Characterisation of Signal Penetration into Buildings for GSM and UMTS

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Abstract — **A study of the extra signal attenuation due to building penetration associated to path loss from the Base Stations to Mobile Terminals, for different types of buildings and rooms is presented for GSM (900 and 1800 MHz) and UMTS. In this study, a statistical model for the attenuation penetration is developed, following the Log-Normal Distribution, applied to a building classification, and supported on measurements of the actual systems under consideration, which can be used for radio network planning purposes. Different types of buildings (High-Integrated, High-Isolated, Low-Integrated, and Low-Isolated) and rooms (Indoor Light, Indoor, Deep Indoor) are considered. A study on the variation of the attenuation per floor, room and building type is performed. An average attenuation of 5.7 dB for GSM900 is observed, with a standard deviation of 11.1 dB.**

Keywords — **Path loss. Building penetration. GSM. UMTS. Log-normal distribution.**

I. Introduction

Mobile and wireless communications are a basic need in modern society. Statistics show that in many countries mobile phone penetration is already higher than the fixed one. Mobile phones are used everywhere, not only outdoor where the user is moving, but also more and more indoor, where sedentary users spend a big part of their day in environments such as their workplace or their home. In these environments, customers demand a good coverage and quality of service. Nevertheless, these systems were not deployed to satisfy specifically these requirements. Operator deployment requirements typically guarantee coverage, with certain quality requirements, of a minimum percent of the geographical area and population (e.g., 90-95% of the geographical area and population covered). Planning tools, key elements for efficient dimensioning of a network, usually provide only outdoor coverage predictions. They estimate the path loss from the Base Station (BS) to the centre of the street where mobile terminals are assumed to be. Therefore, an extra signal attenuation associated to building penetration is required in the planning of the network. A specific attenuation value for building penetration can improve the indoor coverage for a certain percentage of indoor environments.

The estimation of an extra signal attenuation associated to building penetration can be obtained via propagation models [1], [2] and [3], or to predictions extracted from measurement campaigns [4], [5], [6], [7], [8] and [9]. Nevertheless, building construction characteristics and city morphology have strong impact on propagation characteristics, which makes the correct adaptation of these models and predictions a difficult task. In order to extract good measures of this attenuation, a representative set of buildings from the cities of Lisbon and Porto was chosen. Buildings are grouped according to their height and to the existence of surrounding buildings. A large number of rooms were measured in order to have results with statistical significance. A detailed analysis is performed to extract the characteristics of this attenuation. A comparison with other studies is also presented in this paper. The present study, having former studies as background, has the advantage of enabling a fair comparison of the attenuation for the three frequency bands.

The paper is structured as follows. Section II describes the measurement campaign. The results of the campaign are analysed in Section III. Comparisons with previous studies are shown in Section IV. Finally, conclusions are drawn in Section V.

II. Measurement Campaign

A. Introduction

A heterogeneous set of 12 buildings in Lisbon and Porto (Portugal) was selected for measurements. Measurements for the three bands of GSM and UMTS (900, 1800 and 2100 MHz) were carried out in each building, on different floors and in different room types, using the actual systems. The 12 measured buildings are classified into four types, based on [4], [5] and [10]:

- High-Integrated (HIn): a building with more than 6 floors, sharing walls with other buildings (2 measured buildings).
- High-Isolated (HIs): a building with more than 6 floors, not sharing any walls with other buildings (4 measured buildings).
- Low-Integrated (LIn): a building up to 6 floors, sharing walls with other buildings (3 measured buildings).
- Low-Isolated (LIs): a building up to 6 floors, not sharing any walls with other buildings (3 measured buildings).

The 434 measured rooms are classified according to three different categories [5]:

- Indoor Light (IL): a room with a window to outdoors (303 rooms measured).
- Indoor (I): a room without any window to outdoors, but one wall separation to outdoors (73 rooms measured).
- Deep indoor (DI): a room without any window to outdoors, and with at least two walls separation to outdoors (58 rooms measured).

