Indonesian Journal of Electrical Engineering and Informatics (IJEEI)
Vol. 7, No. 3, Sep 2019, pp. 494~507
ISSN: 2089-3272, DOI: 10.11591/ijeei.v7i3.1085

Experimental Determination of Penetration Loss into Multi-Storey Buildings at 900 and 1800MHz

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Article Info

Article history:

Received Mar 01, 2019
Revised Apr 30, 2019
Accepted Aug 23, 2019

Keyword:

Propagation modeling,
Test mobile systems,
Building penetration loss,
Multi-storey buildings,
Standard deviation,
Cubic regression,
Frequency bands

ABSTRACT

This study presents building pentration loss into and around multi-storey buildings at 900 and 1800MHz based on experimental data obtained through drive test, using Test Mobile System (TEMS) investigation tools. The received signal level was measured inside and outside three buildings; the Senate building of the University of Lagos (B1), Mike Adenuga Towers (B2) and the Sapetro Towers (B3) located in Victoria Island, Lagos Nigeria. The building penetration loss (BPL) was derived from measurements, and the average and standard deviations of the BPL were computed. Results showed that the average BPL of 17.0dB and 13.8dB obtained from building B1 at 900 and 1800MHz, respectively, are comparatively higher than those of buildings B2 and B3. The standard deviation of the BPL shows an increase from 5.2dB at 900MHz to 7.8dB at 1800MHz for building B1, whereas it fell drastically from 8.65dB at 900MHz to 1.40dB at 1800MHz for B2, and a similar behaviour as in B1 is seen for building B3, where it rises sharply from 1.55dB at 900MHz to 6.55dB at 1800MHz. This is in agreement with the general trend of increasing penetration loss with increase in frequency except for building B2 where an anomaly is observed. In order to examine the correlation between the measured and the predicted BPL, cubic regression was used to fit a third order polynomial to the measured BPL. Overrall, the fitted models could find useful applications in the design of novel and robust BPL models for modern multi-floored buildings.

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1. INTRODUCTION

The exponential growth of the emerging technologies of Long Term Evolution (LTE) and the evolving fifth generation (5G) technology, has orchestrated the need for robust and sophisticated radio frequency planning techniques to help plan the already congested radio frequency spectrum more efficiently [1] [2]. With the growing need for fast switching multimedia services at various locations, the desire for improved indoor coverage has become a major concern, especially as a great number of mobile subscribers are often indoors [3]. Thus, radio frequency planners need to make great efforts to effectively utilize the allocated bands, to enhance the quality of user experience [4] [5].

Similarly, the dependency of many office applications on wireless technologies has greatly increased in recent times and the limited radio resources to accommodate these growing demands pose great concerns and requires a conscious rethink of the existing technological solutions. Therefore, radio resource planners are exploring various opportunities to use the existing telecommunication infrastructure to deliver robust services to more users, while ensuring good quality of service (QoS), and reducing capital and operational expenditure. In order to address the growing subscribers' concerns such as call drop, poor interconnectivity, noisy reception, and network unavailability, efficient indoor radio network planning and optimization is inevitable, and the need for a comprehensive investigation of the penetration loss into multi-storey buildings at specific frequency bands cannot be overemphasized.

In metropolitan areas, indoor-to-outdoor communication is usually challenged by huge penetration loss arising from complexities of building structures and wall partitions [6]. For effective wireless network planning, the indoor channel is usually modelled both statistically and via signal measurements within the propagation domain [7] [8]. Since users engage the different channels over diverse building floors, inaccurate signal prediction could adversely affect the overall network performance.

The complexity of indoor radio propagation is largely dependent on the nature and location of obstacles per time with the generalized assumption of a static or quasi-static wireless channel. The properties of diffraction, reflection and shadowing becomes a major concern in analyzing the channel alongside defining the electrical characteristics of the obstacles within the channel [9]. Various obstacles such as partitioned walls, furniture or gadgets increases the complexity of path loss prediction within buildings since the path loss coefficient of individual obstacles add up, leading to a corresponding increase in penetration loss [10].

