] \tag{3.25}$$

The number of simultaneous active connections per service is based on equations 3.24 and 3.25.

$$N_{ac_{UL_i}} = \frac{L_{T_{UL_i}}}{l_{UL_{i_k}} \cdot (1 + f_{UL})}$$

$$N_{ac_{DL_i}} = \frac{L_{T_{DL_i}}}{l_{DL_{i_k}}} \tag{3.26}$$

Neighboring cells interference caused in the cell under study depends on the traffic load in those neighboring cells, and due to the soft capacity WCDMA systems characteristic makes that when cells surrounding the cell under study have low traffic load, the capacity of our cell increase, [2].

$$N_{ac_{UL_i}}|_{sc} = N_{ac_{UL_i}} \cdot (1 + f_{UL})$$

$$N_{ac_{DL_i}}|_{sc} = N_{ac_{DL_i}} \cdot (1 + \bar{f}_{DL}) \tag{3.27}$$

The next step is to calculate the maximum allowed traffic load corresponding to the number of active connections available and the grade of service. This step is performed by means of the Erlang-B equations.

$$A_{UL_i}|_{sc} = B^{-1}(N_{ac_{UL_i}}|_{sc}, P_{b_i}^s)$$

$$A_{DL_i}|_{sc} = B^{-1}(N_{ac_{DL_i}}|_{sc}, P_{b_i}^s) \tag{3.28}$$

These values are calculate on soft-capacity conditions. In case of cells carrying the same amount of traffic, the capacity of the cell under study is reduced and so does the maximum traffic load allowed. Therefore the traffic load supported is calculated as follows:

$$A_{UL_i} = \frac{A_{UL_i}|_{sc}}{(1 + f_{UL})}$$

$$A_{DL_i} = \frac{A_{DL_i}|_{sc}}{(1 + \bar{f}_{DL})} \tag{3.29}$$

The total number of users transferring data at the same time per service is estimated as of the individual traffic per service, the service distribution percentage over the UMTS technology, $D_{i,j}$, and the maximum traffic load in the cell.

$$M_{UL_i} = \frac{A_{UL_i}}{a_i^s \cdot D_{i,j}}$$

$$M_{DL_i} = \frac{A_{DL_i}}{a_i^s \cdot D_{i,j}} \tag{3.30}$$

Finally, the population density of the area, ρ, under study and number of sectors of the base station, N_s, are taken into account to obtain the cell range per service due to capacity constraints, as indicated in 3.31.

$$\overline{R_{t_{UL}}} = \left\{ R_{t_{UL_i}} = \sqrt{\frac{N_s \cdot M_{UL_i}}{\rho \cdot \pi}} \quad ; \forall i \in \mathcal{S} \right\}$$
$$\overline{R_{t_{DL}}} = \left\{ R_{t_{DL_i}} = \sqrt{\frac{N_s \cdot M_{DL_i}}{\rho \cdot \pi}} \quad ; \forall i \in \mathcal{S} \right\} \quad (3.31)$$

The algorithm selects the most restrictive cell range by capacity as a temporary solution, obtaining a unique cell range as indicated in Equation 3.32:

$$R_t = min(\overline{R_{t_{DL}}}, \overline{R_{t_{UL}}}) \quad (3.32)$$

The process described is the base of the inner problem solution. However, the obtained cell ranges in this first step can be very different from one service to another. As the goal of the inner problem is to balance the cell ranges of every service, in such a way that the exploitation of the cell capacity is maximized, an iterative process where the load factors of every service defined in the profile are reallocated in each iteration of the algorithm is required.

Once the minimum cell range due to capacity constraints is calculated, the load factors for each service are calculated following the reverse process.

$$L_{UL_i}(R_t) = N_{ac_{UL_i}}(R_t) \cdot l_{UL_i}$$
$$L_{DL_i}(R_t) = N_{ac_{DL_i}}(R_t) \cdot l_{DL_i} \quad (3.33)$$

The aggregated contribution of the services is calculated and the load factor excess is obtained:

$$L_{UL} = \sum_{i=1}^{|\mathcal{S}|} L_{UL_i}(R_t)$$
$$L_{DL} = \sum_{i=1}^{|\mathcal{S}|} L_{DL_i}(R_t) \quad (3.34)$$
$$L_e = \eta_c - max\left(L_{UL}, L_{DL}\right)$$

The excess, L_e, is reallocated to the set of services, the reallocation of L_e depends on an allocating factor, f_a, the service that limited the cell range by capacity obtains the f_a of L_e, and the rest, $1 - f_a$, is equally distributed to the rest of the services. Once L_e is redistributed, the process starts again in Equation 3.26. The algorithm performs as many iterations as necessary until a maximum threshold is met:

$$L_e < \eta_c \cdot 0.01 \quad (3.35)$$

The final cell range due to capacity constraints is defined as the R_t, Equation 3.32, when the condition in 3.35 is met.

3.3.1.3 Estimation of a single site cell range

The estimation of a single site cell range implies the use of both processes detailed above. The solution to the inner problem is given by the capacity study, and in case of the outer problem the

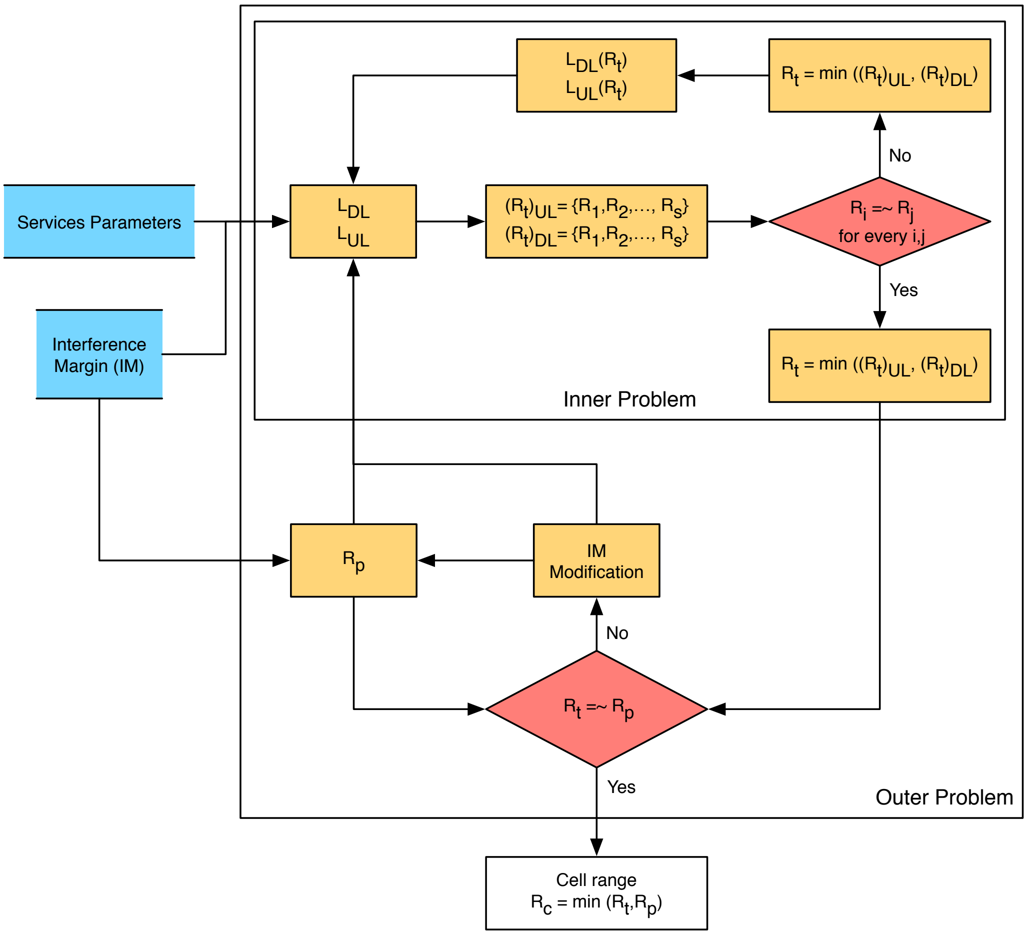


Figure 3.2: Dimensioning algorithm for UMTS technology.

algorithm modifies the maximum allowed interference level of the system until a stop condition is fulfilled. Figure 3.2 shows the full process of the algorithm.

The modification of the IM parameter is not randomly made. The maximum value of the interference margin is given to the algorithm as an input parameter, and it can be reduced, always higher than $1d\beta$, or risen, always shorter or equal to the input data value. The stop condition used by the algorithm is based on two thresholds, th_m and th_M, as indicated in 3.36.

$$th_m \leq \frac{R_p}{R_t} \leq th_M \tag{3.36}$$

It is recommended that deviation of th_m and th_M around 1 is below or equal to 1%, in this thesis, 0.99 and 1.01 values are used, respectively. Once it is met, the final cell range is selected as:

$$R_c = min\,(R_p, R_t) \tag{3.37}$$

3.3.1.4 Estimation of the UMTS Network Deployment

The process followed to perform the capacity and coverage analysis in UMTS is carried out for each possible types of base station defined in the input nodes B file, $NB = \{1 \leq k \leq |NB|\}$. As it happened for the second generation systems, the node B covered area is used to calculate the number of required base stations to deploy, N_{bs}, in a specific area within a district, as indicated in 3.14.

The cost is calculated for each possible solution, k, it depends on the associated cost to the node B under study, C_k, and the total number of base stations installed. The final solution of the algorithm is the one minimizing the total cost, $C_{UMTS}^k(\psi)$.

$$\begin{aligned} C_{UMTS}^k(\psi) &= N_{bs} \cdot C_k \\ C_{UMTS}(\psi) &= min\left(C_{UMTS}^k(\psi)\right) \qquad , \{\forall k \in NB\} \end{aligned} \tag{3.38}$$

3.3.2 HSPA Dimensioning Algorithm

HSPA is a WCDMA based system, it is based on the combination of two standards defined by the 3GPP, High Speed Downlink Packet Access (HSDPA) defined in Release 5, and High Speed Uplink Packet Access (HSUPA) defined in Release 6. The HSPA system dimensioning process is quite similar to the process explained for UMTS technology. It is divided into two main steps, estimation of the coverage cell ranges, and a capacity analysis, for both, HSDPA and HSUPA technologies.

3.3.2.1 Coverage analysis

The Cost231-Hata propagation model is chosen to carry out the coverage analysis. However, HSPA systems have special features that have to be considered in this analysis.

First, the HSDPA standard defines multiple possibilities in relation to the modulation and coding schemes, see Table 3.2. The estimation of the most suitable modulation and coding scheme used for transmitting the data is performed by a monitoring process carried out together by the handset and the node B. The detailed process is described in [98]. According to Release 5, each handset estimates the downlink channel quality and selects the value of the optimal Channel Quality Indicator (CQI) that suits the channel conditions. The CQI determines the block size to be transferred, the modulation and coding scheme, as well as the signal to interference plus noise ratio (SINR).

In order to maximize the capacity of the cell, the number of possible CQI per category has been reduce to those that maximize the offered throughput for each category, as indicated in Table 3.2.

The receiver sensitivity depends on the value of the SINR, the noise power in the receiver, N_{rx}, and the processing gain, G_p. The processing gain corresponds to the spreading factor in HSDPA. It is constant, and its value is equal to 16. The different possibilities defined make the sensitivity of the receiver, handset, differs from one to another CQI selection.

$$S_{rx} = N_{rx} - G_p + SINR \tag{3.39}$$

HS-DSCH Category	Modulation	Number of parallel codes	Inter-TTi	CQI	Offered Throughput (Mbps)
1	QPSK	5	3	15	0.553
1	16QAM	5	3	30	1.194
2	QPSK	5	3	15	0.553
2	16QAM	5	3	30	1.194
3	QPSK	5	2	15	0.829
3	16QAM	5	2	30	1.792
4	QPSK	5	2	15	0.829
4	16QAM	5	2	30	1.792
5	QPSK	5	1	15	1.659
5	16QAM	5	1	30	3.584
6	QPSK	5	1	15	1.659
6	16QAM	5	1	30	3.584
7	QPSK	5	1	15	1.659
7	16QAM	10	1	30	7.205
8	QPSK	5	1	15	1.659
8	16QAM	10	1	30	7.205
9	QPSK	5	1	15	1.659
9	16QAM	12	1	30	8.619
10	QPSK	15	1	15	1.659
10	16QAM	15	1	30	12.779
11	QPSK	5	2	15	0.829
12	QPSK	5	1	30	1.659
13	QPSK	5	1	15	1.664
13	16QAM	10	1	25	7.212
13	64QAM	14	1	30	16.132
14	QPSK	5	1	15	1.664
14	16QAM	10	1	25	7.212
14	64QAM	15	1	30	19.288

Table 3.2: HSDPA terminal categories

The next key point is to establish a relation between the CQI and the value of the SINR. Obtaining a mathematical expression capable to establish this relation is a complex process, multiple studies based on simulators [99], [100], [101], offer graphical solutions to this problem. Starting from these graphical results several analytic expressions are obtained. The expression used to estimate the SINR based on the CQI selected in this thesis, is shown in Equation 3.40.

$$SINR = \begin{cases} 0 & \text{si } CQI = 0 \\ (CQI \cdot 1.02) - 16.62 & \text{si } 0 < CQI < 30 \\ 14 & \text{si } CQI = 30 \end{cases} \tag{3.40}$$

The process to estimate the optimal CQI in the algorithm is based on two possibilities. The first one is based on the estimation of the user demanded throughput, see 3.41, and the second option is the selection of a specific handset category based on the features of the average type of mobile device used by the subscribers and the propagation channel quality.

$$t_u = (t_{MBAS} \cdot D_{i,j}) + \sum_{i=1}^{|\mathbb{S}|} (a_i^s \cdot D_{i,j} \cdot Rb_i^s) \tag{3.41}$$

where t_{MBAS} stands for the throughput, that is the guaranteed minimum binary rate of the mobile broadband access service (MBAS) at the cell edge, and $D_{i,j}$ is the percentage of traffic demand of service i over the technology j, in this case the technology is HSDPA.

The value obtained in 3.41 determines the handset category, that implies the selection of the optimal CQI, CQI_o, based on the maximum offered throughput, t_o, for that specific category. Multiple solutions exists for that case, therefore to determine which CQI is selected the following criteria is used:

$$CQI_o \quad / \quad min\,(t_o - t_u) \tag{3.42}$$

The second option is based on the capabilities of an average user, that is, the capabilities of the most part of the handsets downloading data, and the average propagation channel quality. In this case, the selection of the category fixes the CQI used.

The HSUPA standard shares with HSDPA the existence of different terminal categories based on the number of parallel codes, transmission time intervals (TTI), and spreading factor used to transfer data, see Table 3.3.

Category	Number of parallel codes	TTIs (ms)	Spreading factor	Rate with 10 ms TTI (Mbps)	Rate with 2 ms TTI (Mbps)
1	1xSF4	10	4	0.72	N/A
2	2xSF4	2, 10	4	1.45	1.45
3	2xSF4	10	4	1.45	N/A
4	2xSF2	2, 10	2	2	2.91
5	2xSF2	10	2	2	N/A
6	2xSF2 + 2xSF4	2, 10	2	2	5.76

Table 3.3: HSUPA terminal categories

Receiver sensitivity, in this case the sensitivity of the node B, depends, as it happens in the HSDPA case, on the SNR value as indicated in 3.39. However, there are two aspect to take into account when performing the HSUPA coverage analysis:

- Processing gain (G_p). In this case, this parameter is not a constant, it depends on the binary rate of the service, in this thesis it depends on the minimum guaranteed throughput at the cell edge.

$$G_p = \frac{R_c}{R_b} = \frac{W}{t_u} \tag{3.43}$$

- SNR corresponds to the required E_b/N_0 value. The E_b/N_0 is a continuous function that depends on the user throughput. The estimation of the values of this function is shown in graphical results obtained by simulations of the propagation link, [102], [103]. It is possible to obtain mathematic expressions approximating the graphic results, [68]. The algorithm implemented in this thesis uses the values obtained from [103], see Table 3.4

Category	Number of parallel codes	TTI (ms)	Spreading factor	SNR ($d\beta$) 10 ms
1	1xSF4	10	4	-9.71
2	2xSF4	2, 10	4	-7.78
3	2xSF4	10	4	-7.78
4	2xSF2	2, 10	2	-5.19
5	2xSF2	10	2	-6.36
6	2xSF2 + 2xSF4	2, 10	2	-2.91

Table 3.4: SINR en enlace ascendete HSUPA

3.3.2.2 Capacity analysis

The objective of the HSPA capacity analysis is to estimate the number of required network equipment to fulfill a specific demand. It has to be carried out separately for downlink and uplink.

On the one hand, the HSDPA capacity estimation is based on the maximum allowed throughput of the cell and the generated throughput. The first issue is to estimate the throughput demanded by a single user inside a cell, see Equation 3.41. This value is assumed to be valid for every user in the coverage area of the cell. The total number of users in the cell, M_{DL}, is based on the coverage area of the cell, A_{bs}, the penetration of the mobile broadband service, γ, and a third parameter known as overbooking factor (OBF). The OBF is defined as the inversion of the percentage of users downloading / uploading data simultaneously, it is accepted to have a value equal to 20 [69]. The total demanded throughput in the cell, T_u, is estimated as follows:

$$\begin{aligned} T_u &= t_u \cdot M_{DL} \\ M_{DL} &= A_{bs} \cdot \rho \cdot \gamma \cdot OBF \end{aligned} \tag{3.44}$$

Second, the offered throughput by the cell is calculated. This value depends on multiple factors such as the number of frequency blocks available, N_b, the number of parallel codes used, c, the number of slots per TTI, s, the number of bits per symbol that depends on the modulation scheme selected, b, the effective code rating, EFC, the number of symbols per slots, sy, and the time period between transmission and reception intervals, t_{TTI}. Equation 3.45 indicates how to calculate the total offered throughput of a cell.

$$T_c = N_b \cdot \left(\frac{c \cdot s \cdot b \cdot EFC \cdot sy}{t_{TTI} \cdot 2} \right) \tag{3.45}$$

Finally, a comparison between offered and demand throughput is performed. In terms of downlink capacity, the offered throughput of the cell have to be larger than the demanded by the users. In case this condition is not met, the coverage cell range, which is considered to be the downlink capacity cell range, $R_{t_{DL}}$, is reduced by a 5% factor in this thesis. The goal of this process is to decrease the number of users in the area covered by the cell, and therefore the demanded throughput. This process is repeated until it fulfills the condition in 3.46:

$$T_u \leq T_c \tag{3.46}$$

On the other hand, HSUPA capacity is based on the equations explained for the UMTS case. The process is exactly the same followed in the UMTS case, taking into account that in the HSUPA case there is only one service with a throughput based on Equation 3.41. However, and due to the asymmetric characteristic of the mobile broadband traffic, internet traffic, the modified throughput for the uplink implies the use of a reduction factor, τ. It is accepted to assume that the uplink throughput in the busy hour is a 30% of the downlink throughput, see [66].

$$t_u^{UL} = t_u \cdot \tau \tag{3.47}$$

The simplified HSUPA capacity estimation process is the following:

- Maximum uplink capacity of the cell calculation

$$\eta_{UL} = N_b \cdot \left(1 - \frac{1}{10^{\frac{IM}{10}}} \right) \tag{3.48}$$

- Estimation of the load factor of a single connection, k, for the aggregated service

$$l_{UL_k} = \frac{1}{1 + \frac{W}{(E_b N_0)^{UL} \cdot \upsilon \cdot t_u^{UL}}} \tag{3.49}$$

- Calculation of the total number of active connections
- Application of the Erlang-B equations to obtain the maximum traffic load of the cell, and therefore the total number of users in the cell, M_{UL}.
- Finally, supposed a uniform users density, ρ, and based on the number of sectors, N_s, the capacity cell rage for the uplink is estimated

$$R_{t_{UL}} = \sqrt{\frac{N_s \cdot M_{UL}}{\pi \cdot \rho}} \tag{3.50}$$

The minimum value among uplink and downlink capacity cell ranges is selected as the final capacity solution for HSPA.

$$R_c = min\left(R_{t_{UL}}, R_{t_{DL}}\right) \tag{3.51}$$

3.3.2.3 Estimation of a single site cell range

The previous process is performed for every type of node B defined in the input data. The final cell range for the HSPA is estimated as the most restrictive among the coverage and capacity cell ranges. The complete process of the algorithm is shown in Figure 3.3.

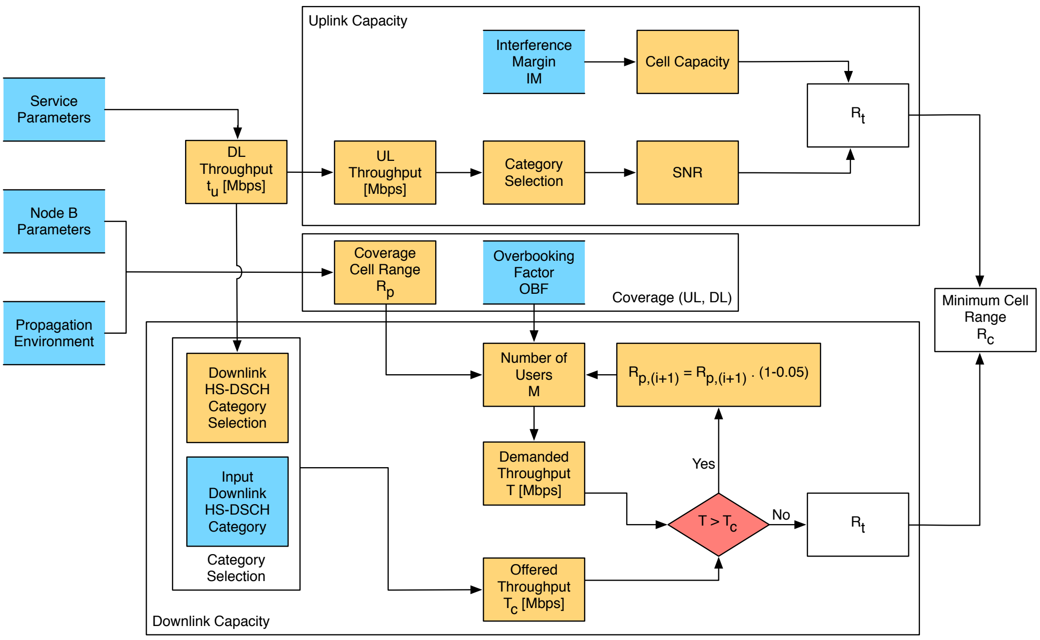


Figure 3.3: Dimensioning algorithm for HSPA technology.