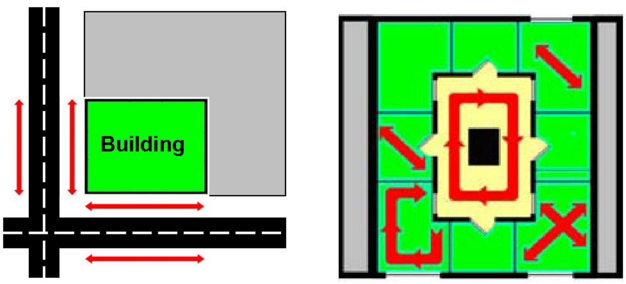
B. *Measurement Procedure*

For the measurement procedure, a Motorola A835 phone was connected to a laptop running the TEMS WCDMA software [11]. The TEMS application acquires signal power samples, collecting, for each BS, a GSM sample every 450 ms and an UMTS one each 30 ms. The accuracy of the received signal power is within 1 dB. For UMTS, a continuous File Transfer Protocol (FTP) session was established, while for GSM a continuous speech connection was established.

The measurement equipment was placed on a small cart and the mobile was placed 1.5 m above floor level. The cart was pushed (manually) along the measuring places with a speed around 0.05 m/s. The adopted measurement procedure consists of the two distinct stages described below:

1. First, outdoor measurements are made along the accessible outside building façades, Figure 1.a). When possible, outside measurements were taken on both sides of the street, the mean power values of both sides of the street provide a good estimation of the mean power received on the middle of the street. From these measurements, an average is calculated, in order to obtain a reference value, for each BS, for the power outdoors at the ground level, P_{ref}^{ext};

2. Then, indoor power measurements, P^{int}, are acquired in the rooms. Measurements followed, whenever possible, an "X" trajectory, Figure 1.b). The criterion to choose/reject the measurements of a BS has been the number of collected samples for that BS. It was considered that there was no statistical relevance if less than 100 samples were collected.



a) around the building b) inside the building

Figure 1 – Measurement procedure.

For each BS, the extra penetration attenuation, L^{int}, is obtained as

$$L_{int} = P_{ref}^{ext} - P^{int} \text{[dB]} \tag{1}$$

The measurement of the reference level outdoors may follow different configurations, depending on the accessible façades, having a big impact on the measured reference level, Figure 1.a). Ideally, the best would be to have measurements around all façades of the building. Nevertheless, this is not always possible, e.g., when buildings are integrated. An integrated building can typically only be measured at one façade (a potential existing interior courtyard may not be accessible). Nevertheless, this non accessible façade has rooms with windows, where some BSs signals can be received at levels higher than on the street on the other side of the building, depending on the position of the measured BS. This dependency on the configuration of BS was avoided by examining the data of a large number of BS.

C. *Analysis of the Measured BSs and Obtained Aamples*

The high number of obtained samples per BS (on average, 16 000 samples for GSM900 and GSM1800, and 226 000 for UMTS) enables a good statistical analysis per BS, for all three bands.

BSs are distributed differently around each building. Table I gives information about the average number of directions of the location of measured BSs per building (N_{DAoA}), the average number of different measured sites (N_{Sites}) and average number of measured BSs (N_{BS}), per band. It is very common to receive signals from co-located BS. Most cells are sectorised (tri-sectorised), and due to reflections on buildings one often receives signals from more than a sector. A site is considered as a location where one or several BSs can be located, e.g., a location with tri-sectorised GSM BSs is considered as one site but three BSs. DAoAs of measured BSs correspond to "angular slices" of 15º, giving information on the diversity of directions of the localisation of measured BSs.

Table I– AVERAGE NUMBER OF MEASURED DIRECTIONS, SITES AND BSS PER BUILDING, FOR EACH BAND.

GSM900			GSM1800			UMTS		
N_{DAoA}	N_{Sites}	N_{BS}	N_{DAoA}	N_{Sites}	N_{BS}	N_{DAoA}	N_{Sites}	N_{BS}
9	13	19	3	4	5	3	4	5

A good set of BSs, N_{BS}, was measured for GSM900 in each building (on average 19 BS from 13 different sites, placed in 9 different directions around the building, on average) when compared to GSM1800 and UMTS (on average 5 BSs from 4 sites, in 3 different directions around the building). In fact, a much higher number of GSM900 BSs are deployed than of GSM1800 and UMTS, which shows up in the measurement results. The low number of GSM1800 and UMTS BSs could result in a dependency of the results on the specific buildings and BS location around the specific buildings. An example of this is given in Figure 2, where it can be seen that the UMTS BSs are not more or less uniformly scattered around the building.