An approach used for indoor signal prediction for network planning is the application of low-resolution microcell model while increasing the indoor penetration margin. This procedure though provides a rough estimate of indoor coverage, has some inherent drawbacks [11] [12]. An alternative method for determining indoor coverage for a large area is through radio wave propagation measurements of each floor of the investigated building. In a situation where there are restrictions to building(s) or to some parts of the buildings for security reasons, it could be very difficult or even not possible to make such measurements. A viable option is to use the outdoor base station and a receiver to measure and predict the pathloss around and into the building [13] [14]. This method takes into cognizance; the complexity of propagation processes between transceivers and building walls, and that of the internal components such as wall partitions, floor materials, wall coatings, furniture and human traffic.

In emerging smart cities like Lagos, multi-storey buildings are being erected for office use and shopping units, which attract large population of subscribers, with varying demands for radio resources. Some models reported in [2, 15, 16, 17, 18] have been proposed for effective prediction of indoor propagation. However, some of these models have been tuned based on high resolution building data and ray-tracing techniques [19]. The influence of human traffic, building structure, changing environment, partition materials and other dynamic factors are often not given adequate consideration or are completely overlooked. Therefore, this paper is aimed at investigating radio wave outdoor-to-indoor propagation prediction at 900 and 1800MHz frequency bands. The goal is to examine the impact of radio wave penetration loss in selected multi-storey buildings, with a view to providing a suitable building penetration loss model, using outdoor-to-indoor measurements campaign. This would help to predict more accurately, the penetration loss into multi-storey buildings for improved network planning and optimization processes.

2. RELATED WORK

Classical studies on indoor coverage prediction and building penetration loss resulting in propagation models with varying degrees of accuracy have been well reported [7] [14] [20] [21]. The performance of these models is dependent on the number of parameters factored into the design of the model. This implies that a robust model could be derived if more parameters from actual measurements are included in the design. However, applying many parameters to the design of the model will inevitably increase the complexity of the propagation model [22]. The following paragraphs present some reports related to building penetration loss.

On the optimization of certain existing indoor propagation models, Flattie [2] reported that the optimized models showed reduced RMSEs of 13.04dB and 9.6 dB for the COST-231 Multi-wall and the optimized - dominant path loss models. The path loss exponent of the optimized model for long-distance path loss modelling was observed to be 2.2 with a corresponding standard deviation of 10 dB in comparison with existing models reported by the author.

Rice [16] carried out a study on radio frequency signal transmission into buildings at 35 mc and 150 mc. The field strength measured at the main floor of each building was referenced to that measured at street level with the building loss obtained as the difference. It was noted that building loss is a factor that can be applied to the field intensity in streets to assist in the prediction of the performance of radio services in buildings. In addition, it was observed that building losses at 35 mc and 150 mc followed a lognormal distribution. In general, the average building loss was seen to be 24 dB at 35 mc, and 22dB at 150 mc. Variations in signal level at lower frequency was found to be slightly greater than at higher frequency, and the standard deviation of the building loss was calculated to be about 14 dB at 35 mc and 12 dB at 150 mc.

More so, Kurner and Meier [17] reported the coverage prediction of outdoor-to-indoor and outdoor wireless channel in urban areas at 1.8 GHz using micro cells. The study integrated some important propagation features in dense urban environments, and the observed standard deviation ranges from 7dB to 9 dB with average value not up to 3 dB. It was concluded that indoor coverage is dependent on the x – y position of the building and the number of floors. It was recommended that more measurements from other cities as well as from macro cells should be taken to validate the correlation factors for the model.

Martijn and Herben [18] carried out a study on radio waves propagation into buildings, and analyzed the results using linear regression. Findings showed that alarming variations occur between the mean signal levels in LOS and NLOS areas of multi-floor buildings. The model was tested against the well-known Hata and COST 231 Hata models, showing RMSEs of 5dB and 8dB, respectively. However, the authors did not emphasize the effect of internal structures and multipath at 1800MHz as in [15].

