About the Location of Base Stations for a UMTS System: Analytical Study and Simulations

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Abstract: **One of the first decisions that a radio network designer must take is the location of base stations and the distance between them in order to give the best coverage to a region and, possibly, to reduce deployment costs. In this paper, the authors give an insight to this matter by presenting a possible solution to a real problem: Planning the base stations layout for a universal mobile telecommunications system (UMTS) in the city of Barcelona. At the basis of this problem, there is the interdependence between coverage and capacity in a wideband-code division multiple access (W-CDMA) system, which is a new element in the planning of BS layout for mobile communications. This aspect has been first treated with an analytical study of the cell coverage range for a specific environment and service. The achieved results have been checked with the help of snapshot simulations together with a geographical information system (GIS) tool incorporated in the simulator that allows to perform analysis and to visualize results in a useful way. By using the simulator, it is also possible to study a more complex environment, that of a set of base stations providing multiple services to a large number of users.**

Index Terms: **Base station location, simulation, universal mobile telecommunications system (UMTS), urban environment.**

I. INTRODUCTION

3G cellular networks have been under intensive research as the technological evolution of the second generation (2G) digital networks, with the aim of offering multiple services such as multimedia applications and high speed data services. With the purpose of creating a standard for 3G technologies, the international telecommunication union (ITU) works on the definition of a standard known as international mobile telecommunications 2000 (IMT-2000). The fundamental mechanisms that have to be defined with accuracy are the modulation scheme for the air interface and the pertinent protocols. Both equipment's producers and standardization bodies, such as the European telecommunications standard institute (ETSI), have chosen wideband-code division multiple access (W-CDMA) as the access scheme.

A. UMTS System

The architecture of the universal mobile telecommunications system (UMTS) network [1] can be divided into two blocks: The commutation and routing network, known as core network (CN), and the access network, known as UMTS terrestrial radio access network (UTRAN). The CN makes it possible, to all the access points of the UTRAN, to communicate each other; on the other hand, the access network gathers the traffic coming from base stations (BS). The handover allows a user to be connected with the system while moving through different cells. Besides the classical handover, for which there is an instantaneous break in the communication between the user and the old BS in order to allow the system to transfer the call to the new BS (hard handover), UMTS introduces a new concept: *Soft handover.* This mechanism allows different BSs to handle the call, so that there is no break in the while moving to a new cell. The same mechanism is known as softer handover when different sectors of the same BS handle with the communication.

W-CDMA, the new access technique used by UMTS, represents a real change. In former systems, the total bandwidth was shared among the users in time slots (TDMA) or in frequency channels (FDMA). In UMTS, communications are codified with a pseudo-random code which is characteristic for the single user. By using codes with a wider bandwidth than the one used by the information, the coding process spreads the signal spectrum. At reception, the despreading mechanism leaves interference as low-power broadband signal, while information, which is high-power narrowband, can be separated with a filter.

Among the drawbacks of this technique, there is the problem known as near-far effect. If all the terminals transmit at the same power, the BS receives with a higher strength the signals coming from the nearest users, while the ones who stand in the boundary of the cell will be heard very softly. The danger is that the nearest users can mask the communication of the farest ones. It is possible to solve this problem applying a power control in every communication, so that ideally every communication reaches the BS with the same average power level. A power control is also applied in the downlink in order to properly share the limited BS power between all the users.

B. Objectives and Previous Research

The purpose of this work is to show how the layout of BSs in a real city scenario is planned in order to provide the best coverage to UMTS users demanding services at multiple rates. The impact of new effects such as the soft handover and the cell breathing are also investigated. This study relies on an analytical study, known as *link budget*, from which it is possible to estimate the single-cell coverage ranges in different environments for a given system capacity. A first approach to this problem was suggested in [3]. Many issues affect system performance (i.e., propagation conditions, traffic density, user's profile, interference conditions, cell breathing, etc.) making the network designer's task quite complex; to this end, software planning tools can make a substantial difference in the study of such complex systems [4]. Starting from simulation analysis in a single-cell environment in which analytical results have been tested, the authors provide a

Manuscript received September 14, 2004; approved for publication by Kyungwhoon Cheun, Division II Editor, November 30, 2005.

Most of the contents of this paper have been presented at the International Conference on Telecommunications 2004 [2].

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first layout of the BSs in the city of Barcelona. In this multiple-cell asset, the intercell interference, the cell breathing, and the capacity requirements due to soft-handover generate new problems that, in the single-cell scenario, do not appear (i.e., noise rise, BS power limits, CPICH power limit, etc.). With the final purpose of providing good coverage, the authors investigate how to improve this first layout by changing the configuration of any BSs (e.g., tilt, height) and, eventually, changing their locations. An optimal planning needs a long process of trial and error, from which one has to adjust parameters in order to finally achieve a good provision of service.

The layout problem has been investigated in recent papers. In [4], the problem of optimizing the configuration of a set of available BSs is targeted by adding new ones when necessary; the authors propose a mathematical programming model which considers the power control typical of W-CDMA and the signal-to-interference ratio (SIR) as quality measure. In [5], an optimization program is presented; with the cell coverage areas as an input, it can provide an optimal coverage of the area under study using the minimum number of BSs. A methodology to calculate the sensitivity of capacity to BS location, pilot-signal power, and transmission power of each mobile is developed in [6]; the authors prove that, by controlling the transmitted pilot-signal power and adjusting the location of the BSs, the coverage region of each cell is monitored, which in turn controls the intracell and intercell interference. This work does not provide a general method to optimize the location of BSs but gives an insight to the general problem of designing the location of antennas in an actual urban environment, with the aim of reaching the best coverage with the lowest number of settlements.

Another purpose of the design is the allocation of the adequate number of traffic channels. UMTS provides circuit switched (CS) and packet switched (PS) communications. In CS networks, by applying Erlang B formulas, it is possible to find out the number of circuits necessary to provide service, with a certain blocking probability, to a specific number of users. Since PS services are often best effort, they do not need circuits' reservation, but they take advantage of the resources unused by the system. There are no formulas that can describe and solve this situation. In this work, the authors show an analytical procedure for the solution of this problem.

