Outdoor-to-Indoor Propagation Characteristics of 850 MHz and 1900 MHz Bands in Macro - Cellular Environments

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Abstract— **Building penetration loss at 850 MHz and 1900 MHz bands in suburban environment is measured. The measurements are conducted in real GSM networks. Four buildings are studied aiming to provide first-order statistics of the signal coverage inside buildings. Results show that the mean building penetration loss for the ground floor is about 15 dB, with standard deviation of 3.5 dB. Additionally, the average rate of the change of penetration loss with height is 0.58 dB per meter. The results show also that building penetration loss may or may not depend on the operating frequency in different environments and propagation scenarios. 1900 MHz-band channels exhibit higher penetration loss values than 850 MHz-band ones by a mean of 2.8 dB.**

Index Terms— **GSM, outdoor-to-indoor propagation, building penetration loss, floor height gain.**

I. INTRODUCTION

Current Personal Communication Systems (PCS) are evolving to meet the increasing demand for high speed data services and capacity. Most of speech and data services providers offer flat rates for smart 3G and 4G devices in a form of phones, laptops, or multimedia devices via mobile networks. In the most recent surveys, it has been found that a high proportion of cellular traffic originates from inside buildings [1].Therefore, one of the main goals of new-coming wireless networks such as the LTE and LTE-A is to extend the indoor coverage of wireless broadband services. However, the wireless communication channel is very complex and its understanding is critical in designing of a personal communication system. For example, maximizing indoor coverage of wireless broadband services is constrained by minimizing adjacent and co-channel interference. In outdoor-to-indoor scenarios, providing high speed data services to users inside building is directly proportional to the available Signal to Interference and Noise Ratio (SINR) throughout the building. Therefore, in order to design an accurate modern wireless system, real detailed spatial data measurements that describe the received signal power are fundamental. Moreover, parameters of the radio channel are statistical in nature. Therefore, an extensive measurements campaign and detailed analysis of the radio channel is of a fundamental importance for reliable characterization of this channel [2]. Several studies regarding measurements-based outdoor-to-indoor building penetration loss characterization and modeling have been published [2-15]. The examined buildings in these publications range from small residential buildings to large office buildings where penetration loss at frequencies up to 8 GHz has been studied.

This study presented in this paper describes intensive detailed measurement campaign conducted inside and around office buildings to characterize mainly the building penetration loss and its effects on in-building coverage. A spatial description of the received signal power transmitted from different GSM base stations serving the examined buildings is presented in details.

This paper is organized as follows. The experimental hardware used, the environment where the buildings are located, and the data collection and processing are described in section II. Section III highlights the most important aspects of the building loss and summarizes the results. Finally, section IV provides the conclusion of this study and suggestions for future work.

II. MEASUREMENT SETUP

A. Environment Description

The measurement campaign described in this paper is carried out on the campus area of Florida Institute of Technology (FIT). The measurements are designed to test the outdoor to indoor building penetration loss for GSM system at both GSM-850 MHz and GSM-1900 MHz frequency bands. The measurements are performed on real commercial networks. The campus area is considered as a part of suburban area populated by buildings of different construction materials and layouts. Macro-cell base stations serving the area have antennas located well above the average buildings heights. Buildings are typically detached office and educational halls with two to seven floors. There are occasional open areas such as parks and playgrounds and the vegetation is modest. Locations of buildings where measurements were conducted are shown in Fig.1. The figure also shows the relative position of the examined buildings with regard to the located GSM-850MHz and GSM-1900MHz base stations.

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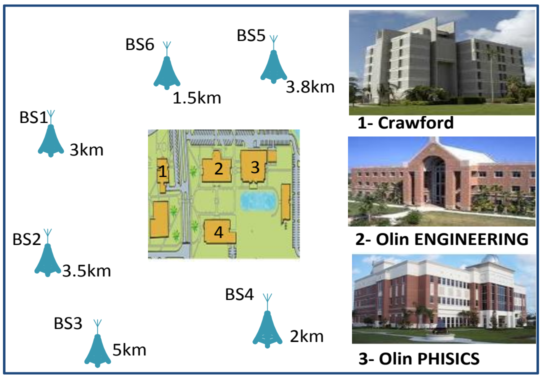

Fig. 1. Locations of examined buildings and base stations

B. *Building Description*

The examined buildings include specialized research and teaching laboratories, classrooms, and conference rooms.

Offices on all floors of all buildings were crowded with typical office furniture. The teaching or research laboratories contained experimental equipment according to the specialized demand of each area of study. In this subsection a brief description of buildings is provided. There are four buildings within the study and they are listed as follows.