3.3.2.4 Estimation of the HSPA Network Deployment

Once the final cell range is estimated, the total number of required HSPA equipment is estimated based on Equation 3.14. The associate cost to each of the possible solution, k, is calculated as indicated in Equation 3.52. The cheapest solution is selected as the final solution of the HSPA deployment.

$$C^k_{HSPA} = N_{bs} \cdot C_k$$
$$C_{HSPA}(\psi) = min\left(C^k_{HSPA}(\psi)\right) \qquad , \{\forall k \in NB\} \tag{3.52}$$

3.4 Fourth Generation Cellular Dimensioning Algorithms

The dimensioning process of the fourth generation system, LTE, is quite similar to the process described for the HSPA technology. Both LTE and HSPA make use of a frequency reuse pattern of 1, similar performance specifications, similar services, and are based on coverage and capacity analysis. The main objective is to ensure good SINR in the network area. In this section a description about the dimensioning process for LTE is given.

3.4.1 Coverage analysis

Based on the same model applied to WCDMA systems, the Cost231-Hata model. The implemented algorithm makes use of an external link level simulator to estimate the value of the required signal to interference noise ratio, SINR, at the cell edge used during the dimensioning process. SINR at the cell edge depends on the modulation and coding scheme selected, the number of resources blocks, the antenna configuration, the gains due to scheduler and HARQ, etc.

In addition, Rayleigh fading, also known as fast fading, margin is not taken into account in the LTE coverage process due to a very short TTI (1ms) and fast AMC/scheduling mechanisms preventing falling into the fading gaps. The IM parameter in LTE represents the safety margin that needs to be taken into account in the maximum allowed cell load in order to compensate the effect of both intra-cell and inter-cell interference.

3.4.2 Capacity analysis

In this case, only downlink capacity analysis is implemented in the algorithm, due to it is the most restrictive case. It is based on the physical resource block concept explained in 2. The total capacity of the cell depends on the available frequency bandwidth, as it is presented in [104] there are up to 6 different options of channel bandwidth from 1.4 MHz up to 20 MHz. Additionally, up to 29 modulation and coding schemes, MCS, for uplink and downlink are defined in the LTE standard developed by the 3GPP in [105].

The cell edge user throughput is calculated as indicated on Equation 3.41, this value determines the minimum MCS index accepted to start the capacity dimensioning process. The starting MCS is the one whose transport block size is larger than the cell edge user throughput. Once the minimum MCS index is selected, the capacity dimensioning process starts.

First, the algorithm calculates the number of total PRBs available, N^{total}_{RB}, based on the available bandwidth, Δ_{BW} as indicated on Equation 3.53. Second, the total number of users is estimated based on the number of PRBs available and the number of PRBs per user, N_{RB}^{user} this last value is obtained by means of the link level simulator.

$$N_{RB}^{total} = \frac{\Delta_{BW} \cdot 0.9}{\Delta f} \tag{3.53}$$

Finally, and based on the numbers of sectors of the evolved node B under study, N_s, and the user density of the area within a specific district, ρ, the cell range due to capacity constraints is obtained as follows:

$$R_t = \sqrt{\frac{N_s \cdot \left(\frac{N_{RB}^{total}}{N_{RB}^{user}}\right) \cdot \gamma \cdot OBF}{\rho \cdot \pi}} \tag{3.54}$$

The described process is executed for every MCS available, and the optimal one is selected as final solution. The algorithm evaluates the cost of every MCS possible solutions selecting the cheapest one as the final solution. The higher the MCS index is, the higher the capacity of one cell is, and therefore its cell range. This evaluation process achieves the balancing coverage and capacity objective, the algorithm selects the MCS that maximizes the cell capacity according to the maximum coverage range for each area within the district under study.

3.4.3 Estimation of a single site cell range

At the end of both coverage and capacity analysis, the algorithm selects the final cell range as the most restrictive one among them, that is the shortest one. This process is carried out for every evolved node B defined in the input data file related to LTE base stations. A complete description of the LTE algorithm is shown in Figure 3.4.

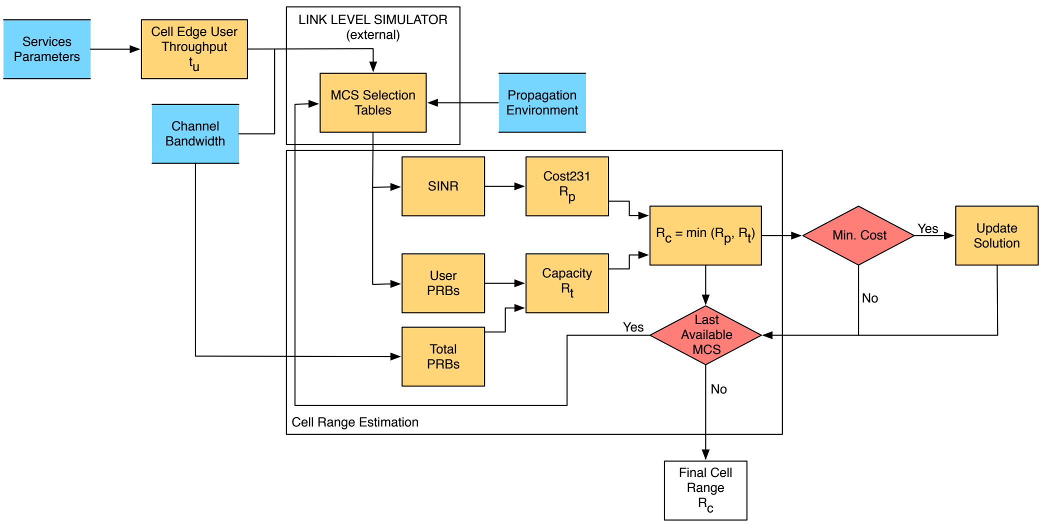


Figure 3.4: Dimensioning algorithm for LTE technology.

3.4.4 Estimation of the LTE Network Deployment

Coverage and capacity studies are carried out for every possible type of evolved node B defined as input data to the algorithm, $eNB = \{1 \leq k \leq |eNB|\}$. The algorithm provides a different final cell range for each of the eNode B types and therefore a different total number of equipment required and associated cost, $C_{4G}^{k}(\psi)$. The total number of base stations is calculated based on the surface of the area under study and the covered area of the corresponding base station, as indicated in 3.14. The final solution is selected as that which minimizes the investment cost.

$$\begin{aligned} C_{4G}^{k} &= N_{bs} \cdot C_{k} \\ C_{4G}\left(\psi\right) &= min\left(C_{4G}^{k}\left(\psi\right)\right) \qquad , \{\forall k \in eNB\} \end{aligned} \tag{3.55}$$

Chapter 4

Proposed Metaheuristic algorithms for the Optimal Service Distribution Problem (OSDP)

In the previous chapter, a set of algorithms for carrying out the radio access network dimensioning process have been introduced. These algorithms perform two main tasks: first, they estimate the number, type and location of the necessary equipment to be installed in order to fulfill a set of propagation and capacity constraints. The second objective, minimizing the invested cost in network equipment is also analyzed by the dimensioning algorithms. However, both processes, the network dimensioning and the cost optimization (carried out by the algorithms in Chapter 3) depend on a specific scenario, E, given as an input to the model.

The scenario E is based on a set of files defining the necessary parameters, such as radio propagation conditions, type of base stations for every technology considered, as well as the set of services, together with the user demand and its distribution over the different technologies, the user classes distribution over the different regions within a district, market penetration and market share. This chapter focuses its efforts on estimating the optimal distribution of the user demand over the technologies to be deployed. This kind of optimization processes have been tackled by means of the application of metaheuristic algorithms such as bio-inspired and evolutionary algorithms in different fields, see Chapter 2.

In this work, a classical evolutionary algorithm, EA, a novel bio-inspired algorithm based on the Coral Reef Formation process, CRO, and a Teaching-Learning Based Optimization algorithm, TLBO, have been implemented and applied to perform the optimization process. In the following sections, a complete description of the algorithms, together with their main features, is given.

4.1 Encoding, Objective and Fitness Function

The objective of these algorithms is to estimate an optimal distribution, $\mathcal{D}$, of the user demand of each of the services defined in $\mathcal{S}$. Optimization algorithms are based on the existence of a set of candidates to solve the problem, these candidates are commonly known as chromosomes or individuals. Each of these individuals is defined by a set of parameters, genes or characteristics, that are the variables to work with to solve the optimization problem. In our case, the individuals are formed by the different services considered in the input services profile, these services are defined, among other parameters, by the distribution of the services over the technologies, this distribution constitutes the individual's characteristics of our problem.

The first step when implementing an optimization algorithm is the population encoding. The encoding depends on the features of the search space of the possible solutions of the problem. Different optimization problems have their own features and multiple encoding schemes such as binary encoding, integer encoding, real encoding, etc. In the case we work on, the search space belongs to the set of the real numbers, limited between 0 and 1, that is, the most suitable encoding scheme to apply in our problem is a real encoding, $D_{i,j} \in [0, 1]$. Figure 4.1 shows the encoding used in our optimization problem.

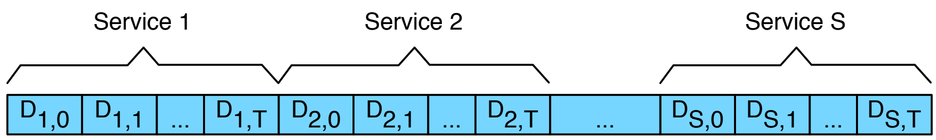


Figure 4.1: Problem encoding definition

Using this encoding, additional constraints have to be taken into account when defining an individual. The model distinguishes between two different types of constraints. On the one hand, the capabilities of each technology to carry traffic of the different services considered, e.g., classical voice service can only be carried by either GSM or UMTS, HSPA or LTE cannot provide this service. On the other hand, and attempting to make the implemented algorithms as close as possible to real world cases, minimum thresholds per service per technology are also available. This last constraint makes possible to take into account factors such as previous network investments and depreciation. Table 4.1 shows an example of both set of constraints.

Service	Technology Constraints				Operator Constraints			
	GSM	UMTS	HSPA	LTE	GSM	UMTS	HSPA	LTE
Voice	-	-	0	0	0.25	0	0	0
Video-Call	-	-	0	0	0	1	0	0
Streaming	-	-	-	-	0	0.4	0	0
Guranteed-Data	-	-	-	-	0	0.4	0	0
Best-Effort	-	-	-	-	0	0.4	0	0
SMS	-	-	-	-	0.25	0	0	0
MMS	-	-	-	-	0.25	0	0	0
MBAS	0	0	-	-	0	0	0.75	0

Table 4.1: Services Technology and Operator Constraints

The key point for every optimization algorithm is the fitness function. Evaluations of the fitness function determine the evolution of the population to the optimal solution. In our problem, the fitness function estimates the investment cost incurred on network equipment, and therefore the problem's objective is to minimize the total cost of the network deployment, $C(\psi)$, fulfilling the quality constraints of the set of services $\mathcal{S}$. The result of the deployment depends on the set of services $\mathcal{S}$, the distribution of these services over the technologies $\mathcal{D}$ and the corresponding scenario E, $\psi(E, \mathcal{S}, \mathcal{D})$. Given E and $\mathcal{S}$, the cost of the deployment exclusively depends on an optimal services' distribution over the technologies, $\mathcal{D}$.

$$\text{Find } \mathcal{D} \quad / \quad min(C(\psi(E, \mathcal{S}, \mathcal{D})))$$

The total investment cost depends on more than one hundred different parameters, such as number and type of sites, base stations and sectors, hybrid or pure sites and base stations, total number of highways and railways sites, base stations and sectors, etc. Due to the many input parameters involved in the analytic expression of $C(\psi)$ and for the sake of simplicity, it can be summarized by dividing it up in three different parts:

$$C(\psi) = C_s + C_{BS} + C_f \tag{4.1}$$

where:

- C_s: Defined as the investment cost of the site, including terrain and civil working investment. This factor depends on the type of technology or technologies' combination installed in each site.
- C_{BS}: Cost of the base station. It depends on the type of technology, the type of base station considered, macro-cell, micro-cell or pico-cell, and number of sectors in each base station.
- C_f: Investment cost of the required frequency-related hardware resources. In the case of 2G-GSM technology the total number of TRX installed in each BS is considered. In 3G-UMTS and 3G-HSPA, the cost is defined by the total number of carriers, radio-frequency (RF) modules, required in the dimensioning process. It is supposed that each RF module is capable of managing only one 5 MHz frequency block. Finally, in LTE, the eNodeBs considered are able to manage the whole set of LTE bandwidth possibilities, from 1.4 MHz to 20 MHz. This makes the price of this equipment to be larger than classic 3G system's NodeBs. This feature makes unnecessary the definition of a new hardware frequency-related cost parameter for LTE.

4.2 The Coral-Reef Optimization Algorithm (CRO)

Corals are marine invertebrate animals that typically live in colonies of multiple identical polyps, although they can subsist as individuals too. One of the main types of corals is the reef-builder coral, also known as hard-coral. These reef-builder corals segregate calcium carbonate by the basis to build exoskeletons. A coral reef is formed by hundred of hard-corals cemented together by the calcium carbonate of their bases.

Corals reproduce both sexually and asexually. Moreover, sexual reproduction can have external or internal fertilization. In both cases, eggs are fertilized by sperm, usually from another colony, developing into larvae. These larvae, depending on the type of fertilization, will settle in a few weeks, days or even hours. Most stony corals are broadcast spawners and fertilization occurs outside the body (external fertilization). Broadcast spawning is based on the production and release of gametes into the water, once the egg and sperm meet together a larva is produced, and once it finds a proper place to attach, a polyp starts growing. On the other hand, few corals brood their eggs in the body of the polyp and release sperm into the water, this sperm goes inside the body of the coral containing the eggs and the fertilization occurs inside the body (internal fertilization). Finally, asexual reproduction, also known as budding, happens when a coral polyp reaches a certain size and divides itself, producing a genetically identical copy of itself. In this type of reproduction, external factors such as storms and boats' grounding can also cause fragmentation.

In this work, we simulate this coral biology, in the CRO algorithm, in order to estimate the optimal distribution of the users' demand for every service defined in the services' profile, $\mathcal{S}$. Therefore, the first step is to determine how to encode the distribution of the user's demanded traffic. As this distribution indicates the percentage of the user's demand of every service that is carried by one specific technology, and it depends on the number of technologies available, a real encoding for this distribution is done, $D_{i,j} \in [0, 1]$. This aspect is described in Section 4.1.

The CRO algorithm is based on four different processes: an initialization phase, a reproduction phase, a larvae allocation phase and a depredation phase.

First, a fraction of the coral reef is initialized from randomly generated corals or polyps. The creation of the initial coral larvae is made by means of a pseudo-random process (note that several technology constraints related to the capabilities of each technology has to be taken into account – Table 4.1 – which might affect the feasibility of individuals). Later on, these larvae are settled into the reef at randomly chosen positions. Note that after the initialization process not all the positions are occupied, this is necessary to guarantee the correct simulation of a coral reef formation in real world.

Second, the reproduction phase consists of three different types of reproduction: external sexual reproduction, implemented by means of crossover operators, see Figure 4.2, internal sexual reproduction, that uses a random mutation, and asexual reproduction carried out by randomly choosing one among the best existing corals and making a copy of it.

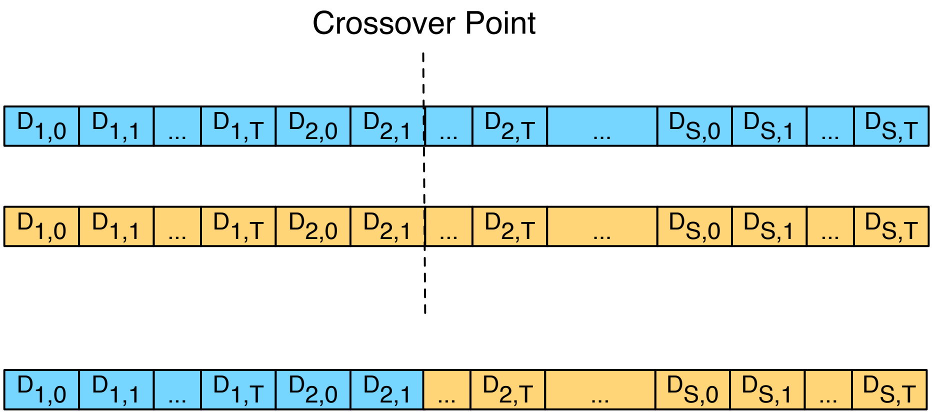
- The external sexual reproduction or **broadcast spawning**, is simulated using a crossover operator applied to a fraction of the existing corals, F_b. Our model implements the following crossover operators: one point crossover, two points crossover and N-swap crossover. The type of crossover operator used in the algorithm is set at the beginning of the process, and maintained during all the generations of it.

  The one point crossover operator randomly selects two parents among the existing corals in the reef, and a random point where the crossover is performed to generate a new coral larva (Figure 4.2(a)). Once the parents are chosen they are no longer used for reproduction purposes at a given iteration. This new coral larva will become a coral at the beginning of the next iteration, after the larvae setting process that will be explained later.

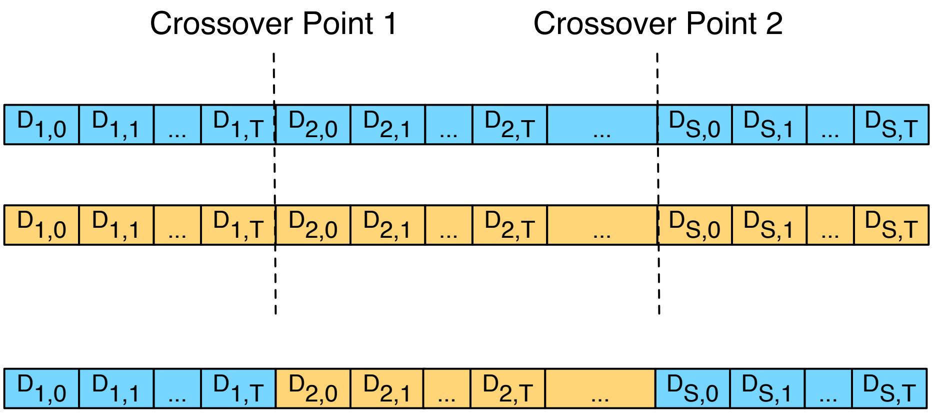
  The two points crossover operator is based on the same process as the one point crossover. In this case, a random selection of two different points, where the crossover is performed, is done (Figure 4.2(b)).

  Finally, the N-swap crossover operator follows the same parents selection procedure, and randomly chooses N blocks of services, in the encoded inhabitant, to be swapped (Figure 4.2(c)).

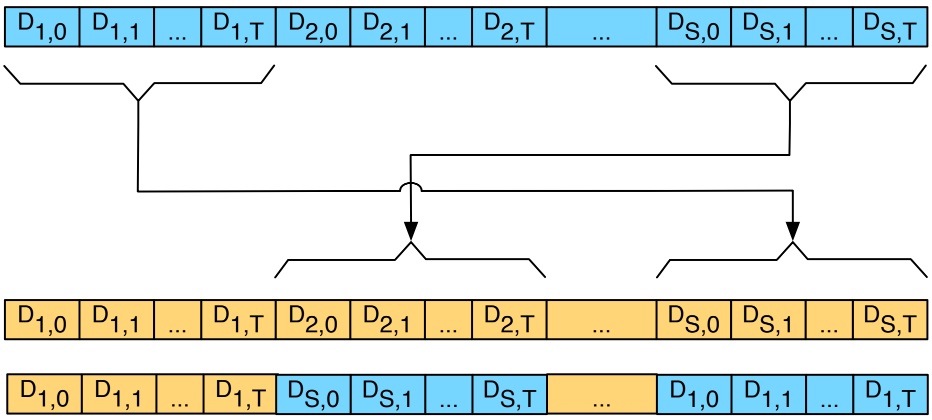
  As has been previously mentioned, the distribution of the traffic demand over the different technologies has to meet specific constraints, which depends on each specific scenario, see Table 4.1. Thus, after the crossover takes place, a reparation phase starts. During this reparation phase, the algorithm checks whether all the constraints are fulfilled, and if not, the larva is repaired. This operation may affect one or several services within the larvae's encoding.



(a)



(b)



(c)

Figure 4.2: Crossover Operators: (a) 1 Point; (b) 2 Points; (c) N-Swap

- Internal sexual reproduction or **brooding**, as it is less likely to occur, has been implemented by using the mutation operator over the complementary fraction, $1 - F_b$, of existing corals at iteration k. The mutation is done over a randomly selected characteristic of the coral, that is a specific percentage of a service over one technology, and it is performed by the aggregation or subtraction of a extremely low randomly generated number to the value of a specific characteristic. As it occurred in broadcast spawning reproduction, a reparation phase follows the brooding method to ensure viable corals.