C. Structure

Section II introduces the theory and analysis about the link budget calculations in different environments. Throughout the link budget, it is possible to find a trade-off between coverage (e.g., cell ranges) and capacity (number of simultaneous users) of a cell in order to dimension all the system. Section III describes the simulator used in this study. By working with propagation models that can be shaped to the scenario under study, the simulation tool calculates the BS coverage ranges. The last two sections focus on the results of the simulations. Section IV analyzes a single tri-sectorial cell environment. Section IV-A is dedicated to study a single service at once: Voice traffic, data services at 64, 144, and 384 kbps. In Section IV-B, all these services are gathered in the same analysis; the purpose is to stress once again the dependence between coverage and the service provided, and between the density of traffic and the cell range, etc. In Section V, we present the layout of BSs in the city of Barcelona. Section V-A shows the first plan of BSs, which follows a hexagonal underlying; it provides good coverage except for some regions. In order to improve coverage, it is necessary to tune the downtilt and orientation of some antennas, and sometimes also to add new BSs. Section V-B presents a second plan where new antennas try to overcome the coverage issues of the first plan.

II. ANALYTICAL EVALUATION OF THE LINK BUDGET

Coverage and capacity are closely related in W-CDMA networks; therefore, both must be considered simultaneously. Once the maximum propagation losses have been estimated, it is necessary to find the equilibrium between coverage (i.e., cell size) and capacity (i.e., maximum number of simultaneous users borne by the cell) [7], [8].

In a light-loaded system, users do not generate much interference, so the coverage is larger. Since the power emitted by a mobile station (MS) is lower compared with the maximum power a BS can transmit, a user far from the BS probably can listen to the signal, while his communication reaches the BS with insufficient strength; that is, the uplink (UL) is coverage limited, at least while the traffic demand is not heavy. On the other hand, changes in the number of users and services have a strong impact on the cell coverage range; this is known as *cell breathing* effect: As load increases, the coverage is reduced. This high concentration of users inside a small area makes interference rise up; the effect is that the power dedicated to the pilot channel (CPICH—control pilot channel) and the BS power sharing become insufficient for all the users inside the cell, making it impossible to provide service in the downlink (DL) to all of them. Therefore, it is commonly said that the DL is capacity limited [3], [9].

A. Coverage Estimation

This first approach to radio network planning is based on the estimation of the maximum losses the radio signal will suffer during its propagation through different environments [8], [9]–[11]. This kind of calculation is known as *link budget* and depends on the environment and on the propagation model chosen. It is independent from the simulation results presented in the following sections: Notice in Section III that the simulation tool carries out its own calculations by using propagation models that better suits the analyzed environment, hence more complex.

Table 1 shows an example of calculation of the area covered by a tri-sectorial cell (i.e., surface in km^2) in an urban environment. Since coverage strictly depends on the density of traffic inside an area, this study starts considering a maximum load of 60% of the pole capacity, where the pole capacity represents the maximum load a system can bear. This should not mean a limitation, as the system is believed to be deployed for coverage initially. Some parameters are set by the standard, e.g., the maximum power an MS can transmit depends on its class. The standard classifies four types of MSs, but Class 4, for which the maximum power is limited to 21 dBm, will be most used.

Table 1. Example of UL budget in an urban environment.

Uplink budget	Total system load: 60%	Urban environment	Pedestrian users						
	Size	Formulas	Voice	CS 64	CS 144	CS 384	PS 64	PS 144	PS 384
Thermal noise density	dBm/Hz	N_0				-174			
Chip rate	kbps	R_c				3840			
BS noise figure	dB	NF				3			
BS thermal noise	dBm	$N_{th} = N_0 + 10\log R_c + NF$				-105.16			
Noise rise	dB					3.98			
BS noise power	dBm	$N_{BS} = N_{th}$ + noise rise				-101.18			
Bit rate	kbps	R_b	12.2	64	144	384	64	144	384
E_b/I_o target	dB	Operator values	3.7	3.4	2.75	1.6	1.85	1.4	1.4
Processing gain	dB	$10\log(R_c/R_b)$	24.98	17.78	14.26	10	17.78	14.26	10
SIR	dB	(E_b/I_0)-PG	-21.28	-14.38	-11.51	-8.4	-15.93	-12.86	-8.6
Sensitivity	dBm	N_{BS} +SIR	-122.46	-115.56	-112.69	-109.58	-117.11	-114.04	-109.78
Body loss	dB	a	3	0	0	0	0	0	0
Vehicular loss	dB	b				0			
Indoor loss	dB	c				16			
Duplexor loss	dB	d				1			
BS wiring loss	dB	e				2			
MS antenna gain	dBi	f	0	0	0	2	0	0	2
BS antenna gain	dBi	g				18			
Total losses	dB	a + b + c + d + e - f - g	4	1	1	-1	1	1	-1
Lognormal fading margin	dB	h				8			
Fast fading margin	dB	i				2			
Control power margin	dB	l				2			
Diversity gain	dB	m				4			
Soft HO gain	dB	n	5	5	5	5	2	2	2
Total fading margin	dB	f m = h + i + l - m - n	3	3	3	3	6	6	6
MS Tx power	dBm	P_{tx}	21	21	21	24	21	21	24
Propagation losses	dB	P_{tx}-sensitivity-f.m.-total losses	136.46	132.56	129.69	131.58	131.11	128.04	128.78
Cell cov. range	km	D	1.196	0.924	0.764	0.866	0.839	0.685	0.719
Tri-sectorial cell cov. area	km²		**2.787**	**1.664**	**1.137**	**1.461**	**1.372**	**0.914**	**1.007**

Table 2. Example of UL budget in a dense urban environment.