Crawford (CRAW) - Seven floors, 28 m high, floor area of 360 m^2, concrete masonry construction for external walls and internal partitions', and narrow windows form 10 % of the building sides.

Olin Physics (O.PHY) **-** Four floors, 18 m high, floor area of 2300 m^2, brick and concrete masonry construction for external walls, 16 % of two sides is windows and 7 % is windows for the other two sides.

Olin Engineering (O.ENG) - Three floors, 13 m high, floor area of 2100 m^2 , brick and concrete masonry construction for external walls, on average a 28 % of the building sides is windows.

Olin Life science (O.LS) **-** It is Similar to Olin Engineering building but with only two floors.

C. *Measurement Procedure Description*

The penetration loss in the study is defined as the difference in mean received signal level between the measurement obtained inside and a reference signal level measured outside near the unobstructed walls of the building [3]. In order to provide reliable references for the respective buildings, over two hundred data points at different locations around each building have been considered. For indoor measurements, the floor area has been divided into small squares the area of each is 2 m^2. With this setup, more than 8 thousand in-building locations using Agilent Digital Receivers have been measured.

The Broadcast Control Channels (BCCH) of 13 surrounding GSM base stations at 850 MHz and 1900 MHz bands were measured. The used receivers perform measurement of received signal levels for multiple frequency channels simultaneously. The analyzer displays the amplitude of the Absolute Radio Frequency Channel Number (ARFCNs) for all BCCH measurements with the corresponding power levels and the associated decoded Base Station Identity Codes (BSIC).Fig. 2 shows Agilent Digital Receivers that have been used to conduct the measurements. The data collection system setup (for both indoor and outdoor locations) is also shown in Fig.2. The receiving antennas are mounted on the top of a wooden mast at height of 1.5 m above the examined floor. The collection system shown in Fig. 2 is wheeled around and inside the buildings on trolley. To avoid undesirable deviations of the received signal level due to body losses and antenna orientation in some static positions, the receiving antenna was slowly tilted and moved within the measured location to average out all these effects.

All locations of the measurement runs are marked on the respective floor plan. In each location, the measurement course lasted 4 minutes which is enough time to get sufficient number of samples for each measured BCC channel. With this setup, the collected data per specific point for each base station allow for determination of the statistical properties of the received signal level at each data point. Kolmogrov-Smirnov test shows that the measurements are distributed log-normally.

Fig.2.The equipment used and the data collecting system in two different locations

Fig. 3 shows sample histograms of measurements for three different base stations taken at a single point that is exactly at the center of the ground floor of Crawford building. GSM channels operating at 850 MHz and 1900 MHz frequency bands are considered.

In order to provide site-specific information about the radio coverage inside buildings, color coded plots were used. Fig. 4 shows a sample scatter plot of received power level measurements on ground floor of Crawford building (left). Dots symbolize location of successive measurement points and the color of each dot indicates basic received signal level in [dBm]. An interpolated view of the same measurements is presented on the right side of Fig. 4. It is recommended in [16] to choose the proper signal length over which the signal data will be averaged over specific location.

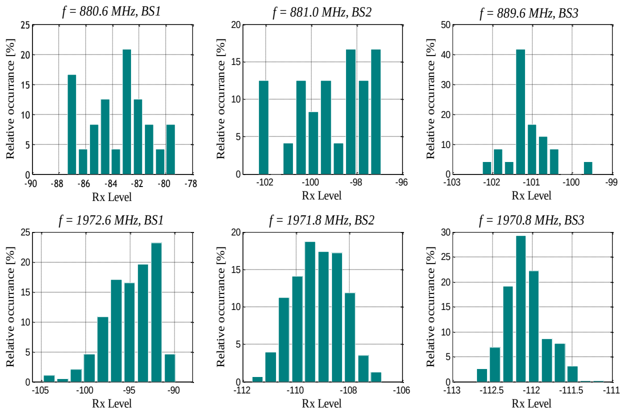

Fig.3. Histogram of measurements taken at a single point location

With the presented measurement setup, approximately three times the wavelength at 850MHz and even twelve times the wavelength at 1900MHz can be covered. Therefore, interpolation can be used to provide interpolated view of the measurements in the whole floor area. The interpolated view in Fig. 4 was created by using spatial interpolation. Inverse Distance Weighting (IDW) interpolation method was used to predict the expected average signal level in places where measurements were not possible. Additionally, IDW was used several times to smooth the interpolated plot that describes the radio coverage of the respective floor plan.