- The asexual reproduction occurs with a very low probability, P_a, at each iteration k. To be performed, the existing corals are sorted by their health function in ascending order, choosing a fraction, F_a, of the corals and making a copy of one, randomly chosen, among the selection.

Using the operators above, the new coral larvae are generated and the setting phase starts. First, the CRO algorithm calculates the health function of every larva. Second, a random position, (i, j), of the reef is chosen to host the larva. On the one hand, if the chosen position is empty, the new larva settles in the reef. On the other hand, if the position is occupied by a previous larva, a comparison of the health function's value is carried out. If the health function value of the new larva is better than the existing coral, then the new larva replaces the former coral and is settled in the reef, otherwise, a new position in the reef, $(i, j)'$ is randomly chosen and the allocation phase for this larva starts from the beginning. The CRO algorithm defines a maximum number of attempts, κ, to settle each larva.

Finally, at the end of each iteration k, the CRO algorithm checks out the status of the reef. Should the reef be full, a depredation phase is performed. A fraction of corals, F_d, having the worst health function is selected as candidates to be discarded. The depredation of the candidates occurs with a very low probability, P_d. Figure 4.3 shows the general process followed by the CRO algorithm.

The process explained above is performed iteratively until a specific stopping condition is met. In our problem, the stop condition is defined by the number of total evaluations of the health function. Once the number of evaluations reaches the defined threshold, the algorithm stops and selects the best coral, in terms of investment cost, as the final solution of the optimization phase.

4.3 The Evolutionary Algorithm (EA)

Evolutionary algorithms are population based heuristics proposed as an approach to artificial intelligence [74]. These kind of algorithms have been applied to many different numerical optimization problems [106], [107], including telecommunications problems [108]. The optimization process performed by evolutionary algorithms is divided into a set of different steps described as follows.

Let us consider a set of M individuals population. First, an initialization phase where the M individuals are pseudo-randomly initialized is performed, during this phase a set of constraints are considered according to the capabilities of each mobile technology carrying the services defined in $\mathcal{S}$. One of the main differences between this EA and the CRO algorithm is the initialization phase, while in the CRO algorithm few of the position in the reef are empty after this phase, the EA has the complete population at the beginning.

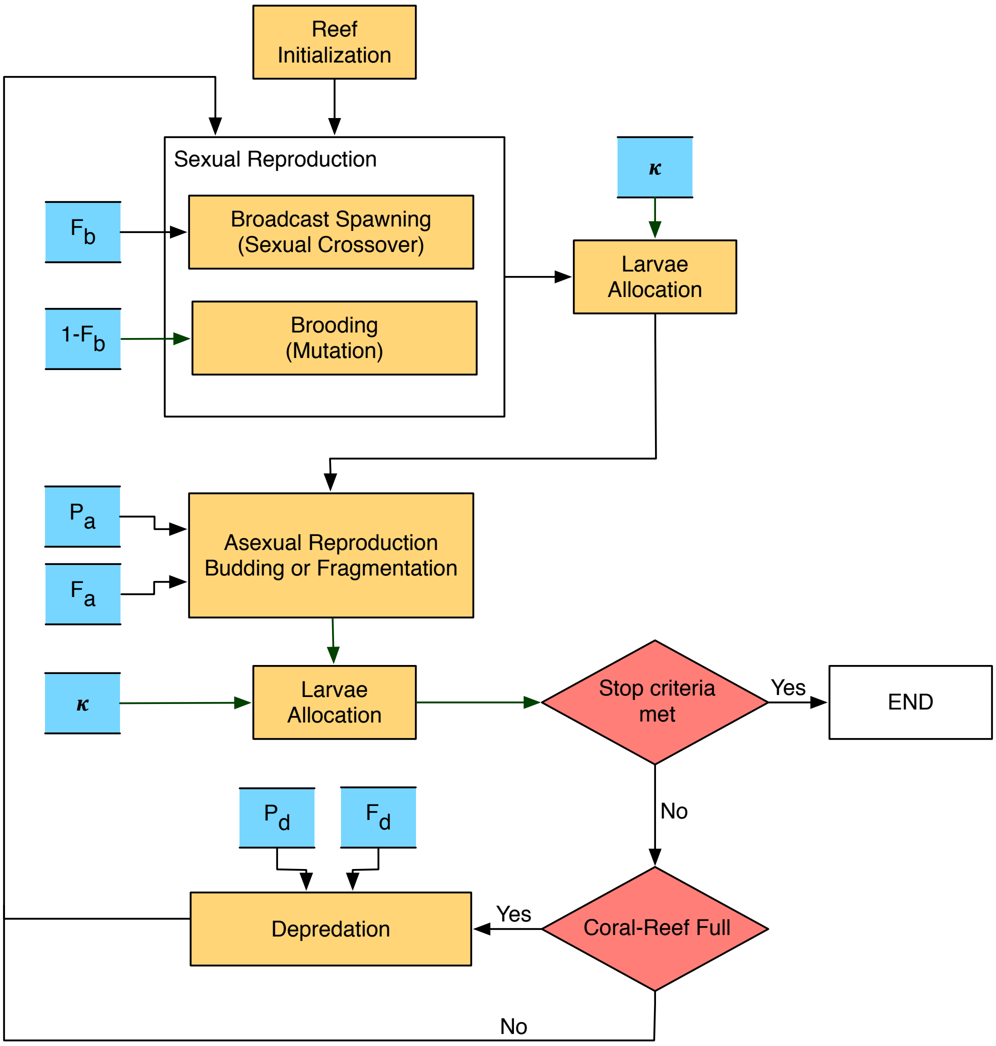


Figure 4.3: Flow diagram of the CRO Algorithm

Once the initialization phase is over, the evolution phase is performed, which is based on the application of well-know crossover, selection and mutation operators, iteratively until a stop condition is met.

- **Crossover operator:** Two different inhabitants are randomly chosen in order to create two new candidates to be part of the next iteration population. The crossover operators implemented for this EA are the same as in the CRO case. After the application of the crossover operator the total size of the population is $2 \times M$.

- **Mutation operator:** Once the new candidates are created, a random mutation is performed over a small fraction of the actual inhabitants. The mutation mechanism is the same as in the CRO case.

- **Selection operator:** At each iteration, k, a set of inhabitants among the total existing ones, parents and new inhabitants formed by means of crossover and mutation operators, is selected according to their fitness function, the algorithm chooses those having the best fitness function, $min(C(\psi))$, based on a typical tournament selection operator. This method selects one candidate to be in the next generation and faces it up to an 80% of the existing population, randomly selected, comparing the candidate's fitness function to the fitness function of each opponent. Those inhabitants with the largest number of victories evolve to the next iteration.

4.4 The Teaching Learning Based Optimization Algorithm (TLBO)

The TLBO algorithm is based on the algorithm proposed in [96]. The algorithm simulates the learning process followed by human beings. The learning process is divided into two main phases, a teacher phase where the influence of a teacher is considered, and the learner phase where the learning is made through interaction with other pupils. The result of a learning process is measured by the final marks of the pupils for every subjects, which defines fitness function of the algorithm. These subjects constitute the characteristics of each of the inhabitants in the developed algorithm.

The algorithm starts with an initialization phase, where all the pupils are defined. Let us assume a total number of M individuals that constitute the set of pupils involved in both learning phases. This phase is subject to the fulfillment of the technology and operator constraints stated in Table 4.1.

The learning process starts with the teacher phase. The teacher phase needs the figure of a teacher, in our problem the teacher is selected based on the value of the fitness function, that is, the teacher is the pupil whose calculated invested cost is minimum, $min(C(\psi))$. At each iteration, k, and assuming a set of subjects equal to $|\mathcal{S}| \times |\mathcal{T}|$, the mean value, $m^k_{(i,j)}$, of the distribution of service i on technology j is calculated. A teacher is selected among the entire population, the selection is done based on the investment cost calculated in the fitness function. The teacher distribution of the services on the different technologies is taken as the starting point of this phase. Based on this teacher, the difference between each of the pupils characteristics and the mean value of the entire population is estimated as indicated in Equation 4.2.

$$\Delta m_{i,j,k} = r_k \cdot (D^t_{i,j} - T_F \cdot m_{i,j,k}) \tag{4.2}$$

where $D^t_{i,j}$ stands for the distribution of the service i on the technology j defined by the teacher t. T_F is a teaching factor applied to the mean value at each iteration, and r_k is a random number in the range $[0, 1]$. The value of T_F is decided randomly as indicated in Equation 4.3.

$$T_F = round[1 + rand(0, 1)] \tag{4.3}$$

Once the mean value and the teacher factor are estimated, the existing population is modified based on the teacher and the value of those parameters. Equation 4.4 indicates the influence of those parameters in the learning process of each pupil in the teacher phase.

$$D'^{Pupil}_{i.j,k} = D^{Pupil}_{i.j,k} + \Delta m_{i,j,k} \tag{4.4}$$

where $D'^{Pupil}_{i.j,k}$ is the new value of the distribution of the service i on the technology j of the individual $Pupil$ at iteration k. Once all the characteristics of a specific individual are updated, the algorithm calculates the investment cost due to that specific distribution of the services, and the new pupil is accepted in case that the new fitness function improves the previous one.

The next step in the learning process is the learner phase. In this phase, the inhabitants learn by interaction between them, no teacher is needed. The algorithm selects two random individuals and performs a fitness function comparison, which determines which of the selected pupils learns from the other one. Let us assume two random inhabitants, $I1$ and $I2$, and $C(\psi_{I1})$ and $C(\psi_{I2})$ the fitness functions of both inhabitants:

$$\begin{aligned} D''^{I1}_{i,j,k} &= D'^{I1}_{i,j,k} + r_i \cdot (D'^{I1}_{i,j,k} - D'^{I2}_{i,j,k}) \qquad \text{if } C(\psi_{I1}) > C(\psi_{I2}) \\ D''^{I2}_{i,j,k} &= D'^{I2}_{i,j,k} + r_i \cdot (D'^{I2}_{i,j,k} - D'^{I1}_{i,j,k}) \qquad \text{if } C(\psi_{I2}) > C(\psi_{I1}) \end{aligned} \tag{4.5}$$

The algorithm accepts the modified individual when its fitness function value is better, in this case lower, than the previous fitness function value.

The implemented algorithm offers the possibility of considering elitism. The elitism operator selects a fraction, F_e, of the best individuals at iteration k, and performs a random mutation on one of the characteristics of the selected subset. Once the mutation is performed, the fitness value corresponding to the new individuals is estimated. Following the same procedure, a set of $F_w = F_e$ worst individuals at iteration k is also chosen. Later on, each of the new individuals is faced up to a randomly selected individual (belonging to the F_w set). The mutated candidate replaces the randomly chosen individual in case it improves the fitness function value, that is, in case it minimizes the investment cost. Figure 4.4 shows the general process followed by the teaching-learning based optimization algorithm.

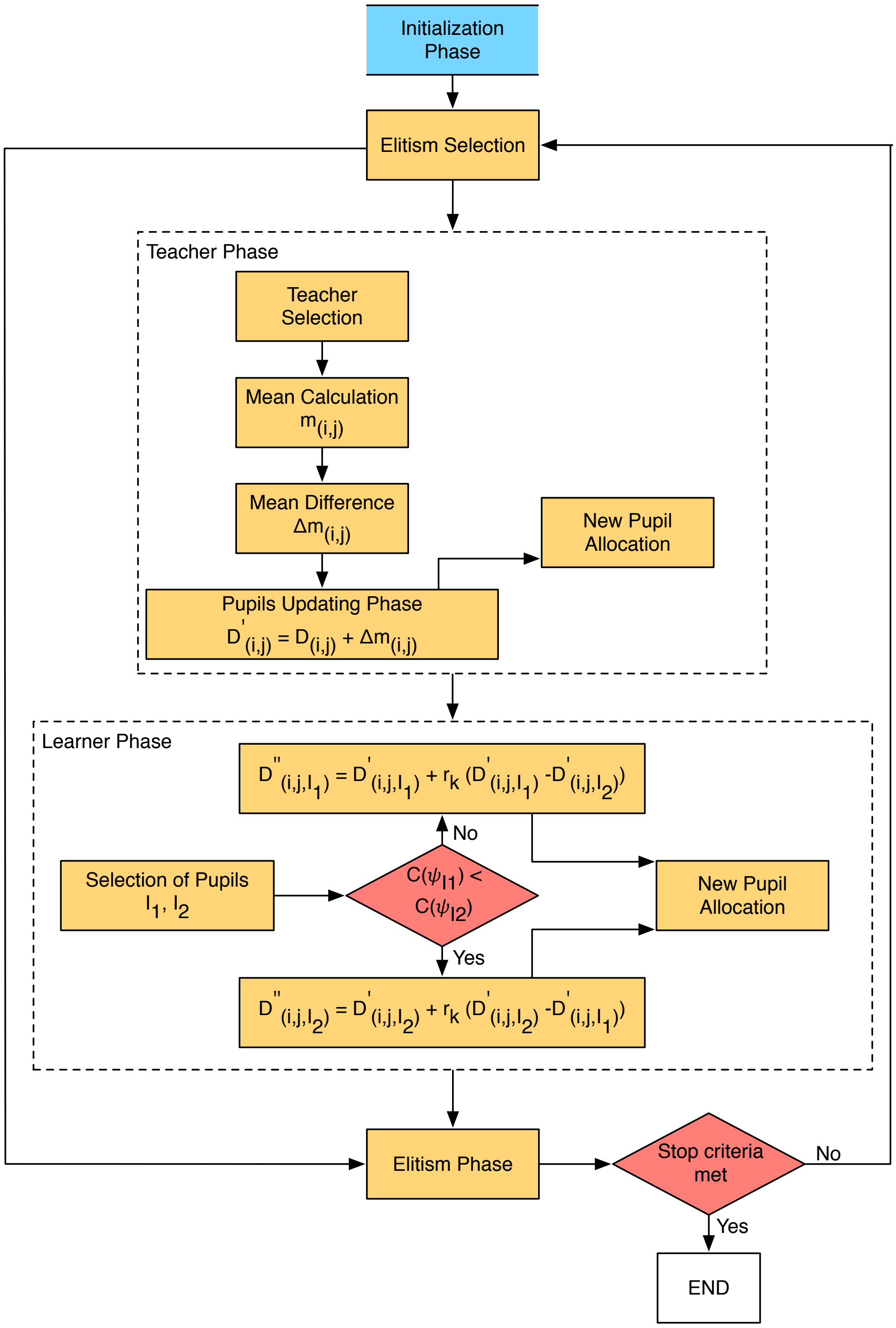


Figure 4.4: Flow diagram of the TLBO Algorithm

Chapter 5

Strategic Network Planning and Optimization Tool

The deployment of an efficient and cost optimized network, due to the installation of a new technology or updating the existing technology, is one of the key that determines the success or failure of the project. For these purposes strategic network planning tools (SNTP) are used, they help the operators managers to take decisions about the most convenient strategy to follow. In this chapter, a general description about the strategic planning and optimization tool developed in this work is given.

The developed tool is based on two modules, the dimensioning module and the optimization module. Both modules, are programmed as dynamic link libraries (dll), making use of the Visual Studio 2010 programming environment, and the C++ language. This makes the modules portable and easy to integrate with different graphical users interfaces such as Excel interfaces, Visual GUIs, etc. In addition, a simple GUI, making easier checking and modification tasks is implemented, also making use of the Visual Studio environment and the Microsoft Foundation Class (MFC).

In previous chapters, 3 and 4, the algorithms implemented to perform the dimensioning process of mobile RAN, as well as the optimization algorithms to solve the optimal service distribution problem, have been explained in detail. Now, we focus on the dimensioning module, which is in charge of estimating the necessary network equipment to fulfill specific coverage and capacity constraints and the associated cost of the solution. The dimensioning result depends on the distribution of the services defined, this input data is provided by the optimization module. Therefore a relation between both dimensioning and optimization modules is established.

5.1 SNPT Origins and Evolution

Current deployment and optimization tool has its origin in a previous existing tool. A first version of the tool was developed in 2006, this version of the tool offered the possibility of dimensioning a 2G network for both single and dual band cases. The algorithm developed for the 2G network dimensioning process was based on the classic Erlang-B traffic model and the application of the Cost231-Hata model for coverage purposes, working on the 900 and 1800 MHz frequency bands. This tool was applied to the regulatory projects in Australia (ACCC, 2006) and Swiss (BAKOM, 2007).

In 2008, the decision of updating the tool to offer the possibility of dimensioning 3G networks was taken. This decision arose complex challenges on the designing process of the algorithms in charge of dimensioning 3G networks, which were solved in a three-steps process. A first approach, where a UMTS technology dimensioning algorithm was implemented, the main features of this algorithm were: a coverage analysis based on the Cost231-Hata propagation model, working on the 2100 MHz frequency band, and a single block capacity analysis. The second step in the process, at the beginning of year 2010, was the updating of the UMTS dimensioning algorithm and the implementation of the one in charge of the HSPA dimensioning process.

On the one hand, a multi block UMTS dimensioning algorithm was developed, offering the possibility of working in multiple frequency bands and with different bandwidths available, for coverage purposes the Cost231-Hata model was used, and the lowest frequency among the available ones was used. On the other hand, and in a parallel way, a single block HSPA dimensioning algorithm, based on the same propagation model used in the 2G and 3G-UMTS cases, was developed. By the end of year 2010, the last of the three steps was implemented. The improvements was related to the extension of the HSPA algorithm to a multi block dimensioning algorithm, together with the possibility of deploying not only a 2G network but also a hybrid 3G UMTS/HSPA network in highways and railways. This second version of the tool was applied to the regulatory process of Swiss (BAKOM, 2010) and Austria (RTR, 2011) in collaboration with the german company WIK-Consult GmbH (WIK) and the University of Cantabria (UC).

Finally, in year 2011, and due to the increasing necessity of analyzing the effect of the new LTE technology, the last updating of the tool was developed. This third version, current version of the tool, offers the possibility of dimensioning 2G, 3G and LTE networks in a hybrid environment. The LTE dimensioning algorithm implemented makes use of an external link level simulator to obtain the necessary data to carry out the coverage and capacity analysis, and it offers the possibility of working with different bandwidths, although only one frequency band has to be considered, that is, all the available bandwidth has to be included in the same frequency band. This last version of the tool has been applied to the german regulatory process (BNetzA, 2012). This project was developed in collaboration with WIK and UC. Figure 5.1 shows the graphical evolution of the tool from the first version to the current one.

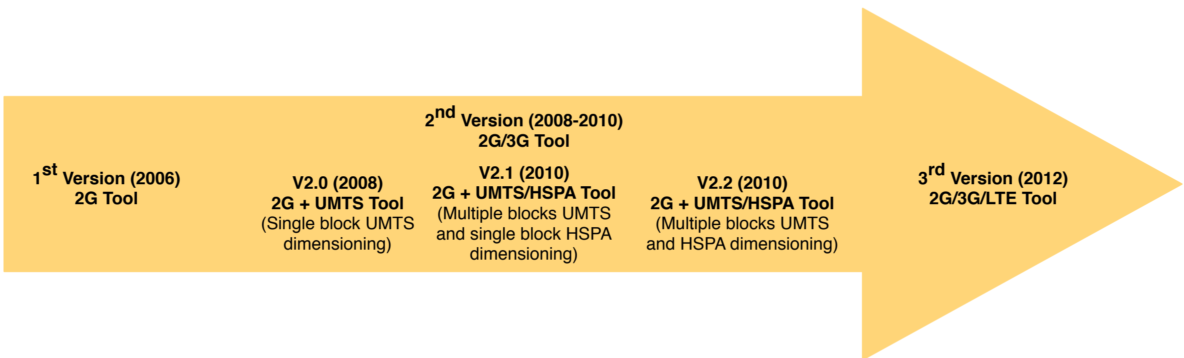


Figure 5.1: Origins and Evolution of the SNPT

5.2 SNPT Input and Output Data Specification

The correct functioning of the current SNPT is based on a set of input files where the scenario, E, is defined. The definition of E is based on the following files:

- Districts: It contains the characteristics of the main cities and villages where the radio access network is deployed. Every city is divided into three different areas, urban, suburban and rural in terms of extension and population. Moreover, the type of terrain, flat, hilly and mountainous of each city is also defined.
- Base stations: A set of three different input files defining the main characteristics of the base stations for each technology, BTS, NodeB and eNodeB. Parameters such as transmission power, antenna height, sectors, carriers, transceivers, etc., are defined.
- Radio Environment Files: Based on three different input files, each of them for the different technologies defined, 2^{nd}, 3^{rd} and 4^{th} generation. They define the most relevant radio propagation features, such as frequency bands and bandwidths available, building losses, fast fading and slow fading margins, etc.
- Services: It contains the set of services considered. Every service is defined by a set of different parameters, among which, the binary rate of the service, the grade of service or blocking probability, together with the quality of the service and the traffic load per subscriber, are the most relevant in the deployment result.
- Device Mobile Files: Three different input files are defined. These files include information related to the transmission power, sensitivity-related parameters and losses for the mobile devices for the 2^{nd}, 3^{rd} and 4^{th} generation technologies.
- Highways and Railways: It defines the main features of the highways and roadways of the country, length and population density.