Uplink budget	Total system load: 60%	Dense urban environment	Pedestrian user						
	Size	Formulas	Voice	CS 64	CS 144	CS 384	PS 64	PS 144	PS 384
Indoor loss	**dB**	**c**				**24**			
Total losses	dB	a + b + c + d + e - f - g	12	9	9	7	9	9	7
Propagation losses	dB	P_{tx}-sensitivity-f.m.-total losses	128.458	124.56	121.688	123.578	123.11	120.038	120.778
Cell cov. range	km	D	0.704	0.544	0.450	0.510	0.494	0.403	0.423
ri-sectorial cell cov. area km²			**0.966**	**0.577**	**0.395**	**0.507**	**0.476**	**0.316**	**0.349**

Class 3 will be used for high data rate transmissions (384 kbps) only. The *noise rise* (i.e., interference caused by other users from the same cell) depends on the system load according to the following expression

$$\text{noise rise} = 10\log\left(\frac{1}{1 - \text{system load}}\right). \tag{1}$$

Moreover, the *bit rate* of the communication and the E_b/I_0 target directly settle the SIR target at the receiver and, consequently, has an impact on the *sensibility* of the BS. The E_b/I_0 target is generally settled by the operator and depends on the environment and kind of service provided. The *fading margin* groups a set of margins: Log-normal and Rayleigh fading, soft handover and diversity gain, power-control, etc. Losses depend on many factors: *Body losses* varies from 3 dB, for situations where the terminal stays very close to the body of the user (i.e., voice calls), to 0 dB for data downloads; *vehicular loss* has been set to zero since the pedestrian user case has been analyzed; *indoor losses* consider reflections over buildings and over other obstacles in an urban environment. Other losses can be taken into account, depending on the equipment's specifications. Both MS and BS *antenna gains* can be considered in the total losses evaluation; normally, only for Class 3 equipments a gain of 2 dBi has to be considered. The values for the BSs antenna gain and for each parameter in the *fading margins* calculation have been taken from technical specifications. Normally, a higher *soft handover gain* is considered for CS services (5 dB versus 2 dB for PS services).

The link budget estimation is carried out using the Okumura-Hata propagation model, in which the propagation losses (L_{OH}) in an urban scenario are computed as

$$L_{OH} = 133.76 + 34.79\log\ d \tag{2}$$

where d is the distance in kilometers. More details can be found in [12] and [13].

Table 1 shows the cell ranges (i.e., D) in the option of providing voice service or data service at different rates. In general, when considering a service with a higher data rate, the cell coverage decreases, unless a higher transmission power is used as in CS384. For this reason, the operator must consider the minimum cell coverage (i.e., the coverage for the most constraining service) in order to guarantee a good coverage to every user, according to the set of services to be provided.

Table 2 displays the link budget for a dense urban environment. Due to the higher density of building, a greater value for *indoor losses* (i.e., 24 dBm) has to be taken into account and, consequently, cell coverage ranges reduce (the other parameters are not displayed since they do not change from the previous analysis in Table 1).

B. Capacity Dimensioning

In a multiple cell-multiple service environment, the total system load η can be computed as

$$\eta = (1+f)\sum_{\text{service}} \eta_{\text{service}} = \frac{N_{\text{service}} SIR_{\text{service}} AF_{\text{service}}}{1 + SIR_{\text{service}} AF_{\text{service}}} \tag{3}$$

where f is the other-cells interference (typically, 0.65 for tri-sectorial sites), η_{service} is the load specific for each service, N_{service} is the number of simultaneous users borne for a specific service (i.e., number of traffic channels for the specific service), SIR_{service} is the signal to interference ratio for each service, AF_{service} is the activity factor of one service (normally set to 0.67 for voice and 1 for all the other services). More details on CDMA capacity for single and multiple cell systems can be found in [14]–[17].

According to this, it is necessary to estimate the amount of traffic (i.e., number of users and kind of services requested by each) handled per BS in order to allocate the correspondent number of traffic channels to the BS [16].

In this process, only CS traffic has been taken into account, since PS services do not need circuit reservation. By estimating the traffic carried with a given GoS, one could visualize PS services being provided during idle periods of CS traffic.

Cell ranges for each environment and load are estimated in the UL budget. We must ensure that the BSs DL power can be shared between all users and that this leaves a sufficient margin for efficient performance.

III. THE SIMULATION TOOL

Coverage calculations can be made by applying propagation models such as the Okumura-Hata. In order to manage with

Table 3. Description of the parameters in (4).

Parameter	Description	Value	Parameter	Description	Value
P_{RX}	Rx power [dBm]		P_{TX}	Tx power [dBm]	
K_1	Constant offset [dB] (intercept)	(-26.5)	*Diff*	Value for diffraction in obstructed path. A positive factor (K_4) is needed since this value is negative.	
K_2	Factor for "log *d*" (slope)	(-40.5)	K_5	Factor for the log H_{eff} log *d* in the Okumura-Hata model	(6.4)
d	Receptor to BS distance [m]		K_6	Correction factor for the antenna effective height at user terminal K_6 H_{meff}	(0)
K_3	Gain for the effective antenna height	(-5.8)	H_{meff}	Antenna effective height at user terminal	
H_{eff}	BSs antenna effective height from the ground		K_{CLU}	Gain for the clutter in which a mobile is moving [dB]	
K_4	Diffraction factor	(0.56)	*AntGain*	Antennas gain (user and BS)	

these formulas, simplifications must be done over the environment under study. By using a computer, it is possible to describe the environment with more detail, so that the study will be more realistic [11], [18]–[20].

The simulation program performs coverage analysis from a set of antennas in a specific environment. In this way, it can determine the coverage area of a set of BSs. It can also study the so called "traffic maps" (i.e., kind of offered services in a region and density of traffic for each service) which are shaped on the simulation environment under study. By analyzing iterative snapshots of the system, the simulator can evaluate the average percentage of calls that the system can handle simultaneously.

A. Coverage and Traffic

The propagation model used in the simulator is based on the Okumura-Hata model, specifically tuned for the city of Barcelona. The model computes the power received at each point of the simulation area as

$$P_{RX} = P_{TX} + K_1 + K_2 \log d + K_3 \log H_{eff} + K_4 Diff + K_5 \log H_{eff} \log d + K_6 H_{meff} + K_{CLU} + \text{AntGain}. \quad (4)$$

Parameters of (4) are displayed in Table 3.

The simulator is combined with geographical information system (GIS) and performs analysis of the coverage provided by a BS; starting from the obstacles that can be found and from the antenna parameters (e.g., frequency band, downtilt, height, etc.), the simulator evaluates losses for that specific environment [11], [18].

