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Building Penetration Loss in the Cellular Radio Environment: A Case Study of Mud, Concrete, Brick and Metal Materials

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Abstract

A study of building penetration loss in the frequency bands of GSM 1800MHz and UMTS 2100MHz, of two different operators, using four building materials (Brick, Concrete, Mud, and Metal) within Ilorin metropolis, was undertaken and presented in this work. The corresponding results were obtained from a significant set of empirical data taken at the above-stated frequency bands and building materials during exhaustive indoor and outdoor measurement campaign carried out within the Ilorin metropolis. The results show an average penetration loss in GSM 1800MHz, 0.77dBm, 0.62dBm, 1.43dBm, 0.91dBm for Concrete, Brick, metal and Mud respectively, while in UMTS 2100MHz, an average penetration loss of 0.66dBm, 0.64dBm.1.70dBm, 1.04dBm for Concrete, Brick, Metal, and Mud respectively, were recorded. Results further established that penetration loss increases with increasing frequency.

Keywords-Building Penetration loss, GSM 1800MHz, UMTS 2100MHz, Signal Propagation, RSSI

I. INTRODUCTION

The wireless medium is the medium of choice, for the purpose of information transmission, today, for one or more of several reasons. Most importantly, the upsurge, in demand, for the radio wave, dictates the need for a proper understanding of its propagation modes, a prerequisite for effective radio network planning. A fall out of the extensive research work on the characterization of signal propagation in the outdoor environment is the realization that environmental structures, buildings, cars, people and street orientation among others also affect signal propagation [1]. While outdoor propagation models, for the predictions of signal levels and path losses, taking these factors into consideration abounds, there is still need for further research on the losses incurred as signal enters buildings. Interestingly, this awareness is, currently firing the interests of researchers, all over the world. This becomes, particularly interesting, considering the varieties in architecture and variety of building materials across all culture and environments of the world.

This study, therefore, measures the average signal losses incurred due to four categories of building materials, Concrete, Brick, Mud, and metal as used in Ilorin, Nigeria. Measurements were made in the downlink frequency band of both GSM 1800MHz and UMTS 2100MHz.

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II. LITERATURE REVIEW

Ferreira, et al [2], measured the attenuation due to building materials by taking measurements of selected buildings in Lisbon and Porto, grouped according to their heights. A Motorola A835 phone was connected to a laptop running the TEMS WCDMA (Test Mobile System Wideband Code Division Multiple Access) software. This application acquires signal power samples, collecting, for each BS, a GSM sample every 450 ms and a UMTS one each 30 ms. They found that the extra attenuation, due to building materials, follows a Log-Normal Distribution, hence, the average and the standard deviation values can be used for a good characterization. An average attenuation of 5.7 dB for GSM900 was observed. It was 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 was obtained by shifting GSM900 CDFs by 1.9 dB.

Faria [3], presents experimental data that validates the use of the *log-distance model* both inside and outside a standard office building. The measurements were performed using off-the-shelf IEEE 802.11b hardware and with distances varying from 1 to 50 meters. The values found for the path loss exponent agree with previously published results (α = 4:02; 3:32). Moreover, linear regression produced models with acceptable standard deviations (< 8 dB) suggests the occurrence of *log-normal shadowing*, as the deviations from the mean (in decibels) closely follow a Gaussian distribution.

Ullmo et al [4], proposed a new approach to modeling radio propagation, in buildings. Their result was a range of models in which one can vary the tradeoff between the complexity of the building description and the accuracy of the prediction. Idim et al [5], using a Samsung Galaxy, GT 35000, mobile phone with RF signal tracker software, installed, took measurements of two existing GSM Operators' signals level outside and inside two selected buildings, one concrete and the other, brick, which are representative of the common building types in Orhuwhorun, Delta State, Nigeria. Their results showed that an average loss of 10.62dBm, and 4.25dBm for the concrete and brick buildings, respectively. Walker et al [6] took 4000 measurements, of radio signals from AMPS sites from fourteen office and industrial buildings in Chicago. He found that: (i) signal level at the first floor of buildings averaged 14dB less than reference levels in the adjacent street (ii) Penetration loss decreases with height (iii) standard deviation of penetration loss ranging from 5 to 11dB attest to the architectural diversity and floor arrangements.

This paper is organized as follows: Section 3 discusses measurements campaign, Section 4 presents results and analysis, while summary, conclusions, and recommendations were presented in Section 5.