A detailed statistical analysis might show some dependency on the configuration, which is also confirmed by the large spread of the median of the Cumulative Density Functions (CDFs) for the different buildings, for the attenuation of penetration for these bands (12 dB for GSM900, compared to

40 dB and 27 dB for GSM1800 and UMTS). Therefore, a detailed analysis per room type and floor, based on the measurement data, only had statistical relevance for GSM900. The resulting CDFs are taken as reference curves. For the other bands, only the obtained average values of the global CDF (for all measured buildings) are considered. The CDFs for GSM1800 and UMTS all have a similar shape as for GSM900, but shifted according to the average value for GSM1800 and UMTS.

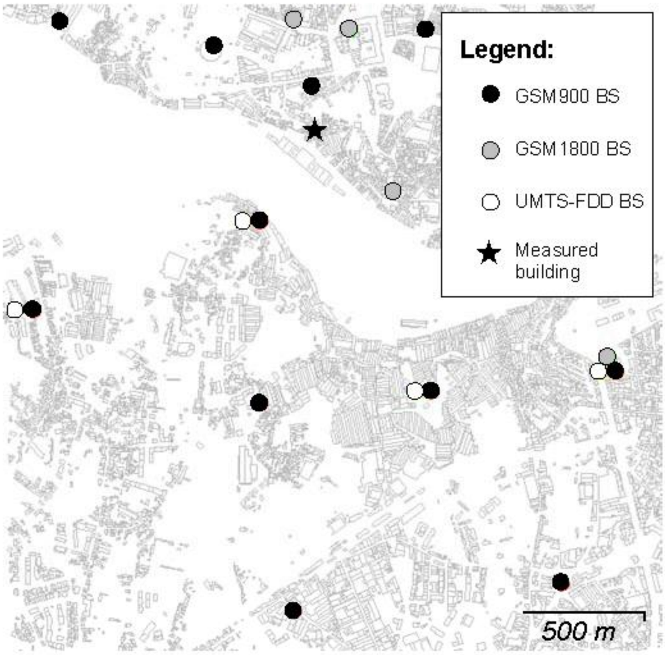


Figure 2 - Measured BSs in a building.

III. ANALYSIS OF RESULTS

A. *Introduction*

The processing of the results shows that the Normal Distribution presents a good fit (for the Probability Density Functions (PDFs), the deviation between the theoretical and the experimental values is below 1 %) for describing the penetration attenuation when it is taken in dB, i.e., the Log-Normal Distribution can be taken to describe the attenuation. As a consequence, for the remainder of the analysis, only the two usual parameters, mean and standard deviation, are considered.

All measurements of attenuation of penetration for the different rooms and buildings were grouped per building and room type. The global results for the average, μ, and standard deviation, σ, of the attenuation of penetration into different types of buildings and rooms, for GSM900, are given in Table II. The averages are weighted for the number of buildings and rooms. An average attenuation of 5.7 dB is observed for GSM900. In the next sections, an analysis per room and building type, as well as per floor level, is presented, in order to better understand the attenuation patterns.

Table II - AVERAGE AND STANDARD DEVIATION VALUES FOR THE ATTENUATION DUE TO PENETRATION INTO BUILDINGS, FOR GSM900.

	Deep Indoor		Indoor		Indoor Light		Av. per building type	
	μ [dB]	σ [dB]	μ [dB]	σ [dB]	μ [dB]	σ [dB]	μ [dB]	σ [dB]
HIn	8.8	8.9	7.2	9.3	4.5	9.4	5.6	9.5
HIs	5.8	11.5	2.0	11.7	1.2	10.1	2.0	10.8
LIn	12.3	11.5	6.2	12.9	5.5	12.9	5.8	13.1
LIs	12.3	12.2	9.0	9.0	8.3	11.2	9.1	11.2
Av. per room type	9.7	11.1	4.8	11.0	5.0	10.9	**5.7**	11.1

B. *Analysis per Room Type*

A detailed analysis per room and building type for GSM900 has been made. All CDFs are of Gaussian distributed variables, evidenced by the high correlation with the corresponding computed Gaussian CDF from the average and standard deviation presented in Table II. As expected, IL rooms present the lowest average attenuation when compared with the other types of rooms.

If the building type is not taken into account, the categories of the room-types can effectively be reduced to two, since the CDFs of IL and I room types overlap, becoming the so-called Light Indoor room type, Figure 3. As a first conclusion, measurements show that it is enough to take only two types of rooms: either on the "border" of the building to outdoors, or in the "core" of the building.