Fig. 1 displays the coverage map around a tri-sectorial antenna, according to the propagation model used in this study. Black represents the signal with power strength under -90 dBm corresponding to the *out-of-coverage* area for this BS.

The area in dark grey is where the strength remains between -90 and -80 dBm. This area extends till the bottom right side of Fig. 1, where there is the sea.

The simulator handles with traffic maps that can be suited to the distribution of users and to the number and kind of services provided. In traditional networks, traffic planning is based on Erlang B. By this method, we can determine the maximum number of simultaneous users inside a cell, depending on the number of channels the BS can handle and depending on the tolerance

Fig. 1. Coverage map for a trisectorial antenna.

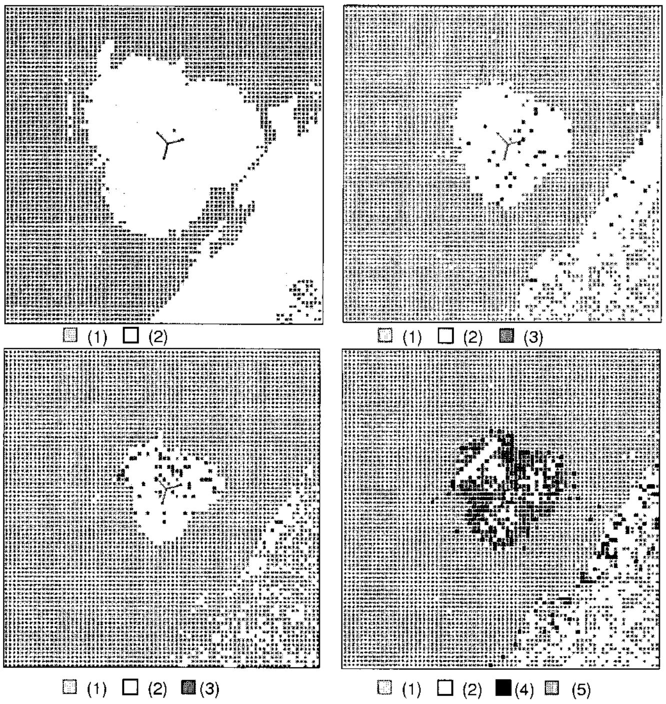
Table 4. Parameters for the first analysis.

Users	Voice	CS data		
Bit rate [kbps]	12.2	64	144	384
Traffic density [E/km^2]	24	24	24	24
Throughput [kbps/km^2]	292.8	1536	3456	9216

accepted on the blocking probability. In the same way, the simulator allows the user to fix the number of traffic channels for each BS and, according to traffic maps, it calculates the probability of providing the services analyzed. Analysis presented in Section IV-A refer to the values displayed in Table 4.

B. Iterative Analysis of Snapshots of the System

The simulator analyzes a finite number of snapshots of the system; in each one, the simulator generates, throughout the simulation area, a specific number of calls of the different services. Depending on the strength that the power emitted from a BS reaches in a specific point where the call has been generated, the simulation tool evaluates if that call can be attended by the system. If the power is not enough, the call will be dropped because of *mobile equivalent radiated power* limit; it represents the limit in the uplink coverage range of that cell. This is not the only reason for a call to be dropped. It can happen that there is sufficient power at that point, but there are no circuits at the BS, so the call cannot be attended. In this case, the system lists this user as dropped due to *primary channel element limit.* By providing the reasons for the dropping of a call, this simulation allows the user to tune the correspondent parameters in order to improve the system capacity. A large number of snapshots lead to an average contribution that can be representative of the system. The tool does not have the facilities to handle with the time intervals in which packet traffic could benefit from the resources unused by the CS traffic. This is why the simulator works with the two services as if both required circuit reservations. This is a limitation in this study, since packet switched traffic cannot be considered in the analysis with its peculiar *best effort* nature; this is why simulations have been run taking into account CS traffic only.



(1) Mobile ERP limit, (2) undropped user, (3) noise rise limit, (4) codes limit, (5) DPCH power limit

Fig. 2. Different coverage ranges for different services.

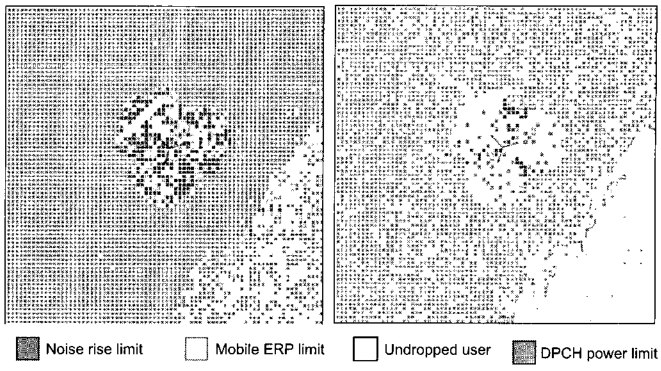


Fig. 3. Coverage area for the 384 kbps data service with different density of traffic (24 E/km^2 on the left, 9 E/km^2 on the right).

Table 5. Traffic channel elements used in the analysis.

Data rate [kbps]	Voice	Data			
	12.2	**64**	**144**	**384**	**384**
Number of CE per circuit	1	2	4	8	8
Traffic density (E/km²)	24	24	24	9	7.2
In-coverage area (km²)	2.86	1.25	0.83	1.25	0.83
Toral traffic (E)	68.64	30	19.92	11.25	5.976
Number of channels (from Erlang B)	80	39	28	18	12
Number of CE (30% added)	104	104	146	187	169
Total blocking probability [%]	**0.7**	**1.2**	**4.1**	**9.3**	**1.2**

IV. SIMULATIONS IN A SINGLE-CELL ENVIRONMENT

In order to simulate the coverage and capacity trade-off, the behavior of a BS has been studied. A single tri-sectorial cell providing just one service has been considered in order to see the dependence of the coverage range with the offered service. The number of traffic channels required by each service has been analyzed. Other papers concerning with similar studies are [11], [19], and [21].