III METHODOLOGY

The measurement campaign was conducted using the N9342C Agilent Handheld Spectrum Analyzer (see figure 1). The analyzer comes with a radio frequency antenna that operates within the frequency range of 100 KHz and 7 GHz as well as a geo-positional system (GPS) receiving antenna attachment for determining GPS coordinates of locations. By specifying the desired frequency band, antenna sensitivity and units of measurement, in dBm, dB or Watt, measurements of signal power level outside and inside four different types of wall namely concrete, cements bricks (popularly called bricks), mud and metal were taken in several locations and at different times. These types of wall represent the major categorization of building materials used in a typical ancient city or urban centre in West Africa. The measurements were carried out in the city of Ilorin, the administrative and political headquarter of Kwara, one of the thirty-six states of Nigeria. Figure 2 provides pictorial samples of each of the building walls while table 1, provides a brief summary of the description of the various measurement locations and building wall materials.

Figure 1 Agilent Handheld Spectrum Analyzer

A. Description of Spectrum used for Measurement

Measurement was carried out across frequency bands within the range of GSM 1800MHz and UMTS 2100MHz downlink allocated to two different operators by Nigerian Communication Commission (NCC). Below are the spectrum allocated to each of the Operators by NCC in the downlink.

Operator 1
GSM 1800 (DL) 1820MHz – 1835MHz, Bandwidth is 200KHz
UMTS 2100 (DL) 2120MHz – 2130MHz, Bandwidth is 5MHz

Operator 2
GSM 1800 (DL) 1850MHz – 1865MHz, Bandwidth is 200KHz
UMTS 2100 (DL) 2140MHz – 2150MHz, Bandwidth is 5MHz

Table 1. Description of Measurement Locations

Material	Propagation Environment	No. of Locations
Concrete	Average height of structures is 13.4m (2floors) and 26.8m (4 floors) with rooms of average dimension of 2.7m x 2.7m.	6
Brick	Mostly Bungalow buildings with a dimension of 6.7m high, 15.2m length and 6.7m width. The rooms dimension is 3.7m x 3.7m.	6
Mud	Bungalows with average height of 5.8m, 15m long and 7m wide and the room size average is 3.0m by 3.7m	6
Metal	These buildings are smaller in size compared to conventional Bungalow buildings, averagely; they are 3.4m high, 4.6m long and 3m wide.	4

Figure 2. (1- Mud building, 2- Concrete building, 3- Brick building, 4- Metal building)

IV RESULTS AND DISCUSSIONS

The measurement results were obtained in 22 locations, with 6 locations each for building materials Concrete, Brick and Mud, while 4 locations are for Metal building material. All the measurements were recorded across frequency bands of GSM 1800MHz and UMTS 2100MHz of two different operators in Nigeria. The measurement was taken, 3 times for both Outdoor and Indoor over a period of 10 seconds. The average of tri-measured values was recorded for both indoor and outdoor in all the building materials across the two frequency bands. The measurement results are shown in Tables 2- 9.

Penetration Loss (PL) for each location in all the building materials, and across the two frequency bands was computed as the difference between Outdoor signal value (dBm) and Indoor signal value (dBm) [5, 7].

From Tables 2 to 9, it can be seen that in all of the locations for each of the building materials, there is no significant difference between indoor and outdoor received signal value.

Table 2. Recorded signal value in Concrete material across two bands for Operator 1

Operator 1 GSM 1800MHz and 2100MHz						
Concrete Sites	RSSI (1800) Outdoor (dBm)	RSSI (1800) Indoor (dBm)	Penetration Loss 1800 (dBm)	RSSI (2100) Outdoor (dBm)	RSSI (2100) Indoor (dBm)	Penetration Loss 2100 (dBm)
C 1	-61.20	-62.03	0.83	-46.45	-47.51	1.06
C 2	-61.16	-62.25	1.09	-46.73	-47.85	1.12
C 3	-61.32	-62.21	0.89	-46.59	-48.27	1.68
C 4	-61.18	-62.16	0.98	-46.54	-47.90	1.36
C 5	-61.46	-61.61	0.15	-47.55	-47.06	-0.49
C 6	-61.07	-62.14	1.07	-46.72	-47.78	1.06
	Average		0.84	`Average		0.97