The deployment module performs the radio access network dimensioning process for every district and the whole set of services. Once the estimation of the required equipment is done, the tool generates a set of output files per technology where the information about the results of the deployment is given, see Figure 5.2. The most relevant output files per technology are:

- The *BA* file: It contains information about the type and number of base stations and sites for a specific technology, together with the associated cost, cell range of each base station and the total covered population per type of area. These information is given for every city and area where the deployment has been performed.
- The *SBH* file: It is a summary countrywide output file. It contains the total number of sites and base stations required in the whole country. This information is given for every type of base stations defined in the input file.
- The *traffic* output files: The total offered traffic, as well as the carried traffic by the network, is indicated in this file. This information is detailed for every type of are, urban, suburban and rural, and for every service defined in the service profile. One *traffic* file per technology is required.

The results obtained from the network deployment in highways and railways are given in four additional output files, *HLR*, grouped into two different categories (2^{nd} and 3^{rd} generation).

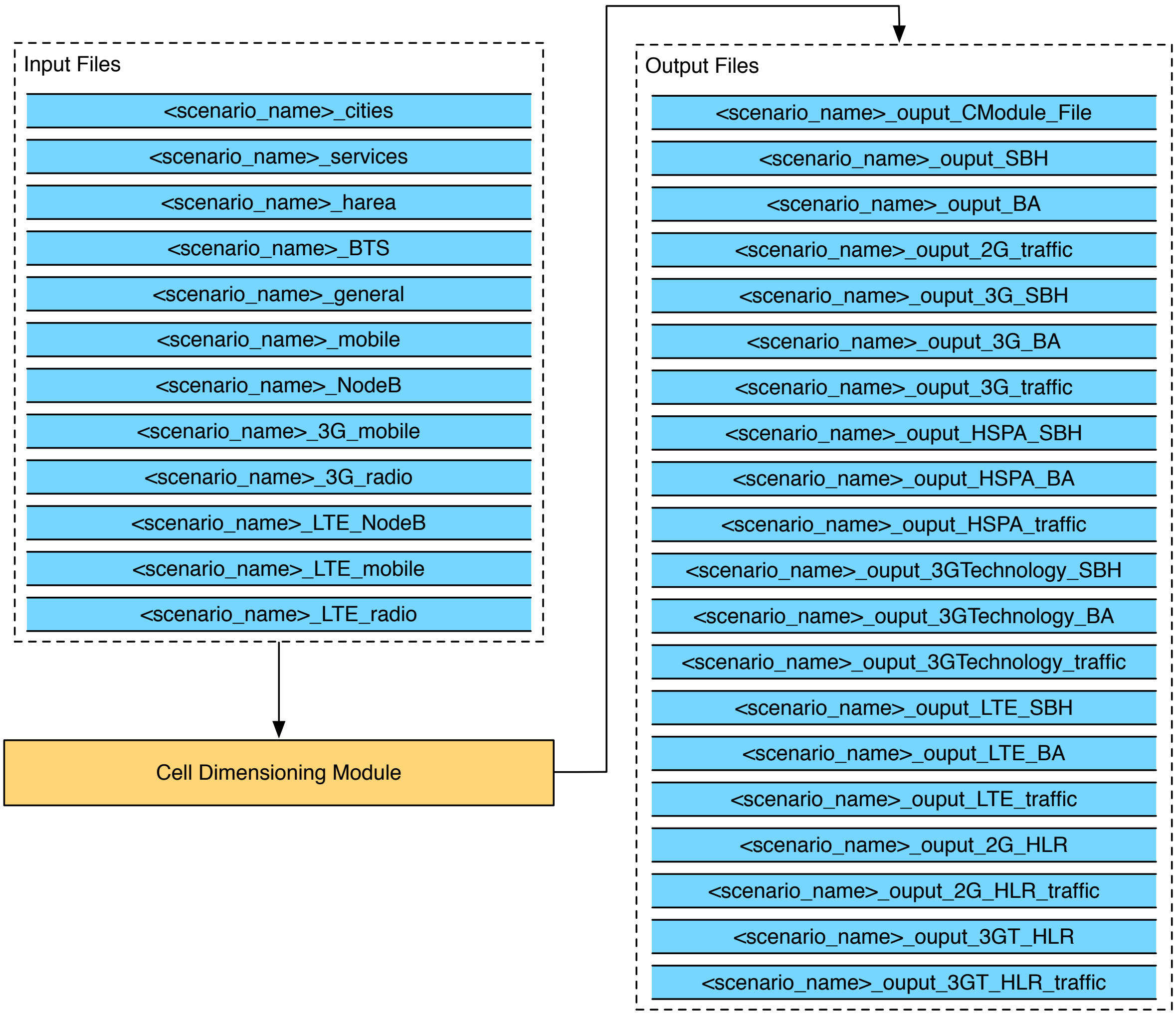


Figure 5.2: Input and Output files definition for the Cell Dimensioning Module

These files contain information about the offered and carried traffic, and type and number of base stations together with the corresponding cell range, in a similar way that has been explained for the cities.

Moreover, the tool generates also a summary output file, *CModule_File*, where the most relevant information about the RAN results is given. This file contains technology-related information such as:

- Number and type of sites, macro, micro or pico.
- Number and type of base stations, pure or hybrid base stations.
- Number of sectors installed in every base station, pure and hybrid sites are considered.
- Number of transceivers for the 2^{nd} generation base stations in pure and hybrid sites.
- Number of carriers for the 3^{rd} generation base stations in pure and hybrid sites.

- Frequency bands in used for every technology deployed.

5.3 Dimensioning Module

This module is based on the algorithms described in Chapter 3. The objective of this part of the tool is to obtain the total number of network elements required to meet the coverage and capacity constraints defined by a specific scenario, E.

The tool allows to perform the dimensioning process in each area within every district defined in the scenario, as well as in the highways of the country under study. There are several possible technology combinations depending on the number of technologies to be deployed, see Table 5.1. In case of highways, only pure second generation technology, GSM-EDGE, or hybrid third generation systems, UMTS-HSPA, are considered.

Option	District / Highway	Type of network	Technology
0	District	Pure 2G	GSM/EDGE
1	District	Hybrid	GSM/EDE + UMTS/HSPA
2	District	Hybrid	GSM/EDGE + LTE
3	District	Pure 3G	UMTS/HSPA
4	District	Hybrid	UMTS/HSPA + LTE
5	District	Hybrid	GSM/EDGE + UMTS/HSPA + LTE
0	Highway	Pure 2G	GSM/EDGE
1	Highway	Pure 3G	UMTS/HSPA

Table 5.1: Technology combinations

Dimensioning algorithms are valid for both districts and highways. From a technical point of view, highways are treated like rural areas when applying the Cost231 propagation model. In addition, the way to estimate the total number of sites and required network equipment differs slightly from the way followed in the districts case, due to highways base station covered terrain is supposed to be longitudinal.

The dimensioning process for each of the technologies considered is carried out independently, minimizing the investment cost related to each of them. However, the tool is capable to reduce the investment cost of the whole network due to two main aspects:

- Site sharing. Besides allowing site sharing between technologies, it also allows to reduce the investment cost related to the site acquisition due to the possibility of sharing it with other operators. In case of only technology sharing, the type of site selected is the largest one, macro, micro and pico sites have different requirements in terms of surface when installing the cabinet and the antenna in the site, and therefore the worst case has to be selected to fulfill the most restrictive case.

- Base Station sharing. This aspect is relevant in third technology systems, where commercial equipment have facilities for UMTS and HSPA technologies integrated in the same cabinet. The tool allows to integrate both technologies by calculating the maximum number of sites and base stations related to both technologies. The selection of the base station in case of an UMTS/HSPA hybrid node B is based on the most restrictive one in terms of capacity, number of sectors and carriers, and coverage, macro, micro or pico cell type.

Once the dimensioning and individual investment cost optimization process is performed, the tool provides a nationwide network equipment summary output. This summary contains information about the total number of network equipment such as type and number of sites per technology combination, type and number of base stations, number sectors, carriers and transceivers, and the different frequency bands used by each technology.

5.4 Optimization module

Based on the algorithms detailed in Chapter 4. The main objective of this part is to configure the different possibilities of the services distribution over the set of considered technologies based on a fitness function criterion, minimizing the investment cost of the dimensioning process. Therefore, it plays an important role in the initial phase of the dimensioning process, defining the user demand to be carried by each of the technologies.

This user demand distribution is used as input data by the dimensioning module and a network deployment result is obtained. Based on this result, the optimization module estimates the total cost of the network. The total investment cost calculation function is defined by the optimization module, this function makes use of the whole information contained in the summary output information, see Section 5.3, and an additional input set of parameters related to the unitary costs:

- Sites. Terrain and civil work investment costs per site. These costs, as already explained, are shared by the technologies considered, and it can be also shared by different operators.
- Base stations. Unitary cost of the different types of base stations considered. The total cost depends on the type of base station, the number of sectors and transceivers in case of second generation systems, number of sectors and carriers in case of third generation networks, or only number of sectors for the fourth generation case.
- Sectors. Cost associated to each sector for a specific type of base station and technology.
- Transceivers. Cost associated to the spectrum unit in second generation systems.
- Carriers. Cost associated to the spectrum unit in third generation systems.

Figure 5.3 shows a simple flow diagram that clarifies the interrelation between the dimensioning and the optimization module.

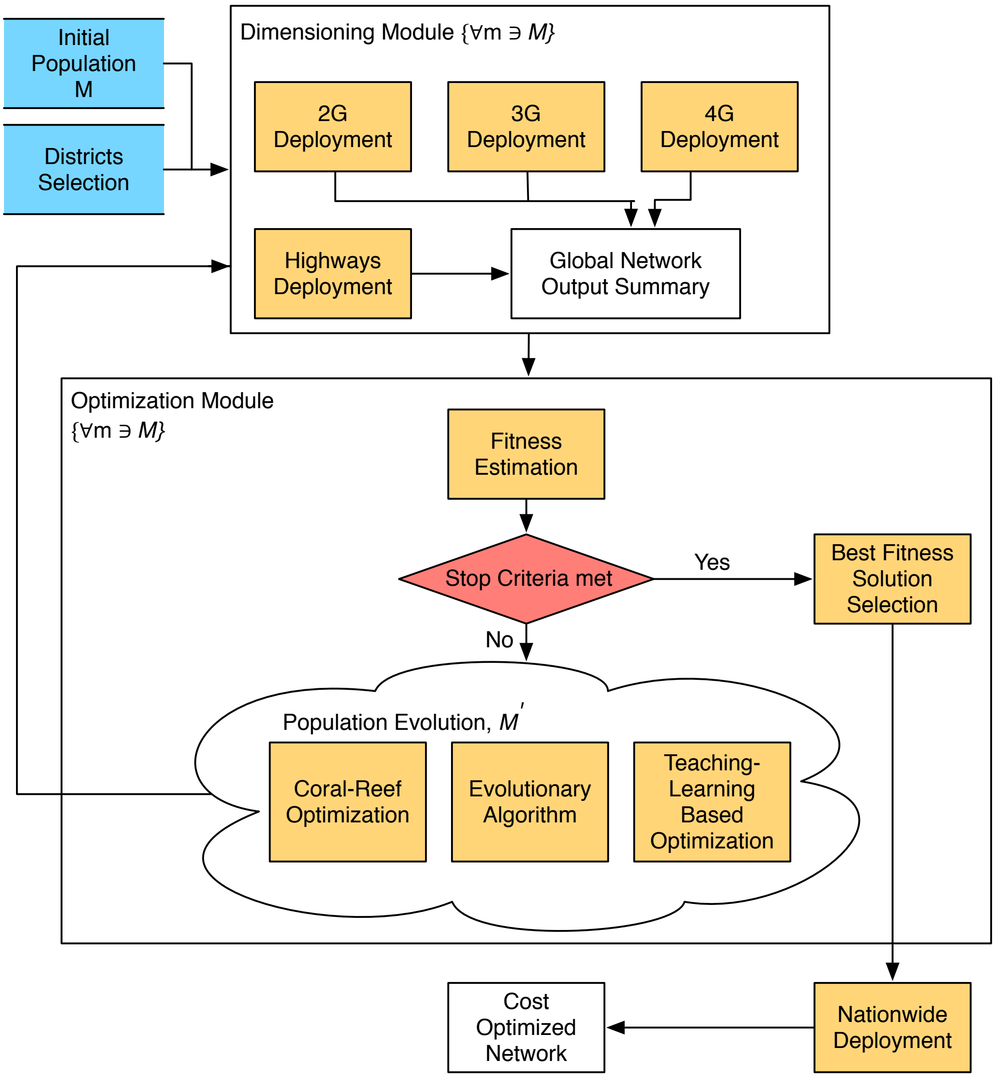


Figure 5.3: Dimensioning and Optimization Software Tool

Chapter 6

Experiments and Results

Multiple applications, such as mobile communications regulatory projects, education, dimensioning and optimization of mobile networks, spectrum impact on costs analysis, etc., are suitable to be solved by the dimensioning and optimization algorithms detailed in Chapters 3 and 4.

In this chapter, the performance, efficiency and application of the developed dimensioning and optimization algorithms are evaluated by means of their application to two different experiments:

- **Experiment A:** Techno-economical study based on the efficiency comparison between the HSPA and LTE technology to provide the Mobile Broadband Access Service. The goal of this case is to determine the most suitable technology, HSPA or LTE, to provide the internet broadband service based on the required investment costs of the cellular network deployed. Only the network dimensioning module is applied, no optimization algorithms are used to balance the traffic demand over the technologies. The distribution of the traffic demand over the set of technologies considered is defined by the user.
- **Experiment B:** Performance evaluation of the metaheuristic optimization algorithms. The aim of this experiment is to evaluate the impact on the resulting investment costs of an optimal service distribution over the set of technologies to be deployed. The developed optimization algorithms, EA, CRO and TLBO, are applied to obtain the most efficient user demand distribution, in terms of investment costs, to be used by the cell dimensioning module to carry out the estimation of the total network equipment. Finally, the investment costs associated to the optimal service distribution and the investment cost of a experience-based traffic distribution are compared.

6.1 Spanish country definition

Experiments are focused on the spanish country. Information about the geographical areas of Spain is obtain from the data provided by MapInfo. MapInfo is a geographic information system software, and it divides the country of Spain into ten thousand geographical areas. The first step is the generation of the set of cities and villages where the radio access network is going to be deployed. In order to achieve this goal, the data provided by MapInfo is used by a *Scenario Generator* module (ScenGen). The ScenGen defines a set of aggregator areas (AgA). The rest of geographical areas (GeA) are aggregated to these aggregator areas in an iterative process. This aggregation process is based on two different set of thresholds, population density and distance thresholds for each type of area (urban, suburban and rural). The process is summarized as follows:

- Data obtained from MapInfo is sorted by the type of area. Urban areas are at the top, suburban areas in the middle, and rural areas are at the bottom.
- For each type of area, they are ordered according to population density.
- The GeA located at the top is chosen as the first AgA. In the following iteration, the AgA is the one with the highest population density, among the not yet aggregated areas.
- Once the AgA is identified, a threshold comparison phase starts. The process evaluates the population density of the AgA. In case that the population density is larger the population density threshold defined for that type of area (urban, suburban and rural), all the not yet aggregated geographical areas inside the aggregation radius defined are aggregated to the chosen AgA.

This process defines the cities file where the radio access network is going to be deployed. In our case, it defines a set of 5354 different cities. For each of the cities the most relevant information, among other parameters, is:

- Total population. Urban, suburban and rural population is detailed.
- Total extension of the city, together with the corresponding area in square kilometers for urban, suburban and rural type of areas.
- Type of terrain, flat, hilly and mountainous.
- Average height of buildings.
- Type of radio access network deployment for every area within a city.

Once the cities are configured, this file is included in the scenario E, and the simulations of the experiments are launched. Note that it is also required an estimation process to carry out the user demand of the different services defined in the service profile. This process is described in Section 6.2.

6.2 Traffic load definition process

The input data used for all the scenarios considered is based on data obtained from the Spanish Telecommunications Market Commission annual report [109]. First, the traffic load of the voice service is obtained from the total annual minutes consumed by the subscribers, Θ_{py}. In this work, a month is considered to have 22 business days, D_m, and 6 business hours per day, H_d. Based on this data, and assuming one call attempt per busy hour, the traffic load of the voice service is estimated as indicated in Equation 6.1.

$$a_{voice}[mE] = \frac{\Theta_{py}/(12 \cdot D_m \cdot H_d)}{60} \tag{6.1}$$

The traffic load of the data services, as there is no information in the Spanish Telecommunications Market Commission (CMT) report, is treated as voice-equivalent miliErlangs[1] (ve-mE), and therefore obtained from the value estimated in 6.1 as indicated in Equation 6.2.

$$a_i[\text{ve-}mE] = a_{voice} \cdot \frac{Rb_j}{Rb_i} \qquad , \forall i \neq j \in \mathcal{S} \tag{6.2}$$

[1]Short Message Service (SMS) and Multimedia Message Service (MMS) excluded

where Rb_j is the binary rate of the voice service, and Rb_i corresponds to the binary rate of the data service i, defined in the input service profile.

Finally, the traffic load of the short message service (SMS) and the multimedia message service (MMS) is calculated. The traffic load of the SMS is calculated from data in [109]. The starting point is the number of SMS per user per year, M_{sms}, and based on the characteristics of this service, 128 bytes of length, L_m, the traffic per user is estimated.

$$a_{sms}[mE] = \left(\frac{M_{sms}}{12 \cdot D_m \cdot H_d}\right) \cdot \left(\frac{L_m \cdot 8}{Rb_{sms}}\right) \tag{6.3}$$

The MMS traffic load is estimated as a percentage of the SMS traffic, this percentage is based on the existing ratio, r, between the SMS and MMS for the whole set of operators in Spain, see [109].

$$a_{mms}[mE] = a_{sms} \cdot r \tag{6.4}$$

In case of the MBAS, the throughput per user is most relevant parameter when dimensioning the radio access network. It determines the total volume of downloaded data. Taking as reference the value in the CMT report, the total volume of downloaded data in year 2011 was of 90.500 Terabytes. The total population registered in Spain in the last 2011 was of 46.152.926 inhabitants, based on this value the corresponding volume of downloaded data per user per month, , V_u, is estimated. This value is taken as reference in order to calculate the minimum guaranteed binary rate for the MBAS that is used to dimension the HSPA and/or LTE network, parameters such as considered business days per month, and hours per business day are taken into consideration in this calculation.

$$R_b[Mbps] = \frac{(V_u \cdot 8)/(D_m \cdot H_d)}{3600} \tag{6.5}$$

The process described is required to obtain the user demanded traffic for every experiment defined. The final results of the amount of traffic per service and the total demand is shown in tables in the corresponding experiment definition's sections.

6.3 Application Example A: Performance and cost impact of HSPA and LTE as MBAS carrier technologies

Mobile Broadband Access Service provides Internet access at very high binary rate to mobile subscribers. HSPA and LTE technologies, due to their technical features such as access mode to the air interface, spectrum efficiency, modulation and coding schemes, etc., are capable of achieving the high binary rates demanded by the user, and therefore they are the most efficient technologies to provide MBAS.

However, there are aspects to be studied when an operator decides to provide MBAS. First, it is convenient to decide which technology, HSPA, LTE, or a mix of them, is going to be deployed. In addition, the spectrum available is also a relevant aspect to analyze due to its impact in the propagation conditions, as well as the bandwidth available in each of the frequency band, which affects the capacity of the network. In this section a study on the type of technology, frequency bands and bandwidth available when providing MBAS with different downloaded data volumes, is carried out.

The objective of this analysis is to evaluate the impact, in terms of provision costs, tthat has he use of HSPA or LTE technology. In order to evaluate this, six different scenarios are defined, Table 6.1 shows the spectrum features, frequency bands and bandwidth available, of every scenario defined. The defined scenarios are coherent with the current sharing of spectrum in Spain [110].

Scenario	Frequency Bands and Bandwidth (MHz)					
	GSM		UMTS	HSPA	LTE	
	900	1800	2100	2100	2100	2600
A	10	19.8	5	5	-	-
B	10	19.8	5	10	-	-
C	10	19.8	5	-	5	-
D	10	19.8	5	-	10	-
E	10	19.8	5	-	-	5
F	10	19.8	5	-	-	10

Table 6.1: HSPA vs. LTE Scenarios Definition

Scenarios defined can be divided by the technology providing the internet access service, HSPA or LTE, and the available spectrum resources. The goal of this division is to compare the different scenarios to evaluate:

- Scenarios $\{A, B\}$ vs. $\{C, D\}$: It determines which technology, HSPA or LTE, is the most efficient one when providing MBAS. The spectrum resources used by HSPA and LTE are exactly the same, and therefore the differences in the results are only due to the different technological features of each of the technologies considered.
- Scenarios $\{C, D\}$ vs. $\{E, F\}$: The impact of the use of a different frequency bands for LTE, with the same amount of available spectrum in both cases, is studied.

A multi-service profile is considered when performing the network deployment simulations based on the scenarios defined in Table 6.1. The user demand used in the simulations is based on the last annual report from the spanish telecommunications market commission (CMT), see [109]. The user demand shown in Table 6.2 is used for all the scenarios defined.

In this first experiment, only the cell dimensioning module of the developed tool is used. The distribution of the services over the different technologies is shown in Table 6.11 (Section 6.4). Note that the distribution is based on a calibration process of the tool for two real world cases, Vodafone and Movistar.

Based on the result of the Equation 6.5, three different values are considered in this study, 428 Kbps, 1024 Kbps and 1536 Kbps, that corresponds to a volume of downloaded data per user per month of 374.65 Mbytes, 881 Mbytes and 1751.2 Mbytes, respectively. The application of the network dimensioning algorithms, detailed in Chapter 3, gives information about the number, type and location of the radio access network equipment required to satisfy the coverage and

A (mE)	Voice	Video Call	Streaming	Guaranteed Data	Best Effort	SMS	MMS	MBAS (Kbps)
90	13	2.48	2.48	1.08	1.08	2.48	2.48	Variable

Table 6.2: Services definition

capacity constraints of each scenario. Based on this information, and applying a simplified LRIC cost model, the cost per megabyte is estimated, and therefore the corresponding provision cost of the MBAS based on the total downloaded data volume per month and user is obtained.