Stavrou and Saunders [20] reported factors influencing outdoor-to-indoor radio frequency propagation. The authors investigated the average predicted penetration loss and frequency versus windowed wall frequency. The study also covers the effect of internal construction and size of the penetration size index as well as the insulation used on the walls. It is worthy of note that some researchers have defined these factors but specific contribution of each parameter to the overall penetration loss has not clearly been discussed.

Kakar et al. [22] carried out a study on the factors impacting on building penetration loss, with particular interests on the external wall configuration, angle of incidence, and receiver height inside the building and adjacent rooms. Results showed a standard deviation of 12 dB and an increase of 1.5 dB per floor moving upward from ground floor. The mean building penetration loss was found to be 18 dB. This was in close agreement with the results reported in [23]. However, the results of the study did not emphasize the effect of internal building parameters such as human traffic within building and the height of the transmitter with respect to the building height.

Similar to the proposed study, multiple regression analysis technique was adopted for path loss prediction in a multi-storey building at 900, 1800 and 2300MHz in [24]. It was reported that path loss within the building was largely influenced by the logarithmic area of the floor, mean signal strength of the floor, number of floors within transmitter – receiver separation and other transmission conditions, which are interdependent with respect to the building arena having line of sight communication.

In a companion paper to [24], Turkmani and De Toledo [25] presented radio transmission in multi-storey building at 1800MHz comparing the metrics of signal strength in rooms, along the isles, and the surrounding streets. The combination of Lognormal and Rayleigh distributions was seen to have predicted the cumulative distribution with fair accuracy. Having 13dB – ground level average penetration loss with respect to increasing floor levels up to six -floors of -1.4dB.

Hoppe et al. [26] focused on electric field strength measurements in estimating building penetration loss and signal transmission into buildings. Results indicated a standard deviation of 7-9 dB in the case a LOS, and 4-6 dB for an NLOS for a log-normally distributed large-scale signal variation. According to the authors, the small-scale signal variation was Rice distributed and the mean building penetration loss was estimated to be 10dB.

Ferreira et al. [27] presented the characterization of signal penetration loss into buildings and found out that the additional attenuation follow a lognormal distribution. At 900MHz, average attenuation of 5.7 dB was documented with increasing building penetration loss as one goes farther into the building and decreases with increasing floor level. It was noted that the results for 1800 and 2100MHz could be derived by shifting the 900MHz CDFs by 1.9 dB.

On LTE based indoor wireless models for radio resources management, Abbas et al. [28] reported the importance of radio environment and its statistical characteristics showing indoor propagation fast fading models could not be modeled with a single distribution and therefore requires non-static models for proper modeling.

Durgin et al. [29] carried out a study on penetration loss in and around buildings with trees. The report focused on the effect building construction, floor plan and external shadowing have on radio wave penetration into homes. Results showed that at 5.85GHz, signal attenuation due to penetration loss averaged over a value of 14dB, 11dB to 16dB due to tree shadowing and 15dB to 21dB due to in house shadowing, depending on the height of the receiving antenna. These factors need to be compared with the propagation phenomena in suburban areas, especially as about 75% of the Nigerian coverage area can be classified as suburban.

In a related work, Seidel and Rappaport [30] carried out a study on 914MHz indoor multi-floored channel propagation modelling. The study developed a site-based model in line with building wall partitioning and number of floors in building by relating the logarithm of distance to signal strength. 5.8dB standard deviation ensued with an average floor attenuation factor of 12.9 dB and 16.2 dB for one floor between the transmitting and the receiving antennas in two different buildings. The attenuation factor for each office partition was 1.4dB while for mild concrete walls, the factor was found to be 2.4dB.

Fernandez et al. [31] carried out a study on building penetration loss and noise levels characterization in medium wave (600 KHz and 1600 KHz). Analytical approach for determining building penetration loss and noise level in the medium wave band was obtained. Results of the study showed about 6.5dB signal attenuation due to building penetration loss at these frequencies, while the indoor and outdoor noise levels remain quite similar. Results also showed a standard deviation between 10dB and 12dB on the signal and noise spatial variations. It was concluded that the analytical approach is subject to errors due to specific environment and other site-specific parameters.