Table 3. Recorded signal value in Brick material across two bands for Operator 1

Operator 1 GSM 1800MHz and 2100MHz						
Brick Sites	RSSI (1800) Outdoor (dBm)	RSSI (1800) Indoor (dBm)	Penetration Loss 1800 (dBm)	RSSI (2100) Outdoor (dBm)	RSSI (2100) Indoor (dBm)	Penetration Loss 2100 (dBm)
B1	-61.55	-62.90	1.35	-47.33	-47.80	0.47
B2	-61.18	-61.88	0.7	-47.17	-47.45	0.28
B3	-61.88	-61.97	0.09	-47.13	-47.66	0.53
B4	-61.81	-61.98	0.17	-46.69	-47.94	1.25
B5	-61.22	-61.85	0.63	-46.98	-47.64	0.66
B6	-61.44	-61.96	0.52	-47.30	-47.50	0.20
	Average		0.58	Average		0.73

Table 4. Recorded signal value in Metal material across two bands for Operator 1

Operator 1 GSM 1800MHz and 2100MHz RSSI						
Brick Sites	RSSI (1800) Outdoor (dBm)	RSSI (1800) Indoor (dBm)	Penetration Loss 1800 (dBm)	RSSI (2100) Outdoor (dBm)	RSSI (2100) Indoor (dBm)	Penetration Loss 2100 (dBm)
ME 1	-61.05	-62.17	1.12	-46.16	-47.86	1.70
ME 2	-61.09	-62.95	1.86	-46.11	-47.79	1.68
ME 3	-61.15	-62.79	1.64	-46.03	-47.87	1.84
ME 4	-61.18	-62.12	0.94	-46.04	-47.71	1.67
	Average		1.39	Average		1.72

Table 5. Recorded signal value in Mud material across two bands for Operator 1

Operator 1 GSM 1800MHz and 2100MHz						
Mud Sites	RSSI (1800) Outdoor (dBm)	RSSI (1800) Indoor (dBm)	Penetration Loss 1800 (dBm)	RSSI (2100) Outdoor (dBm)	RSSI (2100) Indoor (dBm)	Penetration Loss 2100 (dBm)
M 1	-61.33	-62.24	0.91	-46.59	-47.77	1.18
M 2	-61.49	-62.31	0.82	-47.17	-48.35	1.18
M 3	-61.00	-62.36	1.36	-46.83	-47.76	0.63
M 4	-61.18	-62.08	0.90	-46.92	-47.80	0.88
M 5	-61.51	-62.32	0.81	-46.86	-47.96	1.10
M 6	-61.31	-61.86	0.55	-46.72	-47.61	0.89
	Average		0.89	Average		0.98

Table 6: Recorded signal value in Concrete material across two bands for Operator 2

Operator 2 GSM 1800MHz and 2100MHz						
Concrete Sites	RSSI (1800) Outdoor (dBm)	RSSI (1800) Indoor (dBm)	Penetration Loss 1800 (dBm)	RSSI (2100) Outdoor (dBm)	RSSI (2100) Indoor (dBm)	Penetration Loss 2100 (dBm)
C 1	-61.35	-61.83	0.48	-46.99	-47.52	0.53
C 2	-61.42	-61.89	0.47	-47.39	-47.66	0.27
C 3	-61.61	-62.21	0.6	-46.96	-47.68	0.72
C 4	-61.42	-62.41	0.99	-47.09	-47.51	0.42
C 5	-61.27	-62.41	0.94	-47.18	-47.04	-0.14
C 6	-61.52	-62.21	0.69	-47.21	-47.52	0.31
	Average		0.70	Average		0.35

Table 7: Recorded signal value in Brick material across two bands for Operator 2

Operator 2 GSM 1800MHz and 2100MHz						
Brick Sites	RSSI (1800) Outdoor (dBm)	RSSI (1800) Indoor (dBm)	Penetration Loss 1800 (dBm)	RSSI (2100) Outdoor (dBm)	RSSI (2100) Indoor (dBm)	Penetration Loss 2100 (dBm)
B1	-61.41	-61.90	0.49	-46.87	-47.58	0.71
B2	-61.56	-62.39	0.83	-47.18	-47.42	0.24
B3	-61.49	-62.29	0.80	-47.06	-47.68	0.62
B4	-61.47	-61.78	0.31	-46.81	-47.49	0.68
B5	-61.20	-61.96	0.76	-46.96	-47.28	0.32
B6	-61.65	-62.35	0.70	-47.05	-47.76	0.71
	Average		0.65	Average		0.55