Based on the fundamentals of the LRIC model, once the total investment cost is estimated, the annual cost of the investment is obtained. In our case, neither money depreciation nor growth of network utilization is considered, and therefore a simple division between the economic lifetime of the assets is used to obtain the annualized cost of the network. In this scenario, the economic lifetime of the assets are considered to be 10 years [111], [112]. This annualized cost has to be referred to a common unit for all the services. Generally accepted units in communications networks are minutes or downloaded data units. In this analysis the Megabyte is taken as the unit which the estimated costs are referred to, and therefore we obtain the cost per Megabyte, C_{MB}, as indicated in Equation 6.6.

$$C_{MB} = \frac{C(\psi) \cdot (1 + k_{O\&M} + k_a)/Y}{V_u \cdot M \cdot 12} \tag{6.6}$$

where: M corresponds to the total number of MBAS subscribers and $C(\psi)$ is the total investment cost associated to the network deployment. The rest of the parameters in Equations 6.6 and 6.7, $k_{O\&M}$, k_a, Y, are described in Table 6.3.

Concept	Description	Value
Economic Lifetime (Y)	Expected time period during an asset, or network element, is useful, that is, it produces a good or service of value. It corresponds also to the time period over which the asset is depreciated. In this case, it is measured in years.	10
Additional Costs (k_a)	Costs due to aggregation, backhaul and core network. It is defined as a percentage of the RAN costs.	30%
Operation and Maintenance Costs ($K_{O\&M}$)	Costs incurred for operating and maintaining tasks. Defined as a percentage of the RAN costs.	15%

Table 6.3: Economic Parameters Definition

Finally, a flat monthly rate is estimated based on the cost of the downloaded Mbyte. For this purpose, additional factors such as the routing factor, business costs, benefits and taxes are considered. The routing factor indicates the number of times that each network element is used to download a Mbyte. In order to download a file or a webpage, the user has to request the information to download. This request is sent from the mobile device to the network, uplink, and then the network sends the contents to be downloaded in the reverse direction, downlink. This process makes that all the network elements are used twice.

The additional costs used in this process are based on the efficient 25% market share scenario for the Australian regulatory project carried out by WIK, [29]. The business cost corresponds to the ads and marketing campaigns, together with the O&M costs, are considered as a factor of 45% of the RA network invested cost, [113]. The taxes is the last parameter to be considered, in the spanish case the taxes represents the 21% of the total cost per Mbyte. Table 6.4 details the different parameters used in the cost estimation process.

Concept	Description	Value
Business Costs (k_b)	Costs due to ads and marketing campaigns. Define as a percentage of the RAN costs.	30%
Profit (k_p)	Profit can also be considered. In the model, it is defined as a percentage respect to the RAN cost per MB. In order to determine the cost of providing the MBAS, this parameter is set to 0. No profit is considered.	0%
Taxes (k_t)	Value added tax	21%
Routing Factor (τ)	Number of times each network element is used.	2

Table 6.4: Economic Parameters Definition

$$C_{Flat} = (C_{MB} \cdot \tau) \cdot (1 + (k_b + k_t + k_p)) \cdot V_u \tag{6.7}$$

Based on the process described, Tables 6.5, 6.6 and 6.7 show the estimated investment costs, cost per Mbyte and monthly flat rates, for a data volume of 374.65 Mbytes, 881 Mbytes and 1751.2 Mbytes, respectively.

	Investment Costs (M€)			Cost per MB (€)		Monthly Flat Rate (€)	
Scenario	$C(\psi)$	$C_{HSPA}(\psi)$	$C_{LTE}(\psi)$	HSPA	LTE	HSPA	LTE
A	2710.78	581.89	-	0.0027	-	3.105	-
B	2713.16	472.64	-	0.0022	-	2.522	-
C	2832.80	-	437.33	-	0.0021	-	2.334
D	2830.54	-	434.29	-	0.0020	-	2.317
E	2835.37	-	441.68	-	0.0021	-	2.357
F	2831.93	-	436.74	-	0.0021	-	2.331

Table 6.5: Estimated Costs for a user downloaded data of 374.65 Mbytes

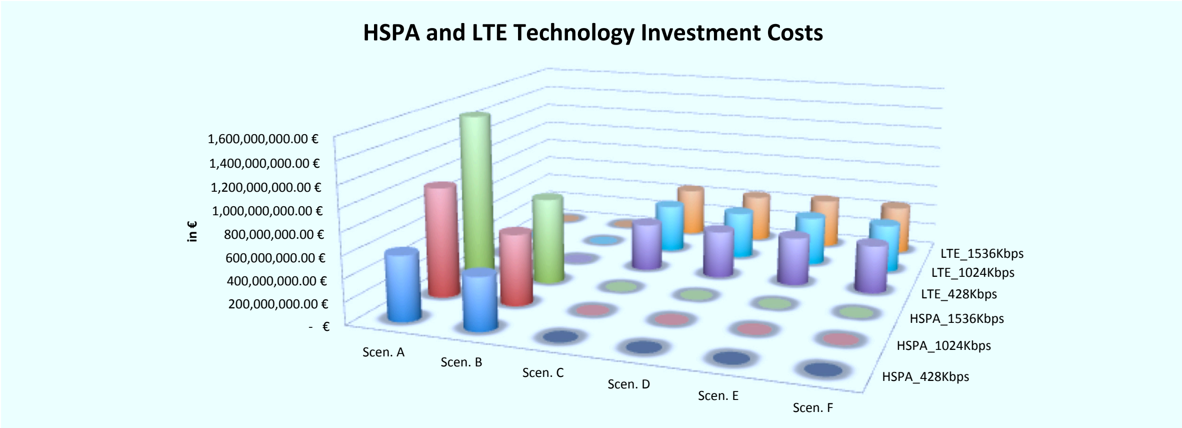
	Investment Costs (M€)			Cost per MB (€)		Monthly Flat Rate (€)	
Scenario	$C(\psi)$	$C_{HSPA}(\psi)$	$C_{LTE}(\psi)$	HSPA	LTE	HSPA	LTE
A	2928.96	998.65	-	0.0021	-	5.672	-
B	2748.26	643.71	-	0.0014	-	3.656	-
C	2840.55	-	449.30	-	0.0010	-	2.552
D	2833.71	-	439.66	-	0.0009	-	2.497
E	2843.77	-	455.59	-	0.0010	-	2.588
F	2837.14	-	446.36	-	0.0010	-	2.535

Table 6.6: Estimated Costs for a user downloaded data of 881 Mbytes

	Investment Costs (M€)			Cost per MB (€)		Monthly Flat Rate (€)	
Scenario	$C(\psi)$	$C_{HSPA}(\psi)$	$C_{LTE}(\psi)$	HSPA	LTE	HSPA	LTE
A	3438.05	1513.28	-	0.0017	-	8.804	-
B	2787.34	790.61	-	0.0009	-	4.6	-
C	2844.09	-	454.88	-	0.0005	-	2.646
D	2835.60	-	442.79	-	0.0005	-	2.576
E	2847.82	-	462.12	-	0.0005	-	2.688
F	2840.06	-	451.03	-	0.0005	-	2.624

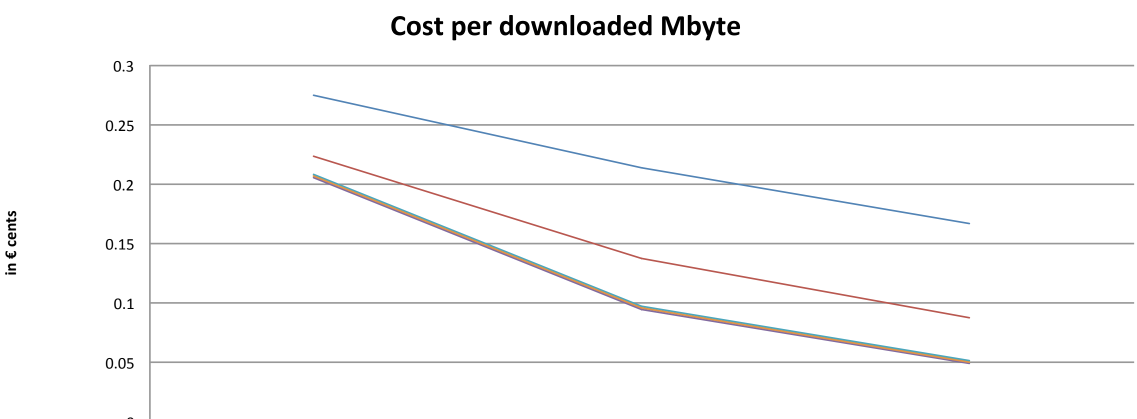
Table 6.7: Estimated Costs for a user downloaded data of 1.75 Gbytes

Figure 6.1 shows a graphical representation of total investment cost per technology, HSPA and LTE, and the estimated cost per downloaded Megabyte.



	Scen. A	Scen. B	Scen. C	Scen. D	Scen. E	Scen. F
HSPA_428Kbps	581,895,404.50 €	472,642,659.17 €	- €	- €	- €	- €
HSPA_1024Kbps	998,645,493.33 €	643,708,619.50 €	- €	- €	- €	- €
HSPA_1536Kbps	1,513,283,725.83 €	790,606,315.50 €	- €	- €	- €	- €
LTE_428Kbps	- €	- €	437,327,660.00 €	434,285,941.00 €	441,682,117.00 €	436,740,313.67 €
LTE_1024Kbps	- €	- €	449,298,100.33 €	439,660,425.33 €	455,585,490.00 €	446,356,612.00 €
LTE_1536Kbps	- €	- €	454,884,689.00 €	442,790,740.00 €	462,122,763.33 €	451,025,359.67 €

(a)



	428 Kbps	1024 Kbps	1536 Kbps
HSPA_Scen_A	0.274440881	0.213173238	0.166467465
HSPA_Scen_B	0.222913718	0.13740757	0.086969963
LTE_Scen_C	0.206258011	0.095908239	0.050039196
LTE_Scen_D	0.204823436	0.093850958	0.048708812
LTE_Scen_E	0.208311715	0.097250361	0.050835414
LTE_Scen_F	0.205980999	0.095280342	0.049614654

(b)

Figure 6.1: Cost estimations for: (a) A countrywide deployment; (b) Cost per downloaded Mbyte

The obtained results give information about the efficiency of HSPA and LTE technology carrying different volumes of downloaded data per user. First, LTE technology deals with an increase of the guaranteed transfer data rate at the cell edge in a more efficient way than HSPA technology does. Increasing the guaranteed transfer rate at the cell edge by a factor of 3.6, from 428 Kbps to 1536 Kbps, the investment costs increment for HSPA and LTE corresponds to a factor of 2.6 and 1.05, for the 2100 MHz and 2600 MHz frequency bands respectively. This implies that most of the LTE cells are propagation driven, and they admit an increase of the traffic demand, in this case in terms of user throughput, with less additional investment costs than HSPA technology, see figure 6.1(a).

Second, HSPA technology is more sensitive to the use of single-block or multi-block deployment than LTE technology. The capacity of the HSPA network is shorter than the capacity of the LTE network, and therefore in case of a mono-block deployment most of the deployed HSPA cells are traffic driven, and the use of a second frequency block makes possible to reduce the total number of nodes B required. This implies a reduction in the investment cost of 18.78%, 35.54% and 47.76% respectively. LTE systems increase the cell capacity by means of the use of higher modulation and coding schemes and a more efficient spectrum use. Due to these reasons, it is observed that in the LTE case the network is propagation driven and the use of a wider bandwidth shows no remarkable improvements in terms of cost, only a maximum improvement of 2.4% is observed for the most traffic loaded scenario, 1.75 Gbytes. Moreover, this effects are also shown in terms of the cost per downloaded Mbyte in Figure 6.1(b). In case of using HSPA technology, the cost per Mbyte in case of using a multi-block deployment instead of a single block network is reduced in a more significant way that in the LTE case.

Finally, from an operator point of view, LTE technology, in case of high guaranteed transfer rates, yields a considerable reduction on the investment costs in comparison to HSPA technology.

6.4 Application Example B: Movistar and Vodafone Scenarios

Movistar and Vodafone are the two largest mobile service providers in Spain. They accumulate the 63.4% of the market share, which represents 37.63 millions of lines, data cards included. Both operators started the deployment of LTE trial networks in multiple cities of Spain such as Valencia, Barcelona and Madrid, however they have not launched any commercial LTE network yet[1]. Movistar and Vodafone will deploy their commercial LTE networks using the spectrum won in the auction celebrated in 2011, where both of them acquired a total bandwidth of 10 MHz in the 800 MHz frequency band, [110], [114]. However, this bandwidth will not be available until 2014, when the deploy of the network will be a reality for Movistar and Vodafone. Other important operators, such as Orange and Yoigo, decided to follow a different strategy, Yoigo is currently deploying a commercial LTE network in the 1800 MHz frequency band with a total bandwidth of 10 MHz, [115], and Orange decided to deploy LTE with its not used spectrum in 1800 MHz and 2100 MHz frequency bands, [116].

The aim of this study is to analyze the economic impact that the deployment of a LTE network has in the investment costs. Two different scenarios, according to the features of each of the operators under study, have been defined. Tables 6.8 and 6.9 show the main features of the scenarios defined, data is obtained from the information of the last annual report of the CMT [10].

In Table 6.10 the radio access network infrastructure installed in Spain is detailed. The information is based on a total population of 46.152.926 inhabitants with a 126.7% of market penetration, that is a total number of lines of 58.475.757 lines.

[1] As of the $1^{st} of May, 2013$

Operator	Frequency Bands and Bandwidth (MHz)					Market Share	Subscribers
	GSM		UMTS	HSPA	LTE		
	900	1800	2100	2100	800	(%)	(Millions)
Movistar	10	19.8	5	10	10	35.2	20.64
Vodafone	10	19.8	5	10	10	28.2	16.99

Table 6.8: Movistar and Vodafone Scenarios Definition

Operator	A (mE)	Voice	Video Call	Streaming	Guaranteed Data	Best Effort	SMS	MMS	MBAS (Kbps)
Movistar	78.57	14	2.67	2.67	1.19	1.19	1.59	0.044	428
Vodafone	82.08	14.4	2.75	2.75	1.22	1.22	1.87	0.052	428

Table 6.9: Movistar and Vodafone User Demand Definition

Technology	Base Stations	BS Penetration Rate (BS / 10000 inhabitants)
2G	56059	9.586
3G	42474	7.26

Table 6.10: National RAN infrastructure

In order to show the correct functioning and the efficiency of the dimensioning module of the tool, a calibration process is done. In this phase, several distributions of the service's demand over the different technologies are estimated and a nationwide RAN deployment is carried out for every of the possible distribution. The goal of this phase is to calibrate the tool in order to obtain the results as close to reality as possible. Table 6.11 shows the final distribution obtained to compare the results of the optimized and the real cases. Results of the RAN deployment obtained for Movistar and Vodafone operators are shown in Table 6.12. These results are based on a total population of 46.175.136 inhabitants, with a penetration rate of 126.7%, involving a total number of lines of 58.503.897 lines. Moreover, the market share for each of the operators considered are a 35.2% for Movistar and a 28.2% for Vodafone, that is a total number of lines of 20.593.372 and 16.498.099 for Movistar and Vodafone, respectively.

In a parallel way, the optimization of the service distribution over the different technologies is performed. The first step is the selection of a fraction of cities, F_c, where the optimization is going to be applied. The districts to be part of the optimization process are selected according to a population density criterion. The selection process is described as follows:

- Maximum and minimum population density of the districts are calculated, Γ_M and Γ_m respectively.
- Estimation of the population density step ($(\Gamma_M - \Gamma_m)/F_c$), and formation of different groups.
- The process seeks one representative city that has every type of area (urban, suburban and rural), and meets the population density constraints of each of the defined groups. Two possible cases:
  - The first city that fulfills these criterions is selected as a representative city and stored into the subset of districts.

Service	GSM	UMTS	HSPA	LTE
Voice	0.765	0.235	0	0
Video-Call	0	1	0	0
Streaming	0.2	0.8	0	0
Guranteed-Data	0.2	0.8	0	0
Best-Effort	0.04	0.06	0.9	0
SMS	0.775	0.225	0	0
MMS	0.538	0.142	0.32	0
MBAS	0	0	1	0

Table 6.11: Calibratied User Demand Distribution

Mobile Operator	Technology	Base Stations	BS Penetration Rate (BS / 10000 inhabitants)
Movistar	2G	18820	9.14
	3G	17214	8.36
	4G	0	0
Vodafone	2G	16832	10.2
	3G	15695	9.51
	4G	0	0

Table 6.12: Movistar and Vodafone RAN infrastructure

– If no district fulfills the first condition, the selection process chooses the district only based on population density criterion.

Following this criterion, most Spanish main cities such as Madrid, Barcelona, Vitoria, A Coruña, etc., are selected.

In addition a set of thresholds per technology and services are also defined. These thresholds are required in order to take into account factors such as the previous investment costs made by real world operators. The goal of defining the thresholds is to force each of the services to be allocated to a specific technology. The thresholds are defined by the user of the tool. In our case, the thresholds definition is based on the type of service. Traditional second generation services such as voice, SMS and MMS, keep a 25% of the user demand over the GSM network, higher data rate services such as streaming, guaranteed-data and best-effort are forced to be carried by UMTS at least a 40% of the user demand, and mobile internet is carried only by HSPA and LTE technology, due to the low number of commercial LTE networks, a 75% of the user demand of MBAS is routed over HSPA technology. Table 6.13 shows the thresholds defined for both, Vodafone and Movistar, cases.

Service	GSM	UMTS	HSPA	LTE
Voice	0.25	0	0	0
Video-Call	0	1	0	0
Streaming	0	0.4	0	0
Guranteed-Data	0	0.4	0	0
Best-Effort	0	0.4	0	0
SMS	0.25	0	0	0
MMS	0.25	0	0	0
MBAS	0	0	0.75	0

Table 6.13: Services Technology Distribution Restrictions

The optimization process is carried out by each algorithm. In case of EA and CRO the chose crossover operator is the 2-Swap crossover operator, based on its best performance in non-restricted environments, [117]. The aim of this case is to evaluate the impact, in terms of investment costs, that the deployment of a hybrid network, together with an optimal service distribution of the services has. The costs obtained from the optimization phase is then compared to the cost obtained with the distribution defined in Table 6.11.

Operator	CRO	EVO	TLBO	Calibration Distr.
	in millions €			
Movistar	2840.155	2841.022	2841.273	3396.391
Vodafone	2676.006	2675.770	2680.706	3043.842

Table 6.14: Investment Cost

As expected, the optimized distribution of the services reduces the economic expense that the operators have to do. A reduction of 567.58 M€ (17.55%) and 373.81 M€ (12.93%), in the worst case (TLBO), is observed for Movistar and Vodafone, respectively. This reduction in costs translates into larger profits due to the fact that the provision of services to the end-user (cost per minute), together with the cost of providing the mobile termination service, is also reduced.

In order to show the importance of this reduction in costs, it is compared to external investments that are done in real world. It represents a 50% of the total investment (1000 € millions) that Movistar is supposed to do on the FTTH network deployment between 2015 and 2017, [118]. Moreover, this reduction represents a 0.053% of the gross domestic product (GDP) of Spain in 2011, [119].

This reduction in costs is based on an optimized distribution of the services over the technologies. The final service distribution obtained by the different optimization algorithms are detailed in Tables 6.15 and 6.16 for Movistar, and 6.17 and 6.18 for Vodafone.

The CRO and EA algorithms show a better performance than the TLBO algorithm. The main reason is that both CRO and EA reduce to the minimum required percentages of traffic load of the less efficient technology carrying data, for example the traffic load of data services over GSM technology is set to zero. Moreover, and despite the fact that UMTS technology is a native data technology, both algorithms allocate most of the traffic load of data services to HSPA and LTE due to the best features carrying data both technologies present. On the contrary, the TLBO allocate data services' traffic load to GSM and UMTS technology, increasing the total investment cost of the network.

Results in Tables 6.19 and 6.20 show a reduction in the base station's penetration rate for both second and third generation systems. It is observed a that the total number of network elements remains the same, Vodafone case, or it is reduced, Movistar case. However, even in cases where the amount of network elements is approximately the same, the internal configuration of this equipment, number of sectors and carriers used, is improved what it is reflected in the final investment costs. Moreover, as shown in Section 6.3, the LTE network is underused in case of a user throughput at the cell edge of 428 Kbps. This situation implies that most of the LTE evolved Node B are propagation driven units, and therefore they can fulfill higher demand of data traffic or higher binary rates without a significant investment on radio access network equipment.