LaSorte et al. [32] carried out a study on building penetration loss in hospital environment at frequencies ranging from 55MHz to 1950 MHz. The results showed an average building loss of 24.8dB to 18.23 dB for 55MHz to 1950MHz frequency range over short-term measurements since the entire spectrum was measured in 12minutes. It was concluded that more detailed long-term measurements were required to validate the results.

Gupta and Joshi [33] carried out a study on 900MHz in-building radio propagation in multi-storey buildings. Statistical models were used to show that several models coexist for different types of radio links. The effect of building structure, antenna positioning and surrounding environment was considered but did not produce specific loss contributed by each evaluation. Results showed an average path loss exponent n, of 2.77, standard deviation of 5.4 dB for same floor and average path exponent of 4.19, standard deviation of 6.5 dB through one floor. An extended version of the results reported in [33] is presented in a companion paper [34].

Dres et al. [35] studied penetration loss into buildings at 2.4 GHz and considered the effect of local media variations, concrete building, and cumulative distributions of received strength. Constant values of 8.5dB to 9.5dB was observed for offices where line of sight measurement was conducted and 10dB to 11.5dB for offices with non-line of sight measurements were conducted.

On signal penetration in cellular environment, Walker [36] observed that the first-floor signal strength averaged 14 dB less than the adjacent street reference level. Standard deviations of penetration loss ranged between 5dB to 11dB, and the loss decreased with height at 1.9dB per floor. Results of measurements in the aluminum-sided part of the building showed a loss of 7.3 dB.

There are several reports on pathloss modeling related to the study on penetration loss. Some of these reports cover building penetration loss for GSM signals [37], indoor wireless channels [21] [23], ultra-dense 5G wireless networks [38] [39], hotspot areas [3], [40], terrestrial environments [41] [42] [43] [44] [45], major high ways [46], DVB-H in the UHF band [47], IMT application [48], coverage estimation in microcells [49], millimeter wave frequencies [1] [50] [51], railway tunnels [52], large building structures [53], Lagoon environment [54], and incident angles and measurement areas [55]. It is worthy of note that the models reported in this paper will add to the existing body of knowledge.

2.1 Building Penetration Loss

The building penetration loss (BPL) from outdoor to indoor L_{O2I} as given in (1) is the additional attenuation in comparison with the theoretical free space path loss (FSPL) denoted as L_{FS} [56].

$$L_{O2I} = A_{av} - L_{FS} \quad (1)$$

$$L_{FS} = 147.5 + 20\log_{10}(f_c) + 20\log_{10}(d) \quad (2)$$

where L_{FS} is expressed in dB, f_c defines frequency given in Hertz, and d is the transmitting and receiving antenna separation distance in meters.

It should be emphasized that the parameter L_{O2I} considers the attenuation due to the penetration through external walls, windows and the losses resulting from the associated elements present in the indoor propagation area [57]. According to [58], this loss is decribed as the Building Entry Loss (BEL), which is *"the additional loss due to a terminal inside a building"*.

Recently, the wireless research group at New York University (NYU) reported a model for BPL, which agree closely with the 3GPP based channel model for BPL. The NYU model [38] [59] is given in (3), and the 3GPP BPL model [59] [60] is given in (4).

$$\mathrm{BPL_{NYU}(dB)} = 10\log_{10}\left(\mathrm{X} + \mathrm{Y}.\mathrm{f_c}^2\right) \quad (3)$$

where f_c is in GHz, for low-loss buildings, $\mathrm{X} = 5, \mathrm{Y} = 0.03$, and for high-loss buildings, $\mathrm{X} = 10, \mathrm{Y} = 5$.

$$\mathrm{BPL_{3GPP}(dB)} = \mathrm{PL_{npj}} - 10\log_{10}\sum_{j=1}^{N}\left(\mathrm{P_j} \times 10^{\frac{\mathrm{L_{material_j}}}{-10}}\right) \quad (4)$$

where $\mathrm{PL_{npj}} = 5\mathrm{dB}$ (extra loss added to the external wall loss as a result of various materials), $\mathrm{L_{material_j}}$ equals penetration loss of material j, $\mathrm{P_j}$ is the proportion of the $\mathrm{j-th}$ material, $\sum \mathrm{P_j} = 1$ and N is the number of material.