A. *One Service*

A.1 Coverage

Table 4 reports the parameters used in this analysis where services are analyzed separately: Coverage is computed for each service as standalone. *Throughput* indicates the effective load (in kbps/km^2) the system has to bear depending on the *bit rate* of each service and on the *offered traffic*. Notice that one Erlang of data at 384 kbps (i.e., one circuit fully busy) needs 31 times the bit rate of one Erlang of voice at 12.2 kbps. An offered traffic of 24 E/km^2 for each service has been considered.

The results of this first analysis are displayed in Fig. 2 which represents a total area of 15 km^2. As the bit rate increases, the coverage range decreases due to the fact that the overall bit rate increases. Each point represents a call randomly generated by the system in that pixel. The brightest areas correspond to the *in-coverage* zones (i.e., users served), while the darkest correspond to non-attended calls (for various reasons, i.e., *out-of-service* area). In Fig. 2, the specific reasons for each case study have been displayed. As the bit rate per Erlang increases to 64 and 144 kbps, interference problems appear inside coverage range (i.e., noise rise). With the 384 kbps analysis (last panel of Fig. 2) problems with overload inside the cell arise, since it is required to bear 24 Erlang/km^2 of traffic at 384 kbps, equivalent to a throughput of 9216 kbps/km^2. Users are not attended due to codes limit and dedicated physical channel *(DPCH) power limit*, which is equivalent to downlink problems in the sharing of the limited BS power.

Fig. 3 displays the cell coverage range in two situations of load for CS 384 traffic: On the right, load has been decreased to 9 E/km^2 (i.e., 3456 kbps/km^2, same overall rate as 24 E/km^2 at 144 kbps) and the cell coverage range is evident. Grey pixels inside it represent the users that cannot be attended due to noise rise problems, while black crosses correspond to users that cannot be served due to *DPCH power limit.*

A.2 Study of Traffic Channel Elements

The simulator allows the user to set the number of traffic channels at each BS. The number of necessary traffic channels is computed according to Erlang B formula [22], in order to guarantee a maximum blocking probability of 2% for the traffic offered inside the coverage area. An extra amount of 30% channels is allocated for handover only. Moreover, each service requires a different number of channel elements (CE, i.e., the number of elements necessary to each traffic channel in order to establish a connection of a given bit rate). The described process is summarized in Table 5.

Total blocking probability in Table 5 includes all the reasons why a call is blocked (e.g., channel elements limit, mobile power limit, noise rise limit, etc.). For CS data at 144 kbps, the "2%

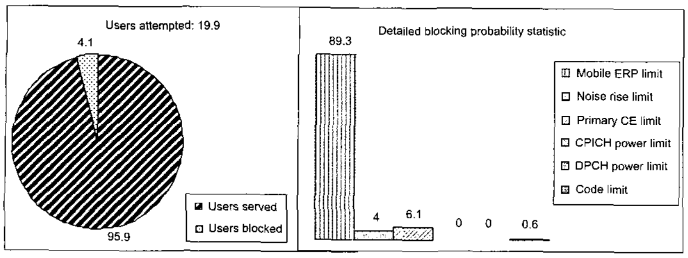


Fig. 4. Report of analysis with the 144 kbps data service.

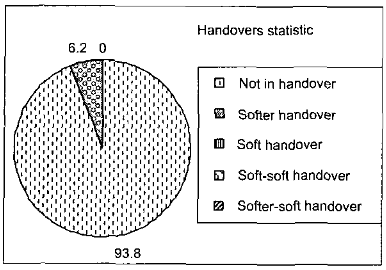


Fig. 5. Handover statistic for the analysis with the 144 kbps data service.

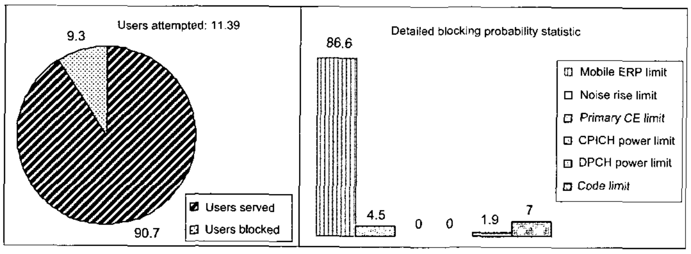


Fig. 6. Report of analysis with 384 kbps and 9 E/km^2.

rule" for maximum blocking probability due to channel elements limit is reached; in Fig. 4 we can observe that only the 6.1% of the total blocking probability (equivalent to 0.25% of the *users attempted*) cannot be attended for *primary channel element limit*. Almost all dropped calls are due to mobile equivalent radiated power (*mobile ERP*) *limit*.

By evaluating the power levels at each point, the simulator estimates the percentage of users who stay in one of the different situations of handover (HO). This is not of great importance in a single tri-sectorial cell environment (e.g., as Fig. 5 shows, it is possible to find users in HO with two different sectors of the same BS, known as *softer handover*). In the analysis presented in Section V more details will be explained about different options of HO.

Table 5 indicates that the total blocking probability reaches 9.3% for CS data at 384 kbps. In Fig. 6, it is clear that the number of traffic channels is sufficient for the density of traffic under study (i.e., 0% of blocking probability due to *primary channel element limit*). Actually, the 86.6% of the blocking probability (8.05% over the *users attempted*) cannot be served due to mobile ERP limit, that is, the effective coverage range for this traffic load is inferior to the one found with the previous analysis. In order to guarantee the same GoS as the one offered to the other services, it is necessary to run simulation in a smaller

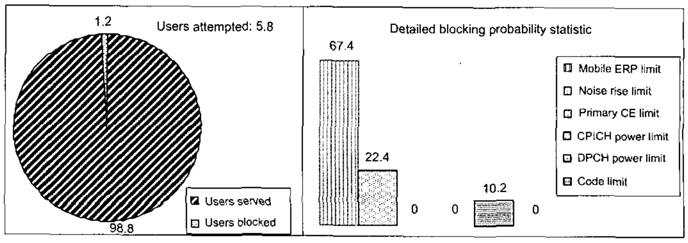


Fig. 7. Report of analysis with 384 kbps and 7.2 E/km^2.