Figure 6.2 show the convergence of the optimization algorithms applied to solve this problem. In both cases, the CRO first candidate solution is the worst in comparison to those obtained by

Opt. Algorithm	CRO				EA			
Service	GSM (%)	UMTS (%)	HSPA (%)	LTE (%)	GSM (%)	UMTS (%)	HSPA (%)	LTE (%)
Voice	0.250	0.750	0	0	0.250	0.750	0	0
Video-Call	0	1	0	0	0	1	0	0
Streaming	0	0.4	0.023	0.577	0	0.4	0.178	0.422
Guranteed-Data	0	0.4	0.023	0.577	0	0.4	0.178	0.422
Best-Effort	0	0.4	0.023	0.577	0	0.4	0.221	0.379
SMS	0.250	0.018	0.252	0.480	0.250	0.003	0.275	0.471
MMS	0.250	0.017	0.237	0.495	0.250	0.095	0.292	0.363
MBAS	0	0	0.75	0.25	0	0	0.75	0.25

Table 6.15: Movistar - Optimized Service Distribution for CRO and EA

Opt. Algorithm	TLBO			
Service	GSM (%)	UMTS (%)	HSPA (%)	LTE (%)
Voice	0.250	0.750	0	0
Video-Call	0	1	0	0
Streaming	0	0.4	0.477	0.123
Guranteed-Data	0.002	0.4	0.064	0.534
Best-Effort	0	0.4	0.034	0.565
SMS	0.255	0.012	0.036	0.697
MMS	0.284	0.006	0.649	0.061
MBAS	0	0	0.75	0.25

Table 6.16: Movistar - Optimized Service Distribution for TLBO

Opt. Algorithm	CRO				EA			
Service	GSM (%)	UMTS (%)	HSPA (%)	LTE (%)	GSM (%)	UMTS (%)	HSPA (%)	LTE (%)
Voice	0.411	0.589	0	0	0.411	0.589	0	0
Video-Call	0	1	0	0	0	1	0	0
Streaming	0	0.4	0.312	0.288	0	0.4	0.066	0.534
Guranteed-Data	0	0.4	0.094	0.506	0	0.4	0.014	0.586
Best-Effort	0	0.4	0.094	0.506	0	0.4	0.066	0.534
SMS	0.250	0.001	0.378	0.371	0.250	0.009	0.223	0.437
MMS	0.250	0.001	0.389	0.360	0.250	0.016	0.276	0.458
MBAS	0	0	0.75	0.25	0	0	0.75	0.25

Table 6.17: Vodafone - Optimized Service Distribution for CRO and EA

Opt. Algorithm	TLBO			
Service	GSM (%)	UMTS (%)	HSPA (%)	LTE (%)
Voice	0.424	0.576	0	0
Video-Call	0	1	0	0
Streaming	0	0.4	0.024	0.576
Guranteed-Data	0.003	0.407	0.033	0.557
Best-Effort	0.01	0.4	0.070	0.520
SMS	0.250	0.005	0.316	0.428
MMS	0.250	0.026	0.351	0.373
MBAS	0	0	0.75	0.25

Table 6.18: Vodafone - Optimized Service Distribution for TLBO

the EA and the TLBO algorithms, due to the CRO algorithm's initial population is shorter than in the EA or TLBO cases, see Chapter 4. However, the best performance, in terms of investment

Operator	Algorithm	Technology	Base Stations	BS Penetration Rate (BS / 10000 inhabitants)
Movistar	CRO	2G	11322	5.49
		3G	16155	7.84
		4G	5912	2.87
	EA	2G	11322	5.49
		3G	16155	7.84
		4G	5912	2.87
	TLBO	2G	11323	5.49
		3G	16143	7.84
		4G	5912	2.87

Table 6.19: Movistar Optimized National RAN infrastructure

Operator	Algorithm	Technology	Base Stations	BS Penetration Rate (BS / 10000 inhabitants)
Vodafone	CRO	2G	12205	7.39
		3G	14623	8.86
		4G	5909	3.58
	EA	2G	12205	7.39
		3G	14648	8.88
		4G	5909	3.58
	TLBO	2G	12249	7.42
		3G	14645	8.88
		4G	5909	3.58

Table 6.20: Vodafone Optimized National RAN infrastructure

costs, is shown by the CRO algorithm, see Table 6.21.

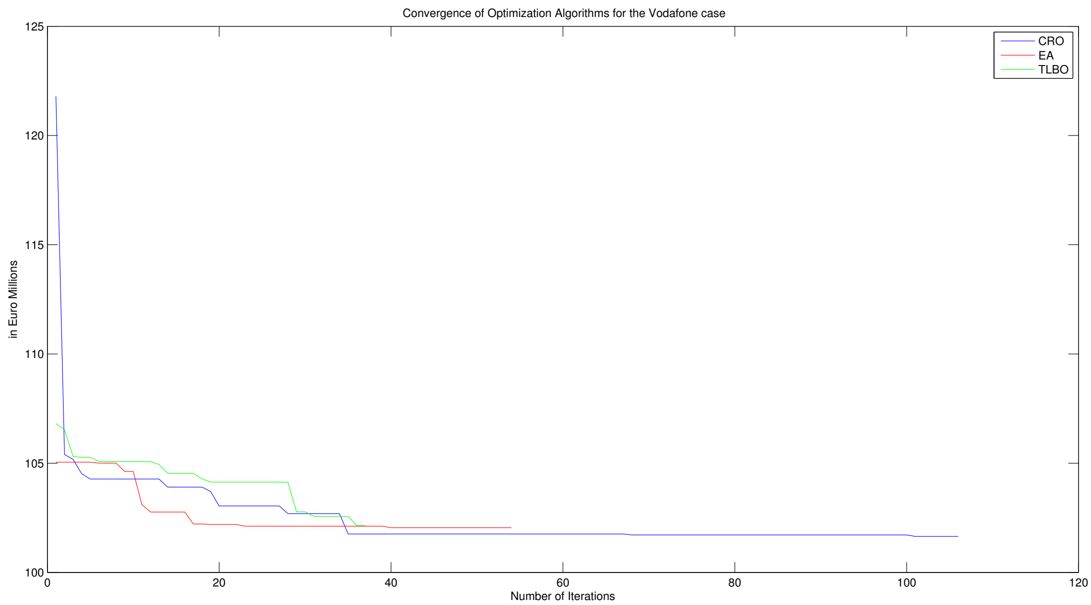
Operator	Algorithm	Initial Cost (M€)	Final Cost (M€)	Reduction (M€)
Vodafone	CRO	121.793	101.648	20.145
	EA	105.049	102.048	3.001
	TLBO	106.808	102.147	4.661
Movistar	CRO	143.313	119.171	24.142
	EA	124.406	119.22	5.186
	TLBO	121.42	119.231	2.189

Table 6.21: Convergence Evolution

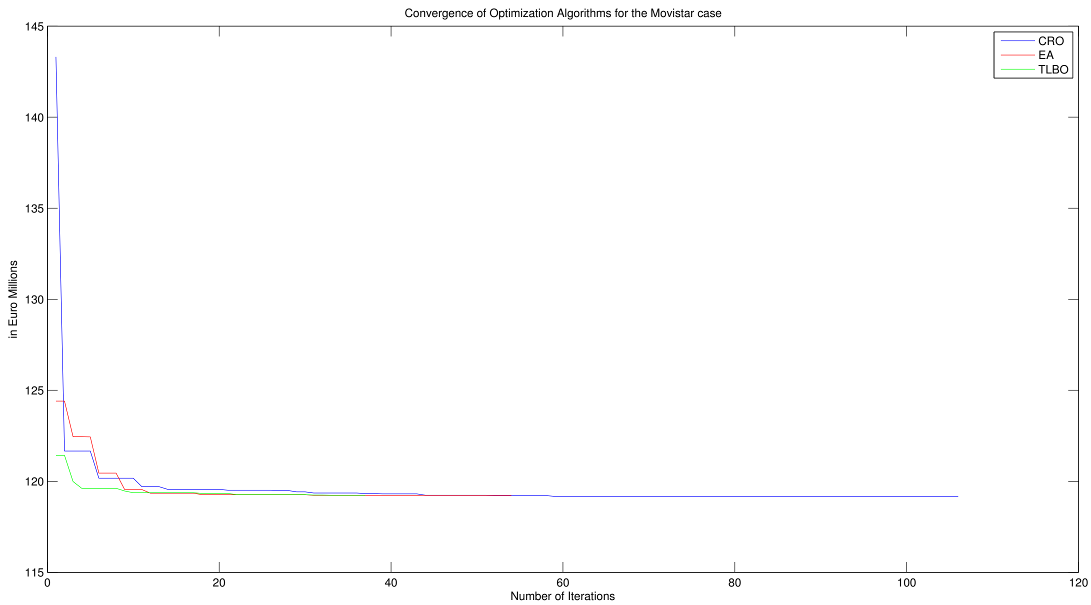
Based on the features of each technology and the results in Tables 6.15 - 6.18, the best performance of the CRO algorithm can be explained. In the Vodafone case, the resulting traffic distribution provided by the CRO algorithm minimizes the use of the GSM and UMTS networks, allocating most part of the data traffic over HSPA and LTE. In the Movistar case, the main difference in efficiency is based on the utilization of the LTE network. The CRO allocates most of the data services to the LTE network, and reduces the traffic demand carried by the HSPA network. Due to the fact that the LTE network has a larger capacity than the HSPA network, the final distribution of the services reduces the number of required base stations in comparison to the results obtained by the EA and the TLBO algorithms.

6.5 Application Example C: Hypothetical Efficient Mobile Operator Scenario

Most of european countries where the mobile technology penetration is more than 100% percent, have four different mobile services providers with network infrastructure, see Table 6.22.:



(a)



(b)

Figure 6.2: Convergence of the Optimization Algorithms for: (a) Vodafone case; (b) Movistar case

This scenario simulates an effectively competitive market situation, and therefore in terms of regulation the operator simulated in this case has a 25% of market share. Based on this, the impact of the allocation of different frequency bands for deploying a LTE commercial network is

Country	Austria	France	Germany	United Kingdom	Spain
Operators	A1-Telekom	Free Mobile	Deutsche Telekom	EE	Movistar
	T-Mobile	Orange France	Vodafone	O2	Vodafone
	Orange	SFR	E-Plus	Vodafone	Orange
	H3G	Bouyugues Telecom	O2	H3G	Yoigo

Table 6.22: Mobile Network Operators

analyzed. The country taken as reference to define the scenario is Spain, and all the data used is estimated based on the data from the last annual CMT report [10].

Three different frequency bands are considered in this study, 800 MHz, 1800 MHz and 2600 MHz. In Spain, LTE working on the 800 MHz will not be possible until the transition from analogue to digital TV is completely finished, it is planned to happen in 2014. The total bandwidth released by the analogue TV is of 72 MHz [110], and assuming a four operators scenario, each operator is supposed to have a total bandwidth of 15 MHz in the 800 MHz, this value is taken as reference for the 1800 MHz and 2600 MHz frequency bands. Table 6.23 defines the spectrum allocation for every considered case.

Operator	Frequency Bands and Bandwidth (MHz)						
	GSM		UMTS	HSPA	LTE		
	900	1800	2100	2100	800	1800	2600
A1	8.75	18.75	5	10	15	-	-
A2	8.75	18.75	5	10	-	15	-
A3	8.75	18.75	5	10	-	-	15

Table 6.23: LTE Scenarios Definition

Note that not all scenarios defined are real world scenarios, for instance, the maximum bandwidth available in the 1800 MHz frequency band is 75 MHz, and therefore in a four operators scenario the bandwidth available for each operator is 18.75 MHz. In scenario A2 the operator has 33.75 MHz in that frequency band (GSM + HSPA). However, based on the defined GSM base stations in the input file of the tool, together with the GSM technology features:

- Maximum number of 3 sectors per site, and 3 transceivers per sector.
- GSM channel bandwidth, 200 KHz, [120].
- Reuse pater of 4 sites per cluster. This value is accepted to avoid interference problems between cells, [121].

The maximum bandwidth used in GSM is equal to 7.2 MHz, and therefore 11.55 MHz planned for the GSM network are completely free, and in our case it is approximated to 15 MHz, to make possible the comparison of the result with A1 and A3 scenarios.

Initially, an analysis based on a mono block frequency deployment for UMTS, HSPA and LTE technologies with a bandwidth of 5 MHz per technology is carried out. The goal of this study is to determine the crossover operator that minimized the investment cost, and take that crossover operator as reference to perform the optimization phase in this section. The results of this process is shown in [117].

Based on the results obtained, the N-swap crossover operator with $N = 2$ is chosen. In Table 6.24 are shown the economic results given by the different optimization algorithms, together with the result due to the distribution defined in Table 6.11.

Frequency Band (MHz)	Bandwidth (MHz)	CRO	EVO	TLBO	Calibration Distr.[a]
		in millions €			
800	15	2483.001	2483.034	2481.201	2888.738
1800	15	2522.614	2517.585	2517.962	2922.278
2600	15	2570.987	2569.311	2568.875	2976.949

Table 6.24: Investment Cost

It is observed an increasing of the invested cost based on the spectrum available. The higher the frequency band for deploying the LTE network is, the larger the final investment cost is. Under the scenario described in Table 6.23 and based on the traffic demand defined in Table 6.2, most of LTE cells are propagation driven and therefore the higher the frequency band is, the worse propagation environment is, and therefore the shorter the cell range is. However, the optimization process is capable of saving about 400 M€ for all the cases under study. Moreover, after the optimization process is carried out, the maximum investment cost, corresponding to the worst propagation environment (2600 MHz), is still cheaper than the experience-based distribution working on the best propagation environment (800 MHz).

In Table 6.25 is shown the required infrastructure obtained for all the cases, for each of the optimization algorithms and without optimization. As it is above mentioned, LTE network is propagation driven due to the features of the traffic demand of the mobile broadband access service, together with the requirement of assigning, at least, a 75% of this service over HSPA technology, and therefore the grade of freedom of the optimization algorithms in relation to LTE technology is quite short. However, the optimization algorithms are capable of allocating a higher percent of the traffic demand of the rest of data services over LTE, in such a way that the number of network elements for 2G and 3G networks are reduced. In this way, the network is capable of satisfying the capacity constraints at the same time they take advantage of the underused LTE network. As a result a reduction on the total investment costs is observed.

Frequency Band (MHz)	Distribution	Base Stations		
		2G	3G	4G
800	Experience-based	15819	14386	5904
800	CRO	10806	13619	5909
800	EA	10949	13590	5904
800	TLBO	10851	13618	5904
1800	Experience-based	15819	14386	6862
1800	CRO	10842	13750	6862
1800	EA	10935	13598	6862
1800	TLBO	10900	13618	6862
2600	Experience-based	15819	14386	8316
2600	CRO	10900	13612	8316
2600	EA	10851	13624	8316
2600	TLBO	10867	13616	8316

Table 6.25: Total Network Infrastructure

[2] A 25% and a 75% of the MBAS is allocated to LTE and HSPA, respectively.

Moreover, the higher the frequency band used for LTE is, the more underused is the LTE cells installed and therefore the more traffic load can be liberalized from 2G and 3G networks, redistributing this load over the LTE network. Results in Table 6.26 show the trend of the traffic load distribution of the most representative data services defined, that is, Streaming, Guaranteed data, Best-Effort data and Mobile Broadband services.

Frequency Band (MHz)	Average Traffic demand over LTE			
	Streaming	Guaranteed Data	Best-Effort Data	MBAS
800	0.418	0.361	0.317	0.25
1800	0.462	0.318	0.336	0.25
2600	0.526	0.405	0.345	0.25

Table 6.26: Data Services Traffic Demand Distribution over LTE Trend

6.6 Optimization Algorithms' Performance

Three different optimization algorithms have been implemented in this thesis. Due to the specific features and implemented operators for each of the algorithms, the performance and therefore the results obtained by them are different. Although the results trend to be similar, it is interesting to evaluate the performance of each algorithm.

To achieve this goal, it is necessary to compare the results obtained by each implemented method. Statistical tests are commonly used tools to perform this comparisons. In this thesis, the chose statistical test is the *t-Test*, which is based on the *t-Student* distribution, and has been used in previous works, [106], [122]. The t-Student distribution is based on the following properties:

- The mean of the distribution is equal to zero, $\mu = 0$.
- Bell-shaped distribution and symmetric with respect to the mean.
- The variance of the distribution, σ, is always greater than 1, and it can be expressed as indicated in Equation 6.8.

$$\sigma = \frac{df}{df - 2} \tag{6.8}$$

  where df is the degree of freedom, which depends on the size of the sample. Supposing a sample size of n, then the degree of freedom for the t-Student distribution is $df = n - 1$. Note that the higher the degree of freedom is, the closer to 1 the variance of the t-Student distribution is. That is, the t-Student distribution in case of $n \to \infty$ can be approximated by a normal distribution $N(0, 1)$.

The process carried out is summarized as follows:

- The sample used in the test is supposed to come from a normal distribution with mean $\mu = 0$ and unknown variance σ.
- Definition of two hypothesis, the null hypothesis $H_0 : \mu = 0$ and the alternative hypothesis $H_1 : \mu \neq 0$.
- Fixing a threshold or significance level, α, for Type I error.
  - Type I error: Reject H_0 when it is true

  - Type II error: Accept H_0 when it is false

- Determine a test statistic (t-Test in our case).
- Determine what observed values of the test statistic should lead to rejection of H_0. In our case, the $t-Stat$ and $p-Value$ parameters. Description on the meaning of this parameters is given later on.
- Test to see if observed data is in a more extreme point that the significance point k
  - If it is, rejec H_0
  - Otherwise, aceept H_0

The t-Test evaluation is based on the "*ttest*" function from MATLAB, which evaluate the correlation of the results obtained by means of different optimization algorithms. A set of $n = 50$ different results, corresponding to ten simulations per scenario and five different scenarios are available for this comparison purpose. The process is based on three main steps: first, two different algorithms are chosen, second the results obtained by one of the chosen algorithms are subtracted from the results of the second algorithm, this simulates that the resulting data come from a distribution with mean equal to zero, and finally, the "*ttest*" function is executed. The process for the CRO and EA results is described in Equation 6.6.

$$\begin{aligned} \overline{CRO} &= \{x_0, x_1, x_2, \ldots, x_n\} \\ \overline{EA} &= \{y_0, y_1, y_2, \ldots, y_n\} \\ \overline{Z} &= \{x_0 - y_0, x_1 - y_0, x_2 - y_2, \ldots, x_n - y_n\} \end{aligned} \tag{6.9}$$

This function allows to determine if the mean of two different distributions is the same, and this is used in this thesis to determine whether the performance of a specific optimization algorithm is better than the other or not. In our case, two different set of samples are considered, both of them with its own mean, μ_x and μ_y. The null hypothesis is then defined as: $\mu_x = \mu_y$, that is:

$$H_0: \quad \mu_z = \mu_x - \mu_y = 0 \tag{6.10}$$

The null hypothesis defined in 6.10 is the one used by default in MATLAB, with a significance level of 5%. Information given by the function is:

- H Parameter: It indicates whether the null hypothesis is accepted or not.
- p-Value Parameter: It indicates the probability of having a result as extreme or more extreme than the value in the sample, accepting the null hypothesis H_0.
- CI or Confidence Interval: It defines an interval for the true mean of $\overline{Z}$ with a probability of $(1 - \alpha)$.
- t-Stat: It is the statistic parameter used to accept or reject the null hypothesis.
- Degree of Freedom (df): It depends on the size of the sample, and it plays an important role in the estimation of the critical values of the t-Student distribution.
- Standard Deviation (sd): It is the standard deviation of the sample $\overline{Z}$.

Based on the given description of the parameters, the null hypothesis is accepted when the p-Value parameter's value is larger than the significance level α. On the contrary, the null hypothesis is rejected if the p-Value is shorter than α. The lower the p-Value parameter's value is, the higher the rejection of the null hypothesis is.

An alternative method to accept or reject the null hypothesis is based on the t-Stat value. The t-Student distribution is composed by a family of distribution depending on the degree of freedom. For each t-Student distribution the critical values, that is, the value that defining the boundary between the samples that lead to the rejection of the null hypothesis and those that lead to the decision not to reject the null hypothesis, are tabled. Therefore, the null hypothesis is accepted when the t-Stat parameter's value is larger than the critical value obtained from the table. In our case, the critical values for the two-teils t-Test and $df = 49$ is equal to 2.010. Figure 6.3 displays a normal and a t-Student distribution, together with the critical values for the two-teils and the one-teils cases.

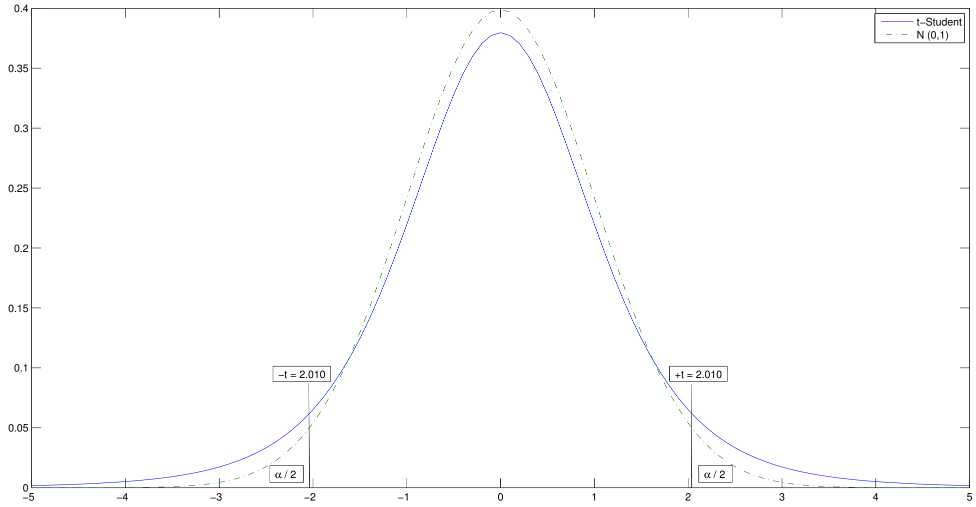
Results obtained after the execution of the "*ttest*" function are shown in Table 6.27.