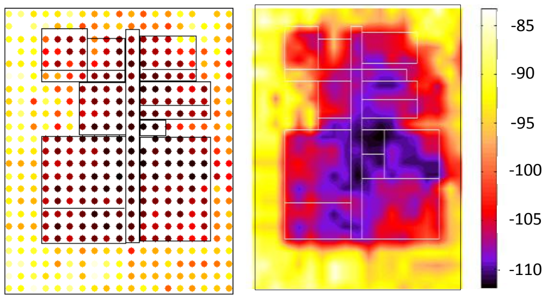

Fig. 4. Scatter plot and its interpolated view of a radio coverage inside building

III. MEASUREMENT RESULTS AND DATA ANALYSIS

In outdoor-to-indoor propagation, building penetration losses can be defined as the additional losses that radio signal encounters as it propagates from outdoor to indoor environment. There are various factors that may influence propagation into buildings. Operating frequency, building construction materials, transmission conditions, floor height where the receiver is located, and indoor partitions' are considered important parameters in characterizing the outdoor-to-indoor building penetration loss [17]. In the following subsections, the effects of the main factors influenced the measured building loss are discussed in more detail.

A. *Average Building Penetration Loss*

Building penetration loss is usually calculated according to its definition. Different ways of calculating building penetration loss are found in the literature. In [8], the floor area of each building was divided into different sections, each of which represents at least one room. The corridors and hallways are treated by the same way. In this case, the section penetration loss is the difference between the average indoor received signal power in the respective section and the average received signal power outside in the perimeter of that section. Then, the average building penetration loss will be the average loss of all considered sections in the respective floor of the measured building.

Another way of calculating the building penetration loss is presented in [18]. In [18], the building loss is calculated as the difference between the averages received powers at a reference point outside building (measured at base station side of the building) and the individual averages of received powers at all specified data points inside building. Various propagation models designed to predict the signal power levels at street levels treat the building loss as additional losses. This makes the calculation of building loss with respect to a reference point located outside that building more practical. Therefore, the second approach was adopted in this study. This process has been repeated for all measured BCCH in the measurement campaign. Table 1 summarizes the average building loss and the standard deviation of the four measured buildings.

TABLE 1
Average and standard deviation of building penetration losses for the different buildings for 850 MHz and 1900 MHz bands at the ground floor

#	Building	850 MHz		1900 MHz	
		Mean	STD	Mean	STD
1	CRAW	13	4.7	13.7	3.0
2	O.ENG	14.6	4.5	17.2	2.47
3	O. PHY	14	4.2	17	1.5
4	O. LS	9.5	4.16	11.1	2.3

Fig. 5 shows a comparison plot of the mean and the standard deviation of ten signals transmitted from five different base stations working at both 850 MHz and 1900 MHz bands. The reported values of mean and standard deviation represent the average mean and the average standard deviation over the four measured buildings. The most noticeable trend from the figure is the trend of decreasing in standard deviation versus frequency.

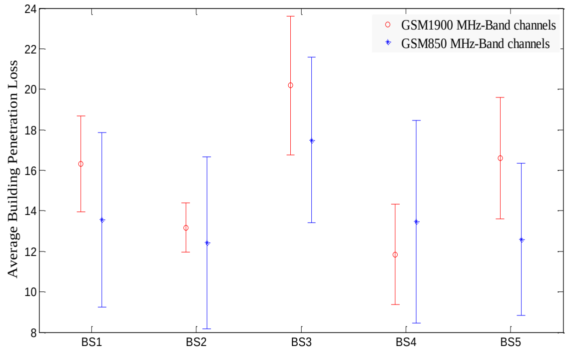

Fig.5. Computed building penetration mean and standard deviation for GSM850-MHz vs GSM-1900 MHz channels using measured data from all buildings.

B. *The Impact of Operating Frequency and Building Materials*

Typically, different electrical properties of building construction materials and objects interacting with electromagnetic waves make different buildings be frequency selective [17]. Consequently, the building penetration loss is known to show frequency dependency [5],[7-9] and [14]. However, some recent studies show slight or no frequency dependency as in [12]. In this study, and for all the measured BCCH channels in 850 MHz and 1900 MHz bands, the operating frequency shows slight impact on the building penetration loss in three buildings. However, no frequency dependency was noticed in Crawford building.

From Table I, the building penetration loss increased by an average of 2.8 dB when the operating frequency increases from 850 MHz to 1900 MHz. These results are in good agreement with the conclusion drawn in [14]. These results can be attributed to the difference in building construction materials between Crawford building and other three buildings.