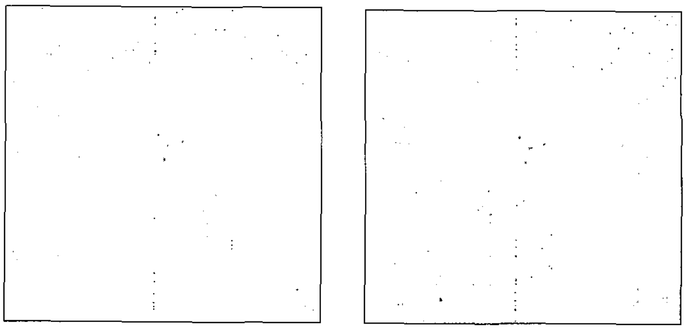


Fig. 8. Comparison of cell ranges with different traffic loads.

area (i.e., 0.83 km^2) and reduce the traffic density to 7.2 E/km^2. As reported in Fig. 7, the percentage of users served is good (98.8%) and only few users cannot be attended due to coverage problems.

B. Sensitivity of Coverage to Traffic Density

It is also interesting to see how the coverage range of a cell varies with the traffic density (i.e., cell breathing effect). The comparison between two different densities of voice traffic is displayed in Fig. 8, where the impact of cell breathing can be observed: On the left, a density of 10 E/km^2 while, on the right, 80 E/km^2. The darkest pixels represent the dropped calls due to *mobile ERP limit*. When the BS has to handle a higher traffic, its range becomes smaller: In the first case, the signal can reach, with sufficient strength, a maximum distance of 1360 m, while in the second only 1 km.

C. Multiservice

Analysis is extended to the multiservice case: Voice and CS data at different rates. For this analysis, the most constraining cell coverage range previously found for the different services has been considered (i.e., the CS144 coverage range in Table 1): Data from the link budget in Table 1 roughly agree with those obtained in Section IV-A and are easier to use (notice that results from simulation provide a map with different ranges for different directions while the link budget provides a single distance). The main impact of multiservice is the different sensitivity of the system performance with respect to traffic increases for different services. A small percentage of growth of traffic at 384 kbps might not be afforded while large percentage of growth for voice traffic can be carried. Table 6 shows three combinations of multiservice traffic targeted to guarantee a fair GoS (i.e., more than 98% of the users attended). The starting point is a case in which

Table 6. Results of the multiservice case study.

Erlang/km²						
Voice 12.2 kbps	CS Data 64 kbps	144 kbps	384 kbps	Total	Number of traffic channels	Total blocking probability (%)
20	0.8	0.8	0.4	22	52	1.2
20	2.4	2.4	2.4	27.2	169	0.7
320	0.8	0.8	0.4	322	390	0.7

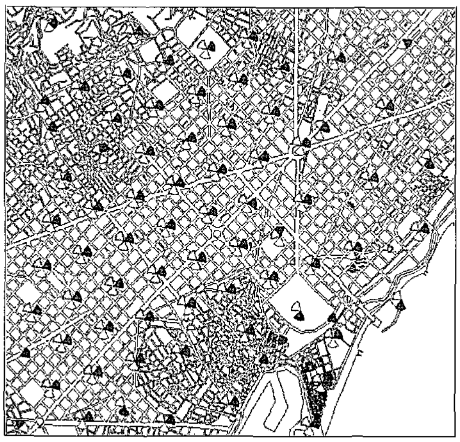


Fig. 9. First plan of nodes B.

data traffic represents a 10% of the voice traffic, as commonly assumed for the first phase of UMTS deployment. Notice how it is possible to increase up to 16 times the density of voice traffic but only 3 times the density of CS data traffic (i.e., more than 3 times leads to poor GoS). In both cases, the required GoS is guaranteed by increasing the number of traffic channels as needed. By further increasing the traffic density, the GoS decreases because of interference and channel codes limit.

V. ANALYSIS IN THE CITY OF BARCELONA

A. *First Plan*

The BS layout must try to cover the whole planned area, the Barcelona downtown in this case. The proposed underlying pattern is hexagonal (i.e., the BSs are located on two 60° axes) with some necessary adjustments. The distances between BSs agree with those found in Section II (hence with simulations of Section IV as well). Antennas are placed at a height of 30 meters (e.g., average roof height) and diffraction due to specific close buildings has not been taken into account (i.e., diffraction is included in the propagation model only). The area considered in this analysis can be divided in two environments: Dense urban (40 E/km^2) in the downtown and urban in the suburbs (20 E/km^2). Fig. 9 shows the geographical distribution; on the left side of the picture there is the city center and the concentration of antennas is denser. The coverage is shown in Fig. 10.

The brighter areas (where the power strength stays between -60 and -80 dBm) represent the regions where the service can be provided, while calls from the users who stay in the darkest grey area (less than -80 dBm) can be blocked due to a lack of coverage.

For the case with voice only, 65 channel elements have been

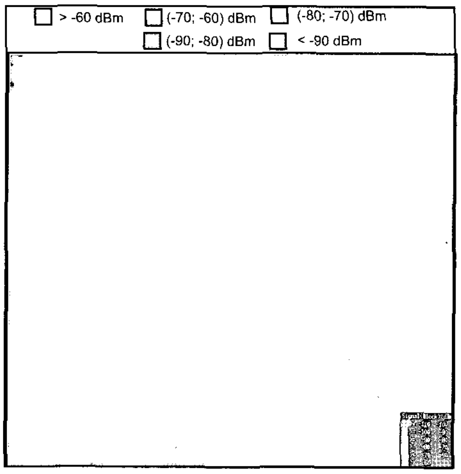


Fig. 10. Coverage range of the first layout.

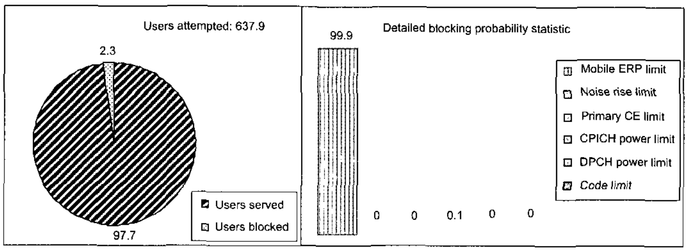


Fig. 11. Report for voice service analysis in the city of Barcelona.