Algorithms	H	p-Value	CI	Stats		
				t-Stat	Degree of Freedom	Standard Deviation
CRO vs EA	0	0.1767	$[-0.0302, 0.1597]$	1.3709	49	0.3341
CRO vs TLBO	1	1.85E-04	$[0.1176, 0.3499]$	4.0446	49	0.4087
EA vs TLBO	1	0.0024	$[0.0628, 0.2752]$	3.1993	49	0.3735

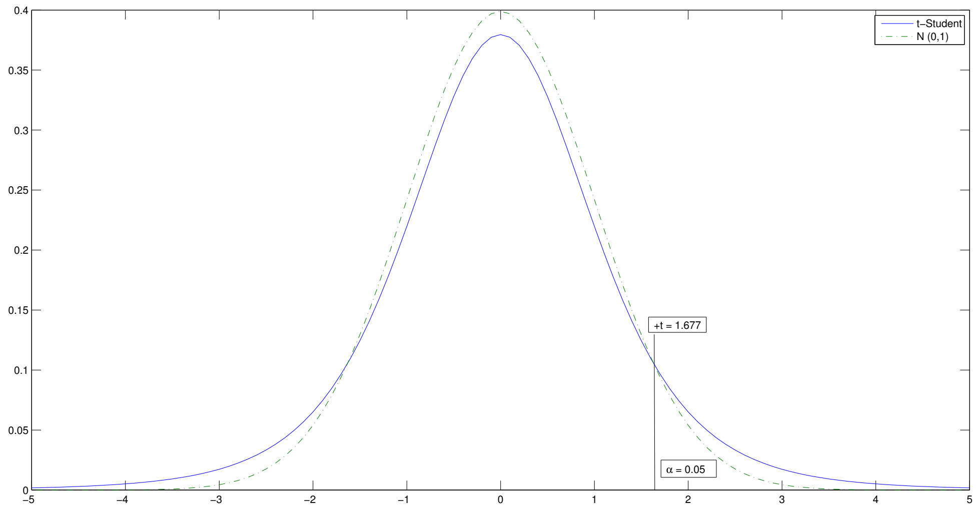
Table 6.27: T-test Evaluation

Three different comparisons have been made. First, the null hypothesis is only accepted in one of the cases, which corresponds to the comparison between the CRO and EA methods. This result indicates that the performance of both methods is quite similar and therefore there is not a significant difference on the results that can be obtained after applying one or another optimization algorithm to our problem. One reason for this behavior is that both algorithms are based on the same crossover and mutation operators. However and despite the fact the difference is not significant, the confidence interval shows a little improvement in case of using the CRO method over the EA method, that is the interval containing the true mean of the sample with a 95% of confidence is slightly displaced towards the positive axis values.

Second, the null hypothesis is rejected for the comparison between the CRO and the TLBO methods, as it happens with the comparison between the EA and TLBO algorithms. In both cases, it is showed and better performance of the CRO and/or the EA over the TLBO method, due to the CI values. Moreover, and based on the resulting value for the p-Value and t-Stat parameters, it is concluded that the highest improvement in the performance is detected for the CRO vs TLBO case, due to the shorter value of the p-Value parameter and the larger value of the t-Stat parameter.



(a)



(b)

Figure 6.3: t-Student vs Normal distribution for the (a) two-tiles t-Student case; (b) one-teil t-Student case

Part III

Conclusions and Future Work

Chapter 7

Conclusions

7.1 Summary

This thesis is focused on the development of a strategic network planning tool and a set of optimization algorithms to solve the services distribution problem over a set of technologies. In order to do this, it is divided into two main parts, a dimensioning and planning module, and a bio-inspired optimization module. The goal of both modules is to provide a set of algorithms capable to perform the dimensioning process of a multi-technological mobile radio access network (RAN) and the optimization of the traffic demand's distribution over the different technologies to be deployed.

In Chapter 2 several research studies related to the planning and dimensioning process of telecommunication networks, together with works focused on the application of heuristic and metaheuristic algorithms to the telecommunications field have been cited. Most of the optimization algorithms in those works attempt to optimize one or multiple parameters that affect to the final result of the planning network process.

The above mentioned planning and dimensioning works are focused on the propagation environment study using simulators, either static simulators or dynamic simulators, setting aside the capacity analysis. The optimization algorithms developed and applied to telecommunications problems are focused on three different problems. First, a set of algorithms focused on solving the channel allocation problem, that is the assignation of frequency resources to establish and maintain the communication between the end-user and the network. The second problem is the location of the base stations of a network, in this case the heuristic algorithms give information about the optimal emplacement of the nodes of a telecommunication network taken into consideration multiple factors such as investment costs, legal aspects and electromagnetic compatibility. Finally, the third problem tackled by means of bio-inspired algorithms is the balance of the links in a telecommunications network, all the studies related to this problem are focused on internet and ad-hoc networks. However, the developed optimization algorithms in this thesis are focused on an additional problem's solution, the optimization of the services' traffic demand over a set of technologies in order to minimize the total investment cost of the radio access network.

This thesis provides two main contributions to the mentioned studies. First, it provides a set of dimensioning and planning algorithms to perform the deployment of a mobile communications RAN. These algorithms are capable of dimensioning a multi-technology network, second, third and fourth generations are considered, as well as a single or dual band option for second generation networks and a single block or multi block deployment for third generation networks. Every dimensioning algorithm implemented is based on two main studies, coverage and capacity, giving both processes an identical grade of importance. The coverage analysis is performed using the Cost231-Hata propagation model with its corresponding frequency and type of terrain correction factors, while the capacity analysis is based on the Erlang-B formulation, together with the special features of each of the technologies such as the access to the air interface technique, modulation and coding schemes, etc. Moreover, these algorithms are applied to nationwide, multi-service and multi-technological scenarios, considering multiple voice and data services offered to the end-user simultaneously.

One of the main objectives of any mobile operator is to increase its profits reducing the costs, one way of achieving this objective is to be able to perform an efficient radio access network dimensioning. The goal of the dimensioning module developed in this thesis is to deploy an optimized network, in terms of investment costs, giving information about the the number, type and location of the required base stations to satisfy specific coverage and capacity constraints. The type of base stations installed (marco, micro or pico-cell), together with the number of sectors and transceivers (2^{nd} generation systems) or carriers (3^{rd} generation systems), are treated as the key point of the internal optimization process of this module. For each technology, j, the algorithms carries out the cell range for each type of base station or combination of base station, in case a dual band or multi block deployment is considered, and therefore the final number of network elements (base stations) required. Based on this equipment, a specific investment cost is assigned to each of those network elements, and a final investment cost per technology is calculated. The final solution is the one that minimizes the investment cost per technology. This process is done for each different type of terrain within a district, and for all the districts defined in the scenario.

The second contribution is an optimization module based on three different metaheuristic algorithms. The goal of this part of the thesis is to give a solution to the OSDP, that is, to figure out the optimal service distribution of the traffic demand over the set of technologies to be deployed. Three different algorithms are implemented: a classical evolutionary algorithm (EA) where three different crossover operators are defined, one and two points crossovers, and the N-swap crossover operator; a bio-inspired algorithm based on the coral reef formation behavior (CRO), using the same crossover operators as the EA; and a teaching-learning-based optimization algorithm (TLBO) that simulates the learning process that human beings follow, in this case the crossover and mutation operators differs from the methods implemented in the EA and CRO.

The above mentioned algorithms are based on a initial population of individuals, that represents each possible solution to the service distribution problem. A fitness function that estimates the cost associated to the resulting network from the dimensioning process based on the features of each individual defined in the population. In the cost estimation process, multiple parameters such as the cost of the site, civil and working costs included, the cost of the base station, depending on the number of sectors and type of cell (macro, micro or pico-cell) and the frequency related hardware cost associated to the transceivers and carriers used by the network, are taken into account. Moreover, two sharing factors are considered: 1) The possibility of sharing the site costs between two different operators and two different technologies, and 2) the possibility of sharing the cost of a base station in case of hybrid their generation systems (UMTS + HSPA).

The algorithms implemented in both modules have been intensively checked, more than 300 results from a set of seven different scenarios have been obtained. In addition, two scenarios corresponding to the two largest mobile operators in Spain have been simulated, the results obtained by the dimensioning module, base stations penetration index (base stations per 10000 lines), are close to the information given by the Spanish Telecommunications Market Commission (CMT), with an error shorter than a 6% for second generation networks. Note that the results from third generation networks are not comparable due to the fact the dimensioning features, mainly focused in the minimum guaranteed binary rate of the MBAS, are different to the specified in the CMT report. Two main techno-economical studies have been carried out, first a comparison of HSPA and LTE technology's performance providing the MBAS have been analyzed, obtaining the cost per Mbyte and a monthly flat rate for three different volumes of downloaded data. The conclusion is that LTE shows an outstanding performance carrying the MBAS in comparison to HSPA technology, reducing the provision cost per Mbyte in a range of 50% to 66% in case of high minimum guaranteed binary rate cases.

The second analysis is focused on the different LTE network deployment strategies adopted by mobile operators in Spain. Three different scenarios based on a hypothetical new mobile operator with a 25% of market share are defined in case of allocating a bandwidth of 15 MHz in the 800 MHz, 1800 MHz, and 2600 MHz frequency bands. The optimization algorithms minimize the effect of the different propagation conditions obtaining a maximum deviation of a 0.3% of the invested cost, which indicates that distributing the traffic demand in an efficient way the cost per provided Mbyte is not affected by the propagation environment. Finally, scenarios based on the constraints of Movistar and Vodafone with a 10 MHz bandwidth in the 800 MHz frequency band, and their corresponding market share and traffic demand, are defined. In these cases, a reduction of 567.48 M€ and 373.81 M€ for Movistar and Vodafone respectively is observed.

Summarizing, the main contributions and experiments of this thesis are:

- The development of a Strategic Network Planning and Optimization Tool, divided into two main modules: a RAN Cell Dimensioning Module, and a Metaheuristic Optimization Module.

- RAN Cell Dimensioning Module: It contains four different algorithms to perform the cell dimensioning process. Every algorithm is able to perform the cell dimensioning process in a multi-service and multi-technology environment. Moreover, different available bandwidths and frequency band for each technology is also considered.

  - **GSM algorithm:** Based on the Release 99 of the 3GPP.
  - **UMTS algorithm:** Based on the Release 4 of the 3GPP.
  - **HSPA algorithm:** Based on the Releases 5 (HSDPA) and 6 (HSUPA) of the 3GPP, together with the possibility of using MIMO (Release 7).
  - **LTE algorithm:** Based on the Release 8 of the 3GPP.

- Metaheuristic Optimization Module: Based on three different algorithms. It carries out the optimization process of the services distribution over a set of different technologies.

  - **Evolutionary Algorithm** (EA).
  - **Coral-Reef Optimization Algorithm** (CRO).
  - **Teaching-Learning Based Optimization Algorithm** (TLBO).

- In order to check the efficiency of the developed algorithms, the following experiments have been developed:
  - **Efficiency comparison of the HSPA and LTE technologies to provide the MBAS:** In this case, a user experience-based service distribution without metaheuristic optimization is used.
  - **Techno-economical study based on the impact of the available frequency bands and bandwidths for the LTE technology to provide the MBAS:** Results are obtained after an optimization process where the metaheuristic algorithms estimate the most suitable service distribution over the technologies to minimize the investment cost of the network.

7.2 Future work

The future lines of work defined for this thesis, as it happens to its structure, is divided into two main fields, the dimensioning module and the optimization module. The future lines of work can be summarized as follows:

- **Update of the LTE dimensioning algorithm:** The constant and fast evolution of mobile communications force to update continuously the algorithms implemented in this thesis, being a "must do" the update of the LTE technology algorithm to consider aspects such as multiple input and multiple output techniques (MIMO), which increases the capacity and therefore the performance of the deployed network.

- **Optimization of the access to the frequency resources:** The access to the spectrum is one of the main problems every mobile operator has to deal with. The application of the developed optimization algorithms, CRO, EA and TLBO, is interesting to help mobile operators in case of future spectrum auctions. In this case, it is necessary to redefine the genes or characteristics of the individuals used by the optimization algorithms. The new individual's characteristics are the set of frequency bands available and the bandwidth in each frequency band. The fitness function remains the same, due to the fact the goal is to minimize the associated cost to network deployment. The final result gives information about which frequency band and bandwidth is the most suitable for each technology to satisfy the capacity and coverage constraints fixed as input data to the model.

- **Frequency refarming:** In the last years a number of studies on the effects that the liberalization of the frequency bands allocated to GSM have been carried out. One of these work is developed in [123], a techno-economical study on the reutilization of the spectrum liberalized by the GSM technology in the 900 MHz is analyzed. The results of this work about the reutilization of the 900 MHz for the UMTS technology show that the benefits obtained are larger than the cost incurred on the liberalization process. Moreover, it is shown the corresponding benefits due to the fact of deploying a third generation network (UMTS + HSPA) in the 900 MHz and 2100 MHz instead of using only the 2100 MHz, however the problem of the non-fair access to the frequency resources in the 900 MHz is also introduced.

  According to this fact, it is planned a future line of work with the algorithms implemented in this thesis. This line is divided into two main steps:

  - Perform a techno-economical study of the current scenarios of the four largest mobile operators in Spain, Movistar, Vodafone, Orange and Yoigo, and to analyze the economical drawbacks that mobile operators, such as Yoigo, with a short or no spectrum available in the 900 MHz frequency band will have to face in order to be competitive in comparison to the rest.
  - Apply the optimization algorithms implemented in this thesis to minimize the non-fair access to the frequency resources.

  The main goal of both studies is to help the NRA on taking decisions about the mobile termination charges defined for each of the mobile operators in Spain. This process is suitable to be done for any other european country, in case all the input data are available.

- **LTE versus fixed fiber networks:** The increasing in the quality and transfer speed of the services, together with the necessity of improvements in the competition framework and innovative capacity of each country, have been presented as a possible solution to the current economical crisis situation. The PhD. thesis in [124], an analysis of the viability of the deployment of next generation networks (NGN) in Spain, together with a study on the different regulatory and public policy challenges have been developed. In line with the roll out of next generation networks, a future line of work based on the algorithms developed in this thesis is defined in order to:

  - Evaluate the results of a comparison between the technical capabilities of the fiber networks and the capabilities of the LTE technology using MIMO techniques.
  - Analyze the economical impact in national economies, in terms of revenues and invested capital of mobile and fixed operators, together with a comparison of the provision cost of broadband access to the end-user.

- **Parallelization of the tool:** The experiments carried out in this thesis have shown the capabilities and the performance of both dimensioning and optimization modules. It has been observed the whole optimization process is a time-consuming process, and therefore different strategies such as a reduction of the number of evaluations, together with the definition of a reduced scenario (shorter number of districts where the network is deployed) have been adopted. A parallelization phase for both dimensioning and optimization processes is proposed as an alternative to on the one hand, minimize the time taken to obtain the results, and on the other hand to perform the optimization process with the whole scenario input data. A first simple parallelization scheme is on going, based on the use of the OpenMP. OpenMP is an application programming interface (API) to developed software applications in multiprocess and shared memory environments [125].

7.3 Results: Publications and Projects

The studies and works developed in this thesis have been published in several national and international congress and journals. Few of these publications have been already cited in previous chapters. A summary of the journal and congress papers is presented in this section.

- Journal papers:

  - J. E. Sánchez-García, A. Portilla-Figueras, S. Salcedo-Sanz, S. Jiménez-Fernández and A. M. Ahmadzadeh, "Coral-Reef Optimization Algorithm Applied to Optimal Service

Distribution Problem in Mobile Radio Access Networks", *Transactions on Emerging Telecommunications Technologies*, submitted, 2013. (JCR: 0.454)

 - J. E. Sánchez-García, A. Portilla-Figueras, S. Salcedo-Sanz and S. Jiménez-Fernández, "2G/3G connect: An educational software for teaching 2G/3G mobile communications to engineering students", *Computer Applications in Engineering Education*, in press, 2013. (JCR: 0.333)
 - A. M. Ahmadzadeh, J. E. Sánchez-García, B. Saavedra-Moreno, A. Portilla-Figueras, and S. Salcedo-Sanz, "Capacity estimation algorithm for simultaneous support of multi-class traffic services in Mobile WiMAX", *Computer Communications*, vol. 35, no. 1, pp. 109-119, January 2012. (JCR: 1.044)

- Conference papers:
  - J. E. Sánchez-García, A. Portilla-Figueras, S. Salcedo-Sanz and D. Gallo-Marazuela, "HSDPA vs. LTE para la Prestación del Servicio de Internet de Banda Ancha en Terminales Móviles", IV Jornadas Jóvenes Investigadores, Universidad de Alcalá, 2013
  - J. E. Sánchez-García, A. M. Ahmadzadeh, B. Saavedra-Moreno, S. Salcedo-Sanz and A. Portilla-Figueras, "Strategic Mobile Network Planning Tool for 2G/3G Regulatory Studies", In Mobile Lightweight Wireless Systems, vol. 81, pp. 291-302, 2012
  - J. E. Sánchez-García, A. M. Ahmadzadeh, S. Jiménez-Fernández, S. Salcedo-Sanz and A. Portilla-Figueras, "Impact of the HSPDA-Based Mobile Broadband Access on the Investment of the 3G Access Network", In Mobile Lightweight Wireless Systems, vol. 81, pp. 303-311, 2012

The work developed in this Ph. D. Thesis has its origin in the Spanish Ministry of Science and Innovation project TEC2006-07010 and has been supported by the Spanish Ministry of Science and Innovation under the project ECO2010-22065-C03-02.

In addition, the developed work has been already applied to real world regulatory studies in collaboration with the German company WIK-Consult GmbH and the University of Cantabria:

- Development of a mobile network cost model for the Swiss regulator BAKOM.
- Development of a 3G mobile network cost model for the Austrian regulator RTR GmbH, [126].
- Development of a mobile network cost model covering 2G, 3G and LTE for the German regulator Bundesnetzagentur, [127].

Bibliography

[1] UMTS Forum. Mobile Broadband Evolution: the roadmap from HSPA to LTE, February 2009.

[2] Harri Holma and Antti Toskala. *WCDMA for UMTS - HSPA Evolution and LTE*. John Wiley and Sons Ltd., 2010.

[3] Global mobile Suppliers Association (GSA). Evolution to LTE. http://www.gsacom.com/downloads/pdf/GSA_Evolution_to_LTE_report_080113.php4, GSA, 2013.

[4] R. Bawa, S. R. Bawa, S. B. Maebius, T. Flynn, and C. Wei. Protecting new ideas and inventions in nanomedicine with patents. *Nanomedicine: Nanotechnology, Biology and Medicine*, 1(2):150–158, 2005.

[5] P. Mell and T. Grance. The NIST definition of cloud computing (draft). *NIST special publication*, 800:145, 2011.

[6] A. Tudzarov and T. Janevski. Functional architecture for 5G mobile networks. *International Journal of Advanced Science and Technology*, 32:65–78, 2011.

[7] A. M. Mousa. Prospective of fifth generation mobile communications. *International Journal of Next-Generation Networks*, 4(3), 2012.

[8] GSM Association and ATKearney. The Mobile Economy 2013. http://www.gsmamobileeconomy.com/GSMA%20Mobile%20Economy%202013.pdf, Last visit: 15th July 2013 2013.

[9] CISCO. Cisco Visual Networking Index: Global Mobile Data Traffic Forecast for 2012 to 2017. http://www.cisco.com/en/US/solutions/collateral/ns341/ns525/ns537/ns705/ns827/white_paper_c11-520862.html, Last visit: 15th July 2013 2013.

[10] Comisión del Mercado de las Telecomunicaciones. Informe Económico Sectorial 2011. http://informecmt.cmt.es/docs/2011/Informe%20Economico%20Sectorial%20CMT%202011.pdf, 2011.

[11] International Telecommunications Union (ITU). Top Mobile Operators in the World, 2005.

[12] John Buckley. *Telecommunications Regulation*. Institution of Engineering and Technology, UK, 2003.

[13] Colin Blackman and Lara Srivastava. *Telecommunications Regulation Handbook*. The World Bank, 2011.

[14] World Trade Organization. Negotiating Group on Basic Telecommunications, 1996.

[15] OFCOM. Mobile termination rates. http://media.ofcom.org.uk/analysts/regulated-prices/, Last visit: 15th July 2013 2013.

[16] Federal Network Agency (BNetzA). Press Release - Mobile Termination Rates. http://www.bundesnetzagentur.de/SharedDocs/Pressemitteilungen/EN/2011/110224MobileTerminationRates.html, Last visit: 15th July 2013 2011.

[17] Federal Network Agency (BNetzA). Press Release - Mobile Termination Rates. http://www.bundesnetzagentur.de/cln_1912/SharedDocs/Pressemitteilungen/EN/2012/121116NewMobileTerminationRate.html?nn=407720, Last visit: 15th July 2013 2012.

[18] P. DeGraba. *Bill and keep at the central office as the efficient interconnection regime.* Federal Communications Commission, Office of Plans and Policy, 2000.

[19] P. DeGraba. Efficient Inter-carrier Compensation for Competing Networks: When Consumers Share the Value of a Call. *Journal of Economics and Management Strategy*, 12:207–230, 2003.

[20] Europe Economics. Contract No. 48544. Cost Structures in Mobile Networks and their Relationship to Prices, 2011.

[21] European Union. Recommendation on interconnection in a liberalised telecommunications market (Part 2 - Accounting separation and cost accounting). recommendation 98/322/ec of 8 April 1998, 1998.

[22] European Union. Recommendation on accounting separation and cost accounting systems under the regulatory framework for electronic communications, 2005.

[23] J.M. Celentano. Carrier Capital Expenditures. *Communications Magazine, IEEE*, 46(7):82–88, 2008.