Fig. 6 shows a sample plot of the difference in building loss between the 850 MHz and 1900 MHz channels for the ground floor of the O.PHY building which exhibits the highest penetration loss values. This plot represents an example of building loss distribution in O.ENG, O.LS, and O.PHY buildings.

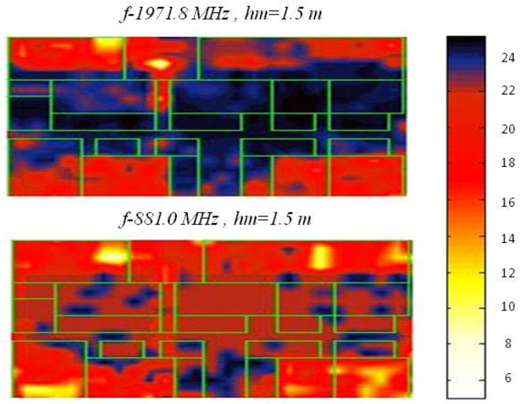

Fig.6 Measured penetration loss in O.PHY building of two GSM channels transmitting from same base station. One channel is in 1900 MHz band (left) and the other is in 850 MHz band (right)

It is obvious from Fig. 6 that 1900 MHz channels exhibits higher building loss than 850 MHz channels especially at the center region of each building. In general, the frequency dependency can be attributed to the difference in dominating propagation mechanisms at different frequencies as the electrical properties of the building construction materials vary with frequency. For example, signals at higher frequencies reach the receiver mainly due to the waveguiding and the diffraction mechanisms. Therefore, buildings that show frequency dependency are more transparent to the lower frequency bands than to the higher ones.

The average building penetration loss values are useful for modeling purposes but they are not always sufficient especially when it comes to interpreting individual results.

For example, Fig. 7 shows a sample plot of the building loss of four different channels in Crawford building where no frequency dependency was noticed. On the top of Fig. 7, comparison plot shows the building loss map of channels 881.0 MHz and 1971.8 MHz transmitting from the same base station (BS2). The average building penetration loss for both channels is the same but with different standard deviation and distribution. Similar comparisons are made between 889.6 MHz and 1970.8 channels transmitting from BS1 on the bottom of Fig. 7.

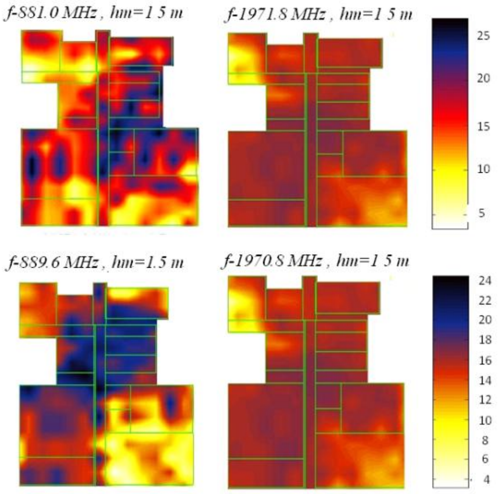

Fig.7. Measured penetration loss of four channels transmitting from two different base stations. Two channel are in 850 MHz band (up) and two in 1900 MHz band (down)

Overall, and for Crawford building, 1900 MHz-transmitters provide smothering coverage than 850 MHz-transmitters with lower values of standard deviation as reported in Table I.

C. *The Impact of Transmission Conditions*

The transmission path into a building can be either Line Of Sight (LOS), Partial Line Of Sight (PLOS), or shadowed with No Line Of Sight (NLOS). In outdoor-to-indoor propagation, the LOS condition is not related to presence or absence of direct path between transmit antenna and receive antenna [2]. Instead, the LOS path is the direct path between the outdoor antenna and the immediate exterior environment to the indoor antenna. In general, it has been observed that the LOS condition affects the standard deviation of the received power levels inside and in the vicinity of the measured buildings.

Outdoor measurements in locations placed in both illuminated and nonilluminated facades of the four measured buildings show relatively high values of standard deviations. For 850 MHz channels, the standard deviation of the outdoor measurements takes values between 4 dB and 7 dB, while, it ranges between 2.3 dB and 5.3 dB for 1900 MHz channels.

On the other hand, indoor measurements confirmed an expected decrease of smaller loss within LOS-areas inside building when compared to NLOS-areas. Fig. 8 shows a comparison plot of received signal power of two GSM 850 MHz transmitters in two different floors that are subjected to different transmission conditions.