If the building types are to be considered in the analysis of the attenuation per room type, the corresponding CDFs can be obtained by introducing the shift $\Delta\mu$, presented in Table III, to the global building independent CDFs presented in Figure 3.

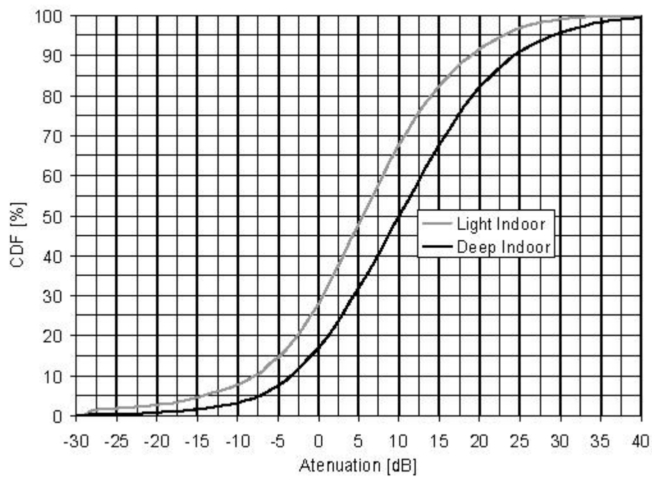


Figure 3 - CDFs of the attenuation of penetration into all buildings, for the two resulting room types, for GSM900.

Table III - DEVIATION FROM THE AVERAGE ATTENUATION OF PENETRATION FOR DIFFERENT TYPES OF ROOMS AND BUILDING TYPES.

Building Type	Δμ [dB]		
	IL	I	DI
HIs	3.8	3.9	3.9
HIn	0.5	-1.0	0.9
LIs	-2.7	-2.8	-2.6
LIn	-0.5	0.0	-2.6

C. *Analysis per Building Type*

In Figure 4, the attenuation per building type, regardless of the room type, is presented.

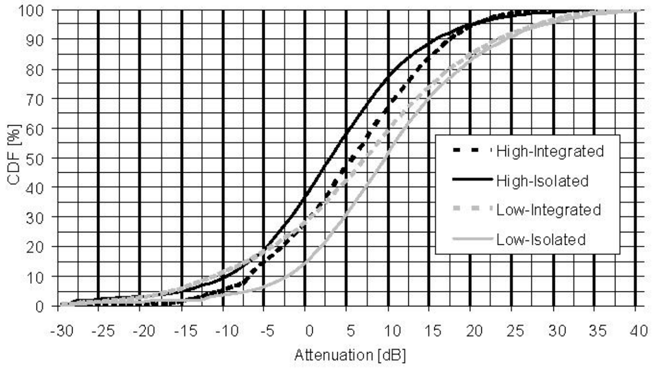


Figure 4 - CDFs for the attenuation into different types of buildings for GSM900.

It can be seen that HIs buildings have the lowest attenuation, with an average value of 2.0 dB, Table II, due to the good propagation conditions, compared with the other types of buildings; this effect is expected, since all façades of HIs buildings are exposed to BSs signals, and the building has less obstruction from other buildings due to its height. LIs buildings present the highest attenuation of all types of buildings, with an average value of 9.1 dB, Table II. LIs was expected to have less attenuation than LIn ones, since they have more exposed façades, but the measurements do not show this. A higher number of measured buildings of these two types would help understanding this effect.

D. *Analysis per Floor Level*

Average attenuation values of penetration, per floor and room type, for the different types of buildings, as well as the average attenuation per floor (independently of the room type) were analysed. High gains (negative attenuations) are observed on high floors of isolated buildings, where in certain cases a much better signal level was received than in the street, due to more favourable propagation conditions (in some cases line of sight with the BS was observed). The highest attenuations are observed, as expected, in DI rooms.

Based on an analysis of data obtained per floor and room type, independent of the building type, trends were built of the average values of attenuation, Figure 5. The correlation coefficient of the fitting of the attenuation curve with respect to the floor level was evaluated and a high correlation between the trend line and the values is observed.