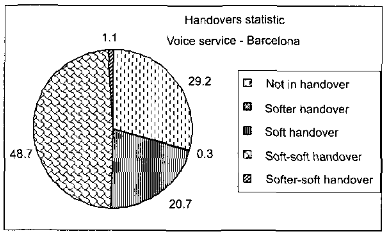


Fig. 12. Handover statistic for voice service analysis in the city of Barcelona.

allocated at each BS (50 plus a 30% for HO only, same as computed in Section IV-A.2). As reported in Fig. 11, the total blocking probability (2.3%) is due to mobile ERP limit, which means that there is a problem in the UL coverage. In order to solve the problem of out-of-coverage areas, it is necessary to reduce the distance between BSs in a second planning step (see Section V-B). Notice in Fig. 12 that only the 29.2% of the users served do not stay in HO. The remaining 70.8% are in one of the different situations of handover: 48.7% is in soft HO with three different nodes B (*soft-soft HO*), 20.7% with two different nodes B (*soft HO*) and a small percentage is in soft HO with three sectors of two different nodes B.

When adding a 10% of data traffic at 64 kbps (i.e., 4 E/km^2 of CS64 in dense urban and 2 E/km^2 in urban) coverage decreases while interference increases. Now the number of necessary channel elements is 78. Fig. 13 reports that the total blocking probability is 6.9%; the 68.4% of the dropping calls are due to coverage reduction (*mobile ERP limit*). We observe the im-

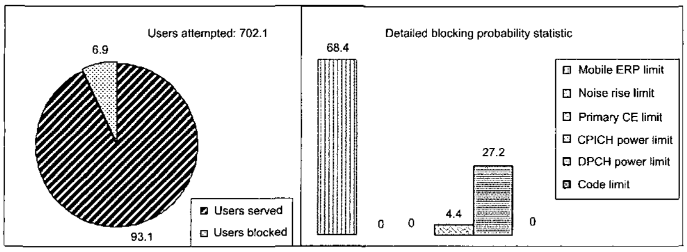


Fig. 13. Report for voice and CS64 data services analysis in the city of Barcelona.

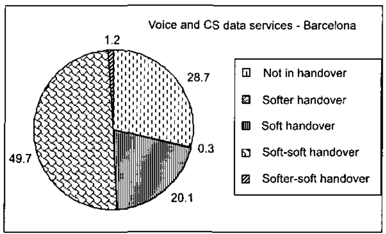


Fig. 14. Handover statistic for voice and CS64 services analysis in the city of Barcelona.

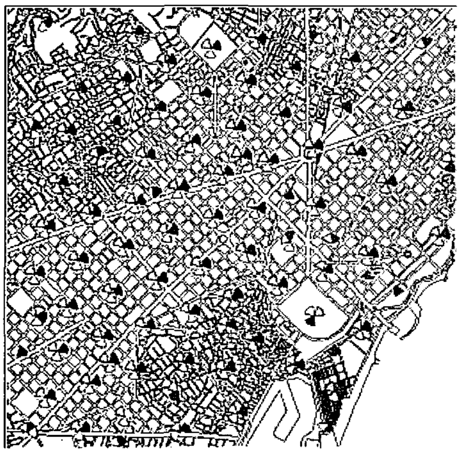


Fig. 15. Second plan of nodes B.

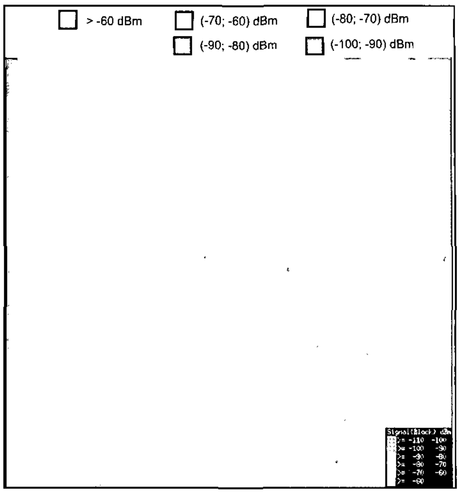


Fig. 16. Coverage range of the second layout.

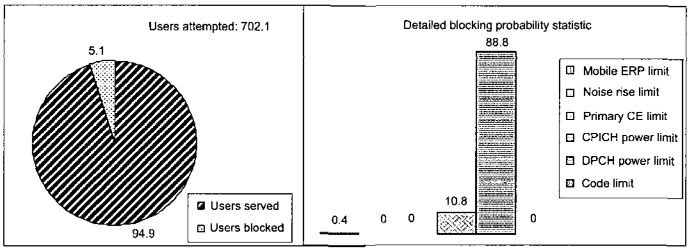


Fig. 17. Report for voice and CS64 data services analysis in the city of Barcelona (second layout).

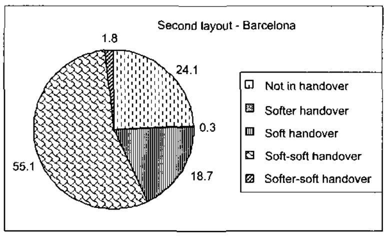


Fig. 18. Handover statistic for the second layout.

pact of cell breathing: The total percentage of users blocked due to mobile ERP limit has increased to nearly 5% while in the previous analysis, with voice service, it was 2.3% only. Against what was found in the voice analysis, other reasons for dropped users appear now. The 27.2% of the dropping calls are due to power limits in the DPCH and the 4.5% in the control pilot channel (CPICH). Fig. 14 shows that the 49.7% of users stays in HO with three BSs; 28.7% are not in HO, while 20% stay in soft HO with two different BSs.

B. Second Plan

With the aim of solving some problems in coverage found in the first plan of the network, the downtilt and direction of some antennas have been tuned and, when necessary, new sites have been added. Fig. 15 shows that, actually, the regular pattern of the first plan has been broken. This second approach to antenna positioning actually offers a better coverage. Fig. 16 displays the signal strength all over the area. If compared to the coverage map of the first plan (see Fig. 10), the signal strength has now improved (i.e., darker areas have been reduced) especially in those regions where users cannot be attended due to *mobile ERP limit*.