Table 8: Recorded signal value in Metal material across two bands for Operator 2

Operator 2 GSM 1800MHz and 2100MHz RSSI						
Brick Sites	RSSI (1800) Outdoor (dBm)	RSSI (1800) Indoor (dBm)	Penetration Loss 1800 (dBm)	RSSI (2100) Outdoor (dBm)	RSSI (2100) Indoor (dBm)	Penetration Loss 2100 (dBm)
ME 1	-61.12	-62.85	1.73	-46.06	-47.82	1.76
ME 2	-61.09	-62.78	1.69	-46.13	-47.76	1.63
ME 3	-61.08	-61.99	0.91	-46.15	-47.79	1.64
ME 4	-61.11	-62.71	1.60	-46.12	-47.84	1.72
	Average		1.48	Average		1.68

Table 9: Recorded signal value in Mud material across two bands for Operator 2

Operator 2 GSM 1800MHz and 2100MHz						
Mud Sites	RSSI (1800) Outdoor (dBm)	RSSI (1800) Indoor (dBm)	Penetration Loss 1800 (dBm)	RSSI (2100) Outdoor (dBm)	RSSI (2100) Indoor (dBm)	Penetration Loss 2100 (dBm)
M 1	-61.46	-62.42	0.96	-46.82	-48.01	1.19
M 2	-61.51	-62.43	0.92	-46.70	-47.81	1.11
M 3	-61.51	-62.44	0.93	-46.91	-47.87	0.96
M 4	-61.29	-62.43	1.14	-46.69	-47.99	1.30
M 5	-61.27	-62.22	0.95	-46.82	-47.77	0.95
M 6	-61.34	-62.02	0.68	-46.79	-47.88	1.09
	Average		0.93	Average		1.10

This means that there is no significant difference in the effects of the four building materials, on the received signals, across the two frequency bands. However, there is an average of 15dBm difference in the received signal between GSM 1800MHz and UMTS 2100MHz, with UMTS being the one with the highest value. The reason is that at 2100MHz, smaller cells are used, a receiver can be served by more than one cell resulting in a combination of two or more signals to produce a better output. In addition, wider bandwidth (5MHz per channel) is used in 2100MHz.

A. *Mean Average Penetration Loss, APL at 1800MHz*

Generally, to observe signal penetration into Concrete, Brick, Metal and Mud materials in GSM 1800MHz, Table 10 and Figure 3 presents APL in GSM 1800MHz across the four building materials.

Table 10: Mean APL at 1800MHz

Materials	Average Penetration Loss (dBm)		Mean Average Penetration Loss (dBm)
	Operator 1 (1800MHz)	Operator 2 (1800MHz)	
Concrete	0.84	0.70	0.77
Brick	0.58	0.65	0.62
Metal	1.39	1.48	1.43
Mud	0.89	0.93	0.91