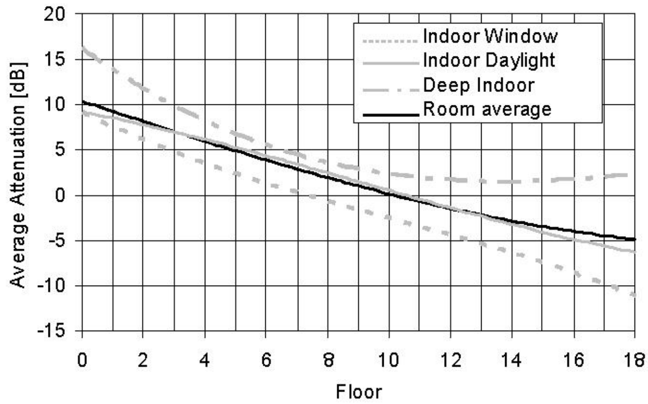


Figure 5 - Estimation of the average attenuation trend per floor level, for GSM900.

For a first estimate on the attenuation for a certain floor of a building, the room average values give a good indication. Values range from -11 to +16 dB. It can be seen that after floor 6 some gains (negative attenuations) can be achieved. As low buildings are defined as buildings up to 6 floors, and high ones above 6 floors, this observed effect evidences that the definition of low and high buildings is a good measure.

High variations of attenuation between consecutive floors are observed, possibly due to specific propagation conditions of each floor. Despite these variations, an expectable average attenuation between floors of -0.8 dB is obtained, evidencing that attenuation decreases when one goes one floor up.

E. *Analysis for the Three Bands*

A large number of CDFs for GSM900 has been computed for the different types of buildings, rooms and floors in the previous sections. As presented in Section II.C, GSM1800 and UMTS measurements results, due to the low number of measurements and BSs, respectively, are only used for the estimation of the average value of attenuation; their associated CDFs are not used, since they present very high variations. For the estimation of the CDFs for GSM1800 and UMTS, a shift of GSM900 CDFs is introduced, corresponding to the difference of average attenuations for GSM1800 and UMTS with the average attenuation for GSM900 ($\Delta\mu_{GSM900}$). The corresponding average, standard deviation and median values of the attenuation of penetration into buildings are presented in Table IV.

Table IV - AVERAGE, DEVIATION OF GSM900, STANDARD DEVIATION AND MEDIAN OF THE ATTENUATION DUE TO PENETRATION INTO BUILDINGS, FOR GSM900 AND GSM1800 AND UMTS.

	μ [dB]	$\Delta\mu_{GSM900}$ [dB]	σ [dB]	M [dB]
GSM900	5.7	0.0	10.8	5.3
GSM1800	7.6	1.9	12.0	7.4
UMTS	7.3	1.6	12.5	7.0

One can see that the average value, μ, for GSM900 is 5.7 dB while for GSM1800 and UMTS 7.6 dB and 7.3 dB, respectively. It can be seen that the $\Delta\mu_{GSM900}$ value from GSM900 to GSM1800 and UMTS is very similar, which might be related to the fact that these systems operate in close related frequency bands (1800 and 2100 MHz, respectively), resulting in similar attenuation effects. On the other hand, the UMTS shift value should be higher than for GSM1800, since the frequency band is higher. Taking this into consideration, and considering a rounding of the number for practical purposes, a common shift of 1.9 dB is suggested to be used for both bands.

In Table V, the attenuation values for penetration into buildings to be considered for different percentiles of coverage, for the different systems are presented. For example, to provide 85 % coverage inside buildings, an extra attenuation factor of 16.1 dB has to be considered for GSM900 and 18 dB for GSM1800 and UMTS.

Table V - ATTENUATION OF THE PENETRATION INTO BUILDINGS FOR DIFFERENT PERCENTILES, SHIFTED FOR GSM1800 AND UMTS.

Percentile of coverage [%]	**Attenuation [dB]**	
	GSM900	**GSM1800 and UMTS**
50	5.3	7.2
85	16.1	18.0
90	18.5	20.4
95	22.4	24.3
98	27.5	29.4
99	31.0	32.9

IV. COMPARISON WITH EARLIER STUDIES

A comparison of the presented global results with earlier studies is presented in this section. The study of Xavier and Venes [4] for GSM900 and GSM1800 was performed for a smaller set of buildings. For GSM900, the results obtained are very similar to the presented ones. However, especially for HIs buildings, much lower attenuations were observed. It can be expected that this discrepancy of results is due to a small average number of measured BSs per building, when compared with the considered values in the present study for GSM900, resulting in a dependency on the geographical distribution of BS around the building.