In Fig. 8 (up), the 3rd floor of O.PHY building is subject to clear LOS path from the west side of the building while the plot in the bottom shows the coverage of a different channel that is obstructed by neighboring building. It is obvious from the plots that the penetration depth is also affected by transmission conditions. The penetration depth increases in areas that are subjected to a clear line of sight with the operating base station. This means that the received signal power undergoes lower linear attenuation than in the other areas of the building. Consequently, modeling the penetration loss at certain distances within LOS-areas inside building is more practical since the effect of other attenuation factors is limited to the minimum with the presence of LOS transmission condition.

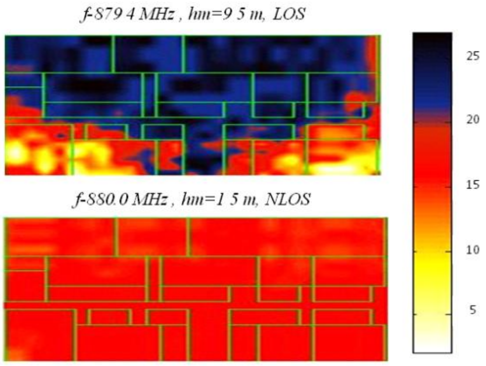

Fig. 8. Radio coverage of two different GSM 850 MHz transmitters in two different transmission condition with O.PHY building (LOS in top) and (NLOS in bottom)

In the presence of windows and with sufficient clearance to the operating base station, an average of 9 dB difference in the building loss between LOS-areas and NLOS-areas inside buildings at the same receive antenna height has been calculated. Fig. 9 shows a sample histograms of the building loss within an area subjected to LOS transmission (top) compared to the building loss within NLOS-area (bottom). Two different GSM channels transmitting from the same base station are considered in the plot.

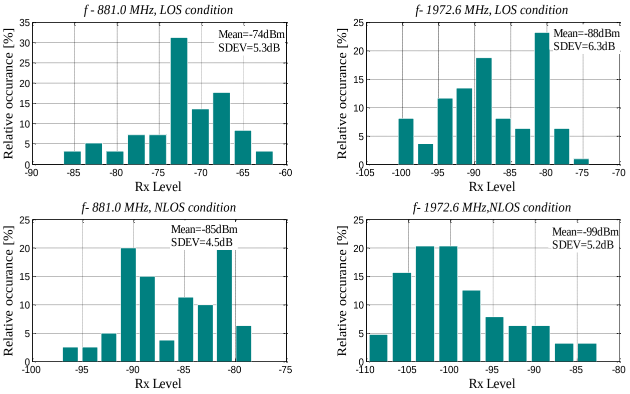

Fig. 9. Comparison of pdf for measurements in two indoor areas subjected to different transmission conditions of two different GSM channels.

From Fig. 9, one may observe that the standard deviation of the received signal powers is slightly higher in the presence of LOS path. This may be related to the higher diffraction the direct path causes when it penetrates the building. In the case of NLOS condition and depending on the layout of the outdoor to indoor setup, it is possible that other possible paths can contribute to the overall field. These paths include diffraction around windows and reflection from neighboring buildings. Overall, the effect of "coverage smoothing" was noticeable in NLOS-areas than in LOS-areas inside building.

D. The Impact of Floor Height and Penetration Depths

The floor height gain is the influence of the receive antenna height on the penetration loss and therefore, on the average received power inside buildings. This gain is well known model used to define the decrease in the building penetration values at higher building levels with respect to its values at ground floor. This effect attributed to the relative height between the transmitter and receiver locations. However, this gain is applicable until a height that is equal to the heights of the buildings that are surrounding the measured one [7]. This effect was evaluated through a regression analysis. Fig. 10 shows a plot of line that best fits the in-building measured received power levels of a list of line-of-sight-GSM channels. Seven floors of Crawford building are considered. The absolute heights of the receive antenna are represented in meters while the power levels are represented in [dBm].

It may be seen that as the floor height increases, the received power levels increase, therefore, the building penetration loss values decreases. For all measurements, the floor height gain takes values between 0.49 dB/m and 0.60 dB/m for GSM1900 MHz channels, while, this gain takes values between 0.662dB/m and 0.96 dB/m for GSM850-MHz channels. On average, the floor gain is 0.58 dB/m.