3. MATERIALS AND METHOD

3.1 Investigated Multi-Storey Buildings

Lagos is a central business hub located in the Southwestern geopolitical zone of Nigeria. High-rise buildings that accommodate about 60% of Lagos workforce are mainly located on the Lagos Island.

The received level and other useful parameters were measured within and outside the Senate Building of the University of Lagos, located in the Akoka campus in Lagos mainland, and two other popular buildings;

Mike Adenuga Towers (MAT) and South Atlantic Petroleum (Sapetro) Towers, both located in Adeola Odeku Street of Victoria Island, Lagos. For ease of identification, the Senate Building of the University of Lagos is hereafter referred to as B1. The Mike Adenuga Towers and the Sapetro Towers are referred to as B2 and B3, respectively.

The buildings are constructed with reinforced concrete, and they are typical high-rise towers ranging from eleven to twelve floors in height. Building B1 comprises of a heavy reinforced concrete with steel rods embedded, and B2 is made up of reinforced concrete coated with gold colour, while B3 has a glassy front view with heavy walls at the back end. The pictorial views of the three buildings are as presented in Figure 1 (a)-(c), respectively.

(a) (b) (c)

Fig. 1. Measurement sites: (a) University of Lagos Senate House (Building B1), (b) Mike Adenuga Towers (Building B2), (c) South Atlantic Petroleum (Sapetro) Towers (Building B3)

3.2 Survey of Investigated Environments

Site survey of the measurements environment provides relevant information about the sites under investigation. It helps in determining near precise locations, identification of obstacles and the general radio environment. This involves site visit to identify optimum installation locations for access points and test for RF interference. This necessitates the evaluation of building floor plans, access, facility inspection and application of site survey tools. In addition, the site survey involves checking to ensure that there is no other radio equipment on site, which could interfere with the experimental setup. During the survey, sample statistics were taken as regards the traffic trend in the buildings to determine the direct effect of human traffic on each building relative to path loss. The survey was key to determining the location of the base stations, its network parameters, the existence of LOS and NLOS propagation paths, as well as other details of the tested buildings.

3.3 Measurements Equipment Setup

The measurement equipment is the Sony Z2 smart phone, simply described as a Test Mobile System (TEMS) pocket phone specifically designed for indoor network drive test. The device has a pre-installed TEMS investigation application duly licensed for both Circuit Switch (CS) and Packet Switch (PS) network verification. Its mode of operation is simplified for new and existing users, the screen shots of its settings and configurations for GSM, WCDMA, and LTE band lock with sample-measured data comprising of the Ec/No in red colours and the RSCP in green colours are as shown in Figure 2.

It simply requires the user to navigate to the control function and lock on any particular band whether LTE, GSM 900 or 1800, or WCDMA. Once this is completed and the settings saved, the user can navigate to the settings on the TEMS app to set the script.

The script makes the job easy, as the user have the opportunity to set both long and short calls and input the switch number as provided by the network switching subsystem engineers of the particular operator. After the script configuration, it is required that the user saves the settings accordingly. To start the investigation, simply tap on the "start recording button" and then tap "start script", the device will automatically dial the switch number provided and then logs the network details for CS.

In addition, the mobile phone is capable of logging details for the PS in the same log file location on the device file manager. After the drive test (DT) is completed, the log file is extracted, and converted to either MapInfo format or Text format on the TEMS phone or a personal computer for post DT analysis.