With this new layout and with the parameters used in the last case presented (i.e., voice plus CS64) it is possible to attend the 94.9% of all the users asking for voice and CS64 data services. Fig. 17 shows how some problems in coverage have been solved (dropped calls due to *mobile ERP limit* are now around the 0.4% of the total dropped users), while problems with power sharing in the downlink cannot be solved by only changing the layout of antennas. The 88.8% of the users that cannot be attended suffer from *DPCH power limit*, while the 10.8% suffers from *CPICH power limit*. A large number of users, 55.1%, stay in HO with three different BSs and 18.7% stays in soft HO, as shown in Fig. 18.

While it was not possible to solve the power sharing problem

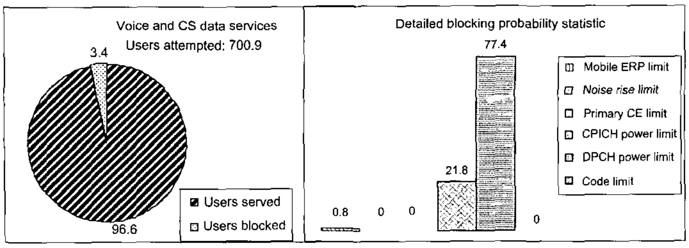


Fig. 19. Simulation report with changes in the power limits of DPCH and CPICH.

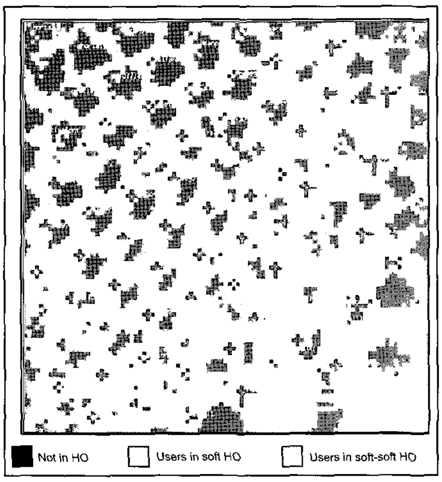


Fig. 20. Users in different situations of HO.

by changing the layout of the BSs, the authors tried to perform new simulations after changing the limits of the power dedicated to DPCH and CPICH. As reported in Fig. 19, there is a partial improvement in performances, since the total blocking probability decreases to 3.4%. No impact on the system load can be appreciated (i.e., there is no dropping call due to the noise rise limit). We could try to tune these power limits further, but this would not be enough to solve the problems inherent to sharing a common resource between too many users and load [23].

While providing the possibility for one user's signal to be recovered from different receivers in the UL, macrodiversity creates an overload in the DL since more than one BS has to provide a part of its limited power to just one user.

The simulator displays, in a specific map, the areas where there is HO. In Fig. 20, the brightest grey represents the area where users stays in *soft-soft HO*, while black limits the area where users do not stay in HO. Finally, the dark grey represents users in *soft HO*. The area where users are held by more than one BS or by more than one sector of a BS is large. In the UL, capacity is increased by such situation, since users can benefit from link-diversity gain. On the other hand, each BS has to carry a greater number of calls; this is known as *overloading effect*. It is necessary to understand which of the two effects dominates. In [9], the authors present an analytical study of the overloading effect. The result is that the soft HO gain due to the reduction in other-cell interference does not increase the system capacity; finally they agree that the overload in the DL dominates capacity of the system. Actually, in the last simulation (see Fig. 17)

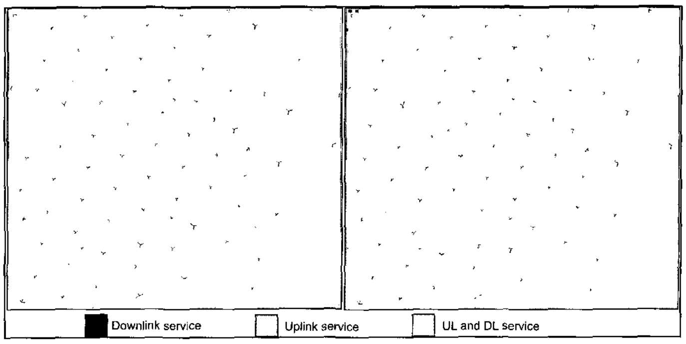


Fig. 21. Service provision in each link.

it seems that the problems in provisioning services are strictly related with the overloading effect (this should be further researched since the simulations carried out here are not enough to solidly state this conjecture).

Further analysis with higher data rate services shows that, while coverage keeps on being good, problems in the DL limit the grade of service. Comparing the results over the two links for the previous analysis, it can be observed that, for voice services only (Fig. 21 on the left), the system can provide service everywhere; when adding data services, problems appear in giving service in the downlink (areas colored with a darkest grey). This result sticks out, once again, the difference between the two links. In the UL the signal suffers from lots of losses and so it is necessary to position the antennas quite near. On the other hand, the great problem in the DL is the power that users have to share. Depending not only on the number of users but, principally, on the kind of services they require, the 20 W each BS can transmit have to be shared among them. Many users inside the coverage area of a group of BSs can get the system overloaded; the power of each BS is not enough to satisfy all their petitions. This is why, even if services in the UL can be provided to all the users (i.e., there are no problems of coverage), in the DL the BS cannot reach them.

VI. CONCLUSIONS

In this study, the authors investigated the location of the UMTS base stations in a real environment. To this end, a complex process of analysis has been followed, which leads to determine the cell coverage ranges and the system capacity. By using a simulation tool, the dependence of cell dimensions with the service rate and the traffic load has been displayed. Moreover, a realistic urban scenario has been studied. The result is that with voice traffic only there won't be great problems with the configuration proposed, while services at higher rates increase system's load. Changes in the antennas' downtilt, orientation and position of the first planning results in an improvement of the coverage offered to the area under study. These changes do not solve the problems of overload in the system; neither a better tuning of the power allocated to some channels (i.e., DPCH and CPICH) makes the difference. The authors agree with [9] in the fact that soft handover, while reducing the other-cell interference, increase the overload of a cell since more than one BS has to allocate a portion of its power to the same user.

ACKNOWLEDGMENTS

This work has been funded by the Spanish Ministry of Science and Technology and by FEDER through CICYT project RUBI 2003-01748.

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