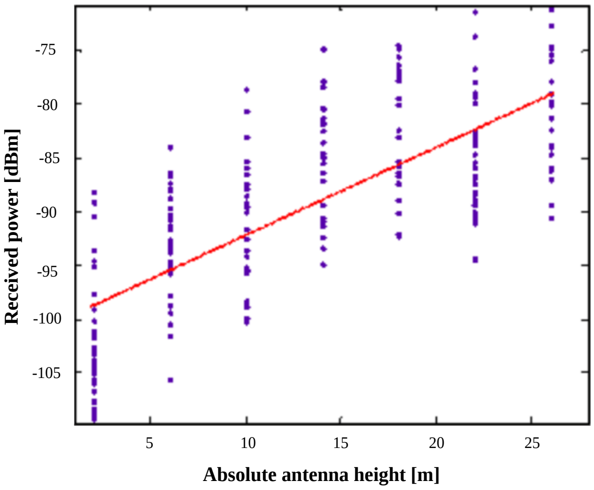

Fig.10. Average received power levels of four GSM channels versus receiver heights in high-rise building together with best fit line.

This gain rate is in very good agreement with the findings in [2], [4], and [5]. For the other three buildings (O.ENG, O.LS, and O.PHY), floor height effect was obvious between the ground floor and higher floors but not between the higher floors themselves. This fluctuation in the floor height gain effect in these buildings may be attributed to the relatively low heights of these buildings with respect to the heights of macrocellular base stations. Therefore, the floor height gain may not always be observable in such scenarios.

The other interesting observation regards the increase in the floor height is the increase in penetration depth of the radio signal as it propagates through the building. For signals transmitted from base stations that are in the LOS with the measured building, the additional path loss becomes more linear at higher floors. Fig. 11 shows plot of interpolated view of the received signal level for three different floors in Crawford building. On the top, the measurements of the received power levels of signal transmitted from base station 2 within the 1st floor. The radio coverage map of the 3rd floor is shown in the lower left whereas the coverage map of the 5th floor is shown in the lower right.

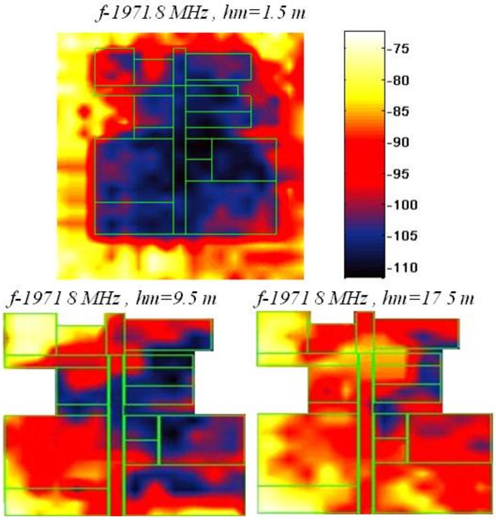

Fig.11. Increasing in the penetration depth of the signal propagation for one base station within three different floors inside building

IV. SUMMARY AND CONCLUSIONS

This paper documents a measurement campaign that was designed to characterize the outdoor-to-indoor propagation channel at 850 MHz and 1900MHz GSM bands was set up.

The building penetration loss, which is one of the critical parameters in personal communication systems design, has been evaluated for 4 office buildings. An average building loss of 15 dB with a standard deviation of 3.5 dB was reported. Operating frequency, transmission conditions and floor height have shown significant influence on the received power levels inside buildings.

The results of these investigations showed that the building loss increases slightly by a maximum of 2.8 dB as the operating frequency increases from 850 MHz to 1900 MHz for buildings with same construction materials.

However, one of the measured buildings, which is constructed with different materials showed no frequency dependency. The measurements also showed noticeable reduction in the building loss when the receiver moves away from shadowing region from ground floor upward to higher levels. An average floor height gain of 0.58dB confirms previous results reported in the literature. In addition, the influence of the transmission condition on the building penetration loss was obvious in terms of mean values and standard deviations. An average difference in building loss value of 9 dB between LOS-areas and NLOS-areas has been calculated. Moreover, the transmission condition together with the floor heights has an obvious influence on the penetration depth and the distribution of the building loss inside buildings. Overall, the results for the different parameters are realistic and in good agreement with the results from similar studies. This research will serve as a base for future studies concern with modeling of narrowband and wideband outdoor-to-indoor channels at 1900 MHz band.

In future work, an empirical prediction model for 1900 MHz signals will be proposed. This model will be based on narrowband and wideband measurements that are conducted in real GSM and UMTS system networks. This model will be useful for rapid deployment and link design for personal communication systems.

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