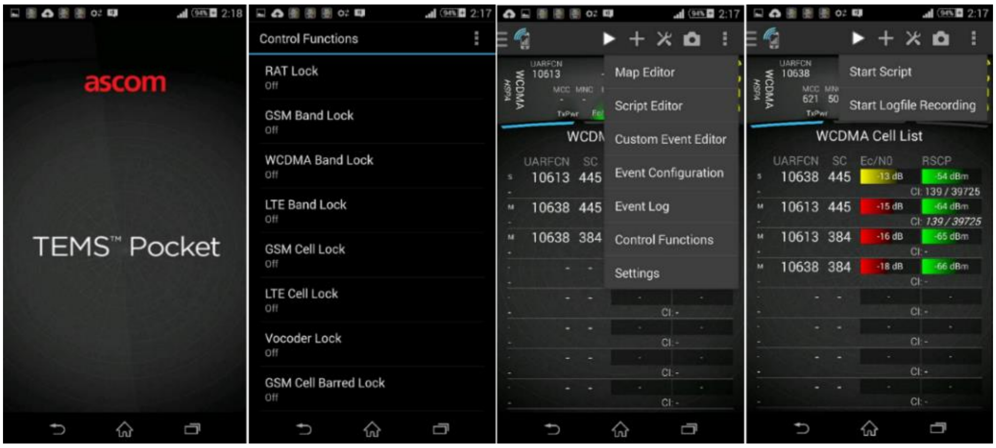

Fig. 2. Measurements equipment – TEMS pocket phone showing screen shots of settings and configurations for GSM, WCDMA, and LTE band lock with sample-measured data comprising of the Ec/No in red colours and the RSCP in green colours

3.4 Measurements Procedure and Modeling Parameters

The TEMS installed on the Sony Z2 smart phone was used for the measurement of the received signal power. Since indoor reception of satellite signal is very poor for position location, the GPS device is disconnected such that the “pin point” tool of the TEMS software is used for signal path tracing. The architectural plan of each floor was carefully converted to a MapInfo readable file; that is a “.tab” file and uploaded into the TEMS tool by using the Map icon. Afterwards, the system was setup based on the expected key performance indicators (KPIs) for signal measurement.

For a better view of test results, the TEMS phone was connected appropriately to the USB port of the computer in which the TEMS discovery software had been installed. The test took about 3 to 4 hours at each of the buildings and its environs. The measurements were carried out at designated points in each floor across most of the floors of the entire building. The personal computer loaded with data collection software was used to properly view the measured data. Settings for frequency range, distances and time were performed on the TEMS phone. The Tx-Rx distance is then obtained by plotting the receiver co-ordinate against the transmitter coordinates.

Field measurements were taken at the 900 and 1800MHz frequency bands in three different multi-storey (office) buildings. In order to analyze the impact of human traffic, measurements have been taken for during working hours and off working hours, using TEMS investigation tools installed on a Sony Z2 mobile phone. Received signal level was measured and recorded at various floors of the multi-storey buildings. The mobile phone was carried along while walking through different rooms on each (accessible) floor of the buildings, at near constant mobile antenna height, and the transmitter-receiver distance is limited to around 2.5km.

The average building height is taken to be 20m, with building-to-building distance of 15m, and street width of 10m. Correction factor for shadowing effects is taken to be 10.2 dB [61]. Measurement time at each point was maintained at approximately 60 seconds, and the radio channel measured which supervised and monitored the traffic channels. The tested transmit antennas (base stations) with various heights ranging from 25-30m above rooftop and the effective isotropically radiated power is 46 dBm. Further details of the modeling parameters are available in our earlier reports [19] [42].

4. RESULTS AND DISCUSSION

4.1 Results of Propagation Measurements

The mean received signal strength for building B1 at 900 and 1800MHz is as shown in Figure 3. Similarly, the mean received signal strength for buildings B2 and B3 at 900 and 1800MHz are as shown in Figures 4-5, respectively. The average received signal strength per floor for buildings B1, B2 and B3 at 900 and 1800MHz are as shown in Figure 6. The penetration loss obtained for buildings B1, B2, and B3 at 900 and 1800MHz are as shown in Figure 7.

In order to observe the correlation between meseasurements and the predicted penetration loss, cubic regression was used to fit a third order degree polynomial to the measured penetration loss. For the tested buildings, the corresponding pathloss with norm of residuals are given in equations (5)-(10). In addition, the description of the buildings, mean and standard deviations, and penetration losses of measured data are as presented in Tables 1-2. Finally, a comparative analysis of the measured penetration loss with penetration losses reported in related works is presented in Table 3.