Tanis and Pilato [6] showed an average penetration loss of 19.2 dB for 880 MHz and 15.7 dB for 1922 MHz, resulting in a difference between the two bands of 3.5 dB. A similar study was made by Toledo et al. [7], which showed a penetration loss of 14.2 dB, 13.4 dB and 12.8 dB for 900 MHz, 1800 MHz and 2300 MHz respectively. This study realises a 0.8 dB difference between 900 and 1800 MHz, and a 1.4 dB difference between 900 and 2300 MHz. It should be noted that these studies have a lower attenuation at higher frequencies, which they assumed is caused by a frequency selectivity of the building materials. However, this study noticed the opposite effect. The study by Toledo et al. [7] also investigated the average attenuation per floor and found a number of 1.4 dB per floor, below the 6th floor. On the higher floors they saw a 0.4 dB decrease per floor, which is very similar to the results obtained in this work, although no distinction was made between the per floor penetration losses between lower and higher floors.

With respect to the variations of attenuation between consecutive floors, Martijn and Herben [8] observed values between 1 and 2 dB, while this study found an average value of 0.8 dB. For buildings of more than 6 floors, a gain was observed in the higher floors for both studies. COST231 [9] reports an increase in loss for GSM1800 of 2 dB, which is in agreement with the values obtained in this report. Depending on the storey height, a 1.5-2 dB/floor or a 4-7 dB/floor was obtained. The latter values were taken for buildings with storey heights of about 4-5 m. The present study did not take into account the storey height of the rooms. However, COST231 showed a gain by going up into the building, which was confirmed in this study.

V. CONCLUSIONS

A characterisation of signal penetration into buildings for GSM and UMTS is presented. The extra attenuation follows a Log-Normal Distribution, hence, the average and the standard deviation values can be used for a good characterisation. An average attenuation of 5.7 dB for GSM900 is observed. It is concluded that attenuation of penetration into buildings increases as one goes “deeper into the building” (5 dB to indoor light, 6 dB to indoor, and 9 dB to deep indoor, on average), and decreases as one moves “up in the building” (0.8 dB with each floor level). Results for GSM1800 and UMTS can be obtained by shifting GSM900 CDFs by 1.9 dB.

REFERENCES

[1] M. Keenan, and A. J. Motley, “Radio coverage in buildings”, *British Telecom Technology Journal*, Vol. 8, No. 1, Jan 1990, pp. 19-24.

[2] C. Törnevik, J.-E. Berg, and F. Lots, “900 MHz propagation measurements and path loss models for different indoor environments”, in *Proc. IEEE VTC’93*, New Jersey, USA, May 1993.

[3] P. Karlsson, *Indoor propagation for personal communications services*, Ph.D. Thesis, University of Lund, Sweden, 1995.

[4] D. Xavier, and J. Venes, *Characterisation of signal penetration loss into buildings for GSM* (in Portuguese), Graduation Project, Instituto Superior Técnico, Lisbon, Portugal, Sep. 2002.

[5] A. Claro, C. Pardelinha., F. Gil, J. Ferreira, J. Queijo, S. Almeida and L.M. Correia, *Signal Requirements for 2W Mobile Phones*, Internal Report, Instituto Superior Técnico, Lisbon, Portugal, July 1998.

[6] W. J. Tanis and G. J. Pilato, “Building penetration characteristics of 880 MHz and 1922 MHz radio waves”, in *Proc. of VTC’93*, Secausus, NJ, USA, May 1993, pp. 206-209.

[7] A. F. Toledo, A. M. D. Turkami and J. D. Parsons, “Estimation coverage of radio transmission into and within buildings at 900, 1800 and 2300 MHz”, in *IEEE Personal Communications*, Vol. 5, No. 2, Apr. 1998, pp. 40-47.

[8] E. F. T. Martijn and M. H. A. J. Herben, “Characterization of radio wave propagation into buildings at 1800 MHz“, in *IEEE Antennas and Wireless Propagation Letters*, Vol. 2, 2003, pp. 122-125.

[9] E. Damosso and L. M. Correia, *Digital mobile radio towards future generation systems (COST 231 Final Report)*, Office for Official Publications of the European Communities, Luxembourg, Luxembourg, 1999.

[10] Optimus, *Internal communication*, Lisbon, Portugal, Oct. 2005.

[11] Ericsson, TEMS WCDMA, www.ericsson.com (Mar. 2006).