[24] Andersen. Study on the implementation of cost accounting methodologies and accounting sepration by telecommunication operators with significant market power. Technical report, European Commission DG Information Society, 2002.

[25] NERA. Reconciliation and integration of Top-Down and Bottom-Up models of incremental costs. Technical report, Oftel, 1996.

[26] Swedish Post and Telecommunications Agency PTS. Model reference paper: Guidelines for the LRIC bottom-up and top-down models. Technical report, PTS, 2002.

[27] C. Courcoubetis and R. Weber. *Pricing Communication Networks*. John Wiley and Sons Ltd., 2003.

[28] M. Taschdjian. Pricing and tariffing of telecommunications services in Indonesia: principles and practice. http://pdf.usaid.gov/pdf_docs/Pnacw864.pdf, Last visit: 15th July 2013 2001.

[29] M. Binkmann, K. Hackbarth, D. Ilic, W. Neu, and KH. Neumann. Mobile termination cost model for Australia. report for the Australian Competition and Consumer Commission, 2007.

[30] European Commision. Commision Recommendation of 7 May 2009 on the Regulatory Treatment of Fixed and Mobile Termination Rates in the EU, 2009.

[31] Wavecall Corporation. Wavesight. http://www.wavecall.com/accurate.php, Last visit: 15th July 2013.

[32] K. Rizk, J. F Wagen, and F. Gardiol. Influence of database accuracy on two-dimensional ray-tracing-based predictions in urban microcells. *Vehicular Technology, IEEE Transactions on*, 49(2):631–642, 2000.

[33] S.A. Ghorashi, E. Homayounvala, F. Said, and A.H. Aghvami. Dynamic simulator for studying WCDMA based hierarchical cell structures. In *Personal, Indoor and Mobile Radio Communications, 2001 12th IEEE International Symposium on*, volume 1, pages D–32–D–37 vol.1, 2001.

[34] I. Virtej. Radio network-planning simulator for telecommunication systems. In *Workshop on Radio Communications*, 1999.

[35] A. Wacker, J. Laiho-Steffens, K. Sipila, and M. Jasberg. Static simulator for studying WCDMA radio network planning issues. In *Vehicular Technology Conference, 1999 IEEE 49th*, volume 3, pages 2436–2440, 1999.

[36] J. Laiho, A. Wacker, and T. Novosad. *Radio Network Planning and Optimisation for UMTS*. John Wiley and Sons Ltd., 2001.

[37] J. Laiho, A. Wacker, T. Novosad, and A. Hamalainen. Verification of WCDMA radio network planning prediction methods with fully dynamic network simulator. In *Vehicular Technology Conference, 2001. VTC 2001 Fall. IEEE VTS 54th*, volume 1, pages 526–530, 2001.

[38] L. Mendo. *Capacidad en sistemas celulares W-CDMA*. PhD thesis, Escuela Técnica Superior de Ingenieros de Telecomunicación, Universidad Politécnica de Madrid, 2001.

[39] S. Hurley. Planning effective cellular mobile radio networks. *Vehicular Technology, IEEE Transactions on*, 51(2):243–253, 2002.

[40] J. Montero, E. Frech, J. L. Miranda, R. García, B. Gónzalez, I. Berderana, and P. Martínez. *Herramienta de Planificación de la red UMTS*. Telefónica I+D and Telefónica Móviles, Revista Comunicaciones de Telefónica I+D.

[41] AWE Communications. Winprop API. http://www.awe-communications.com, Last visit: 15th July 2013.

[42] AIRCOM. http://www.aircominternational.com/Products/Planning/asset.aspx, Last visit: 15th July 2013.

[43] Mentum. http://www.mentum.com/index.php?page=cellplanner&hl=en_US, Last visit: 15th July 2013.

[44] M. Hata. Empirical formula for propagation loss in land mobile radio services. *Vehicular Technology, IEEE Transactions on*, 29(3):317–325, 1980.

[45] International Telecommunications Union. ITU-R Recommendation P.529-2: Prediction methods for the terrestrial land mobile service in the VHF and UHF bands. Technical report, International Telecommunications Union, 1997.

[46] European Cooperation in the Field of Scientific and Technical Research EURO-COST231. Urban Transmission Loss Models for Mobile Radio in the 900 and 1800 MHz Bands, 1991.

[47] E. Damosso. Digital mobile radio: Cost 231 view on the evolution towards 3rd generation systems. *European Commission*, 1998.

[48] J. Walfisch and H. L. Bertoni. A theoretical model of UHF propagation in urban environments. *Antennas and Propagation, IEEE Transactions on*, 36(12):1788–1796, 1988.

[49] L.R. Maciel, H. L. Bertoni, and H. Xia. Unified approach to prediction of propagation over buildings for all ranges of base station antenna height. *Vehicular Technology, IEEE Transactions on*, 42(1):41–45, 1993.

[50] H.H. Xia and H. L. Bertoni. Diffraction of cylindrical and plane waves by an array of absorbing half-screens. *Antennas and Propagation, IEEE Transactions on*, 40(2):170–177, 1992.

[51] F. Ikegami, T. Takeuchi, and S. Yoshida. Theoretical prediction of mean field strength for urban mobile radio. *Antennas and Propagation, IEEE Transactions on*, 39(3):299–302, 1991.

[52] P. L. Rice, A. G. Longley, K. A. Norton, and A. P. Barsis. *Transmission Loss Predictions for Tropospheric Communications Circuits*, volume NBS Technical Note 101 Vol. 1. U. S. National Bureau of Standards, 1965.

[53] A. G. Longley and P. L. Rice. Prediction of tropospheric radio transmission loss over irregular terrain. a computer method-1968. Technical report, DTIC Document, 1968.

[54] M. J. Feuerstein, K. L. Blackard, T. S. Rappaport, S. Y. Seidel, and H. H. Xia. Path loss, delay spread, and outage models as functions of antenna height for microcellular system design. *Vehicular Technology, IEEE Transactions on*, 43(3):487–498, 1994.

[55] C. Pérez-Vega. *Caracterización Estadística de la Atenuación en el Canal de Propagación en Interiores*. PhD thesis, Universidad de Cantabria, 2002.

[56] K. S. Gilhousen, I. M. Jacobs, R. Padovani, A. J. Viterbi, Jr. Weaver, L. A., and C. E. Wheatley. On the capacity of a cellular CDMA system. *Vehicular Technology, IEEE Transactions on*, 40(2):303–312, 1991.

[57] K. Sipila, Z. C. Honkasalo, J. Laiho-Steffens, and A. Wacker. Estimation of capacity and required transmission power of WCDMA downlink based on a downlink pole equation. In *Vehicular Technology Conference Proceedings, 2000. VTC 2000-Spring Tokyo. 2000 IEEE 51st*, volume 2, pages 1002–1005, 2000.

[58] S. Burley. Downlink capacity estimation in a WCDMA cellular network. In *Personal, Indoor and Mobile Radio Communications, 2001 12th IEEE International Symposium on*, volume 1, pages 26–30, 2001.

[59] C. Cordier and S. Ortega. On WCDMA downlink multiservice coverage and capacity. In *Vehicular Technology Conference, 2001. VTC 2001 Fall. IEEE VTS 54th*, volume 4, pages 2754–2758, 2001.

[60] M. D. Yacoub, A. F. De Toledo, P. R. Gomez, P. J. Jeszensky, and E. B. Feris. Microcellular reuse pattern in an urban environment. In *Personal, Indoor and Mobile Radio Communications, 1998. The Ninth IEEE International Symposium on*, volume 2, pages 645–649, 1998.

[61] C. K. d'Avila and M. D. Yacoub. Reuse efficiency for non-uniform traffic distributions in CDMA systems. *Electronics Letters*, 34(13):1293–1294, 1998.

[62] C. K. d'Avila and M. D. Yacoub. Frequency reuse efficiency in CDMA systems: from an uniform to a bell-shaped traffic distribution. In *Telecommunications Symposium, 1998. ITS '98 Proceedings. SBT/IEEE International*, pages 161–165, 1998.

[63] C. K. d'Avila and M. D. Yacoub. The linear method to evaluate the frequency reuse efficiency of cellular CDMA systems. In *Global Telecommunications Conference, 1999. GLOBECOM '99*, volume 1A, pages 127–131, 1999.

[64] C. K. d'Avila and M. D. Yacoub. Reuse efficiency in a quasi-real CDMA network. In *Personal, Indoor and Mobile Radio Communications, 2000. PIMRC 2000. The 11th IEEE International Symposium on*, volume 1, pages 87–91, 2000.

[65] D. J. Bem, M. J. Nawrocki, T. W. Wieckowski, and R. J. Zielinski. Modeling methods for WCDMA network planning. In *Vehicular Technology Conference, 2001. VTC 2001 Spring. IEEE VTS 53rd*, volume 2, pages 962–966, 2001.

[66] Nokia Siemens Network. Mobile broadband with HSPA and LTE - capacity and cost aspects. Technical report, Nokia Siemens Network.

[67] D. Avidor and S. Mukherjee. Downlink dimensioning for the HSDPA standard. *Wireless Personal Communications*, 32(2):139–152, 2005.

[68] J. M. Cardoso-Lopes. Performance Analysis of UMTS/HSDPA/HSUPA at the Cellular Level. Master's thesis, Universidade Técnica de Lisboa, 2008.

[69] H. Holma and A. Toskala. *LTE for UMTS, OFDMA and SC-FDMA Based Radio Access.* John Wiley and Sons Ltd., 2009.

[70] S. Abdul-Basit. Dimensioning of LTE Network - Description of Models and Tool, Coverage and Capacity Estimation of 3GPP Long Term Evolution radio interface. Master's thesis, Helsinki University of Technology, 2009.

[71] I. Rechenberg. *Evolutionsstrategie: optimierung technischer systeme nach prinzipien der biologischen evolution.* Frommann-Holzboog, 1993.

[72] H. P. Schwefel. *Numerical Optimization of Computer Models.* John Wiley and Sons Ltd., 1981.

[73] L. J. Fogel. *Biotechnology: concepts and applications.* Prentice-Hall Englewood, 1963.

[74] L. J. Fogel, A. J. Owens, and M. J. Walsh. Artificial intelligence through simulated evolution, 1966.

[75] H. J. Bremermann. Optimization through evolution and recombination. *Self-organizing systems*, pages 93–106, 1962.

[76] A. S. Fraser. Simulation of genetic systems. *Journal of Theoretical Biology*, 2(3):329–346, 1962.

[77] D. E. Goldberg, K. Deb, and J. H. Clark. Genetic algorithms, noise, and the sizing of populations. *Complex systems*, 6:333–362, 1991.

[78] A. Ter-Sarkisov, S. R. Marsland, and B. R. Holland. The k-bit-swap: a new genetic algorithm operator. In *Proceedings of the 12th annual conference on Genetic and evolutionary computation*, pages 815–816. ACM, 2010.

[79] C. Maple, L. Guo, and J. Zhang. Parallel genetic algorithms for third generation mobile network planning. In *Parallel Computing in Electrical Engineering, 2004. PARELEC 2004. International Conference on*, pages 229–236. IEEE, 2004.

[80] F. Garzia, C. Perna, and R. Cusani. Optimization of UMTS network planning using genetic algorithms. *Communications and Network*, 2(3):193–199, 2010.

[81] R. S. Rambally and A. Maharajh. Cell Planning using Genetic Algorithm and Tabu Search. In *Applications of Digital Information and Web Technologies, 2009. ICADIWT'09. Second International Conference on the*, pages 640–645. IEEE, 2009.

[82] T. Vanhatupa, M. Hannikainen, and T. D. Hamalainen. Genetic algorithm to optimize node placement and configuration for WLAN planning. In *Wireless Communication Systems, 2007. ISWCS 2007. 4th International Symposium on*, pages 612–616. IEEE, 2007.

[83] J. Munyaneza, A. Kurien, and B. Van Wyk. Optimization of antenna placement in 3g networks using genetic algorithms. In *Broadband Communications, Information Technology & Biomedical Applications, 2008 Third International Conference on*, pages 30–37. IEEE, 2008.

[84] S. M. Gaber, M. E. El-Sharkawi, and M. N. El-deen. Traditional Genetic Algorithm and Random-weighted Genetic Algorithm with GIS to Plan Radio Network. *URISA Journal*, 22(1):33, 2010.

[85] J. Y. Wang, J. B. Wang, X. Song, M. Chen, and J. Zhang. Network planning for distributed antenna-based high-speed railway mobile communications. *Transactions on Emerging Telecommunications Technologies*, 2012.

[86] C. Y Ngo and V. Li. Fixed channel assignment in cellular radio networks using a modified genetic algorithm. *Vehicular Technology, IEEE Transactions on*, 47(1):163–172, 1998.

[87] L. Wang, S. Arunkumaar, and W. Gu. Genetic algorithms for optimal channel assignment in mobile communications. In *Neural Information Processing, 2002. ICONIP'02. Proceedings of the 9th International Conference on*, volume 3, pages 1221–1225. IEEE, 2002.

[88] K. N. Sivarajan, R. J. McEliece, and J. W. Ketchum. Channel assignment in cellular radio. In *Vehicular Technology Conference, 1989, IEEE 39th*, pages 846–850. IEEE, 1989.

[89] M. Duque-Antón, D. Kunz, and B. Ruber. Channel assignment for cellular radio using simulated annealing. *Vehicular Technology, IEEE Transactions on*, 42(1):14–21, 1993.

[90] F. Jaimes-Romero and D. Muñoz-Rodriguez. Evolutionary searching in cellular radio systems planning. *European transactions on telecommunications*, 10(1):85–96, 1999.

[91] X. Fu, A. G. Bourgeois, P. Fan, and Y. Pan. Using a genetic algorithm approach to solve the dynamic channel-assignment problem. *International Journal of Mobile Communications*, 4(3):333–353, 2006.

[92] H. Kamal, M. Coupechoux, and P. Godlewski. Tabu search for dynamic spectrum allocation in cellular networks. *Transactions on Emerging Telecommunications Technologies*, 23(6):508–521, 2012.

[93] E. Mulyana and U. Killat. Load balancing in IP networks by optimising link weights. *European transactions on telecommunications*, 16(3):253–261, 2005.

[94] Z. Liu, M. Kwiatkowska, and C. Constantinou. A self-organised emergent routing mechanism for mobile ad hoc networks. *European transactions on telecommunications*, 16(5):457–470, 2005.

[95] S. Salcedo-Sanz, J. Del Ser, I. Landa-Torres, S. Gil-López, and A. Portilla-Figueras. The coral reefs optimization algorithm: Simulating a reef formation for solving hard optimization problems. *Elsevier Science*, 2012.

[96] R. V. Rao and V. Patel. An elitist teaching-learning-based optimization algorithm for solving complex constrained optimization problems. *International Journal of Industrial Engineering Computations*, 3(4):535–560, 2012.

[97] 3rd Generation Partnership Project; Technical Specification Group GSM/EDGE. Radio Access Network; Radio Transmission and reception. Technical report, 3GPP, 1999.

[98] ETSI TS 25.214 V5.3.0. Universal Mobile Telecommunications System (UMTS); Physical layer procedures (FDD). 3GPP TS 25.214 version 5.3.0 Release 5, 2002.

[99] J. Soo-Yong and C. Dong-Ho. An enhanced channel-quality indication (CQI) reporting scheme for HSDPA systems. *Communications Letters, IEEE*, 9(5):432–434, 2005.

[100] F. Brouwer, I. de Bruin, J. C. Silva, N. Souto, F. Cercas, and A. Correia. Usage of link-level performance indicators for HSDPA network-level simulations in E-UMTS. In *Spread Spectrum Techniques and Applications, 2004 IEEE Eighth International Symposium on*, pages 844–848, 2004.

[101] N. El Heni, X. Lagrange, and P. Maule. Optimization of link adaptation and HARQ schemes for multicast in high speed cellular networks. In *Wireless Communication Systems, 2009. ISWCS 2009. 6th International Symposium on*, pages 131–135, 2009.

[102] H. Holma and A. Toskala. *HSDPA/HSUPA for UMTS, High Speed Radio Access for Mobile Communications*. John Wiley and Sons Ltd., 2006.

[103] K. Mäkeläinen. *HSUPA Workaround for MultiRadio Planner*. Nokia Siemmens Network, 2007.

[104] 3rd Generation Partnership Project. Evolved Universal Terrestrial Radio Access (E-UTRA); Base Station (BS) radio transmission and reception. Technical report, 3GPP, 2008.

[105] 3rd Generation Partnership Project. Evolved Universal Terrestrial Radio Access (E-UTRA); Physical layer procedures. Technical report, 3GPP, 2008.

[106] X. Yao, Y. Liu, and G. Lin. Evolutionary programming made faster. *Evolutionary Computation, IEEE Transactions on*, 3(2):82–102, 1999.

[107] D. B. Fogel. An introduction to simulated evolutionary optimization. *Neural Networks, IEEE Transactions on*, 5(1):3–14, 1994.

[108] H. S. Lim, M. V. Rao, A. W. Tan, and H. T. Chuah. Multiuser detection for DS-CDMA systems using evolutionary programming. *Communications Letters, IEEE*, 7(3):101–103, 2003.

[109] Comisión del Mercado de las Telecomunicaciones. Informe Anual 2011. http://cmtdata.cmt.es/cmtdata/jsp/inf_anual.jsp?tipo=1&openid=8381, Last visit: 15th July 2013.

[110] Ministerio De Industria Turismo Y Comercio de España. *Consulta pública sobre actuaciones en materia de espectro radioeléctrico: Refarming en bandas 900 MHz y 1800 MHz, dividendo digital y banda 2.6 GHz*, 2010.

[111] M. F. Emmenegger, R. Frischknecht, M. Stutz, M. Guggisberg, R. Witschi, and T. Otto. Life cycle assessment of the mobile communication system umts: Towards eco-efficient systems (12 pp). *The International Journal of Life Cycle Assessment*, 11(4):265–276, 2006.

[112] GSM Association. Comparison of fixed and mobile cost structures. http://www.gsma.com/publicpolicy/wp-content/uploads/2012/09/Tax-Comparison-of-fixed-and-mobile-cost-structures.pdf, GSMA, 2012.

[113] T. Smura, A. Kiiski, and H. Hämmäinen. Virtual operators in the mobile industry: a techno-economic analysis. *NETNOMICS: Economic Research and Electronic Networking*, 8(1-2):25–48, 2007.

[114] Gobierno de España. Ministerio de Industria, Turismo y Comercio. Plan de actuaciones para la liberación del dividendo digital. http://www.minetur.gob.es/telecomunicaciones/es-es/novedades/documents/plan_marco_dividendo_digital.pdf, Last visit: 15th July 2013.

[115] http://www.redestelecom.es/comunicaciones/noticias/1067271000303/yoigo-toma-delantera-competencia.1.htmlyoigo-toma-delantera-competencia.1.html, Last visit: 15th July 2013.

[116] http://www.redestelecom.es/comunicaciones/noticias/1067314000303/orange-8-julio-oferta-4g-seis-ciudades-espanolas.1.htmlorange-8-julio-oferta-4g-seis-ciudades-espanolas.1.html, Last visit: 15th July 2013.

[117] S. Salcedo-Sanz, J. E. Sánchez-García, A. Portilla-Figueras, S. Jiménez-Fernández, and A. M. Ahmadzadeh. Coral-Reef Optimization Algorithm Applied to Optimal Service Distribution Problem in Mobile Radio Access Networks. *Transactions on Emerging Telecommunications Technologies*, submitted, 2013.

[118] http://www.xataka.com/otros/orange-y-vodafone-se-unen-para-competir-en-la-fibra-optic utm_source=feedburner&utm_medium=feed&utm_campaign=Feed%3A+xataka2+(Xataka), Last visit: 15th July 2013.

[119] Instituto Nacional de Estadística. http://www.ine.es/jaxi/menu.do?type=pcaxis&path=%2Ft35%2Fp008&file=inebase&L=0, Last visit: 15th July 2013.

[120] T. Halonen, J. Romero, and J. Melero. *GSM, GPRS and EDGE performance: evolution towards 3G/UMTS*. Wiley. com, 2004.

[121] Ericsson. *GSM Cell Planning Principles*. Ericsson.

[122] K. S. Gan, P. Anthony, J. Teo, and K. O. Chin. *Performance of Varying Genetic Algorithm Techniques in Online Auction*. Intech, 2012.

[123] A. Moral-Caballero. *Aplicación del análisis tecno-económico a la gestión del espectro radioeléctrico. El caso de la reutilización de las bandas GSM en Europa*. PhD thesis, Telecomunicacion, 2011.

[124] A. Vergara-Pardillo. *Aplicación del análisis tecno-económico al despliegue de redes de acceso de próxima generación. El caso de la competencia entre plataformas, la regulación y las políticas públicas en España*. PhD thesis, Telecomunicacion, 2011.

[125] B. Chapman, G. Jost, and R. Van Der Pas. *Using OpenMP: portable shared memory parallel programming*, volume 10. MIT press, 2008.

[126] WIK-Consult. Erstellung von Bottom-up Kostenrechnungsmodellen zur Ermittlung der Kosten der Zusammenschaltung in Festnetzen und Mobilnetzen Mobilfunknetz. https://www.rtr.at/en/komp/Bottom_up_2010, Last visit: 15th July 2013.

[127] WIK-Consult. Analytisches Kostenmodell für ein Mobilfunknetz. http://www.bundesnetzagentur.de/cln_1912/DE/Sachgebiete/Telekommunikation/Unternehmen_Institutionen/Marktregulierung/massstaebe_methoden/kostenmodelle/mobilfunk/mobilfunk-node.html, Last visit: 15th July 2013.