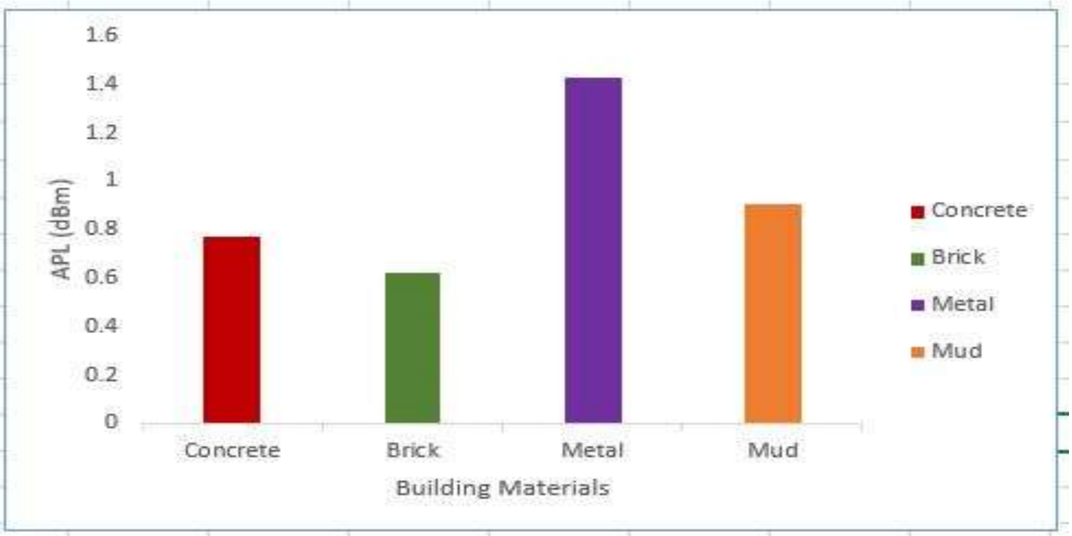

Figure 3: Mean APL at 1800MHz

Looking at Table 10 and Figure 3, in the GSM 1800MHz, it was observed that the mean APL in the four building materials varies. Higher mean APL of 1.43dBm was obtained in Metal materials. This is because metallic materials highly reflect signal, also normal metals used in buildings have exceedingly high conductivities (between 10^6 and 10^8 S/m) [8] and therefore, strongly attenuate radio waves. The mean APL of 0.91dBm obtained in Mud material can be attributed to the fact that surfaces of Mud buildings are rough, therefore signal propagation into this material suffer through scattering. Additionally, particles of Mud buildings are compact and the walls are thick which may lead to signal absorption. In Concrete material, mean APL of 0.77dBm was recorded, while in Brick material, mean APL of 0.62dBm was obtained. The reason for lesser mean APL in Brick material is because Brick buildings are porous, the walls are less thick when compared to walls of Concrete and Mud buildings, and signal reflection is not high when compared to Metal buildings. It was reported by [5] that penetration loss through Concrete materials is higher than Brick, which is also confirmed in this report.

B. Mean Average Penetration Loss, APL at 2100MHz

In order to compare penetration loss obtained in UMTS 2100MHz and GSM 1800MHz without referencing any operator, Table 11 and Figure 4 presents the mean APL obtained across the four building materials only in UMTS 2100MHz.

Table 11: Mean APL at 2100MHz

Materials	Average Penetration Loss (dBm)		Mean Average Penetration Loss (dBm)
	Operator 1 (2100MHz)	Operator 2 (2100MHz)	
Concrete	0.97	0.35	0.66
Brick	0.73	0.55	0.64
Metal	1.72	1.68	1.70
Mud	0.98	1.10	1.04

Figure 4: Mean APL at 2100MHz

From Table 11 and Figure 4, at UMTS 2100MHz, the highest mean APL was obtained in Metal (1.70dBm), followed by Mud (1.04dBm), and then Concrete (0.66dBm) and Brick (0.64dBm). A similar explanation for the value of the penetration loss in GSM 1800MHz also explains the penetration loss obtained in UMTS 2100MHz for all the four building materials. However, one can observe the value of the mean APL obtained in both GSM 1800MHz and UMTS 2100MHz is not the same. There is an average of 0.13dBm difference in penetration loss between the two bands in all the four building materials. From Figures 3 and 4, one can conclude that penetration loss increases with increasing frequency and this is in line with the report in [9].

C. Result Summary

- Generally, at GSM 1800MHz, mean APL obtained are 0.77dBm for Concrete, 0.62dBm for Brick, 1.43dBm for Metal and 0.91dBm for Mud. The conclusion here is that signal is less penetrated in Metal, Mud, Concrete and Brick materials in that order.

- In UMTS 2100MHz, mean APL of 0.66dBm was obtained for Concrete, 0.64dBm for Brick, 1.70dBm for Metal and 1.04dBm for Mud. Also, like GSM 1800MHz, signal is less penetrated in Metal, Mud, Concrete and Brick materials in that order. An average of 0.13dBm difference was calculated for penetration loss between GSM 1800MHz and UMTS 2100MHz.
- It was found that in every aspect of the analysis and discussion presented in section 3.1 and 3.2, penetration loss increases with increasing frequency and this statement was also confirmed in [9].

V CONCLUSION

This research work presents the effects of building materials in the outdoor to indoor environment signal propagation in the frequency bands of GSM 1800MHz and UMTS 2100MHz of two different operators in Ilorin metropolis of Kwara State, West Africa Nigeria. The building materials considered are Brick, Concrete, metal, and Mud. The result obtained from measurements carried out both indoor and outdoor for each of the different materials shows that for GSM 1800MHz, the mean APL obtained are 0.77dBm for Concrete,0.62dBm for Brick, 1.43dBm for Metal and 0.91dBm for Mud. In UMTS 2100MHz, mean APL of 0.66dBm was obtained for Concrete, 0.64dBm for Brick, 1.70dBm for Metal and 1.04dBm for Mud. In relation to the frequency of operation, it was observed that penetration loss increases with increasing frequency. Therefore, it is reasonable to conclude that penetration loss is higher in Metal, followed by Mud, Concrete, and Brick, while it also increases with increasing frequency.

This work, along with others before it, has opened a new frontier in radio path profiling, thus creating a new paradigm in radio network planning. This additional parameter, 'building penetration loss' will henceforth continue to change the face of radio propagation models enabling network designers and operators to take this into consideration, as they do their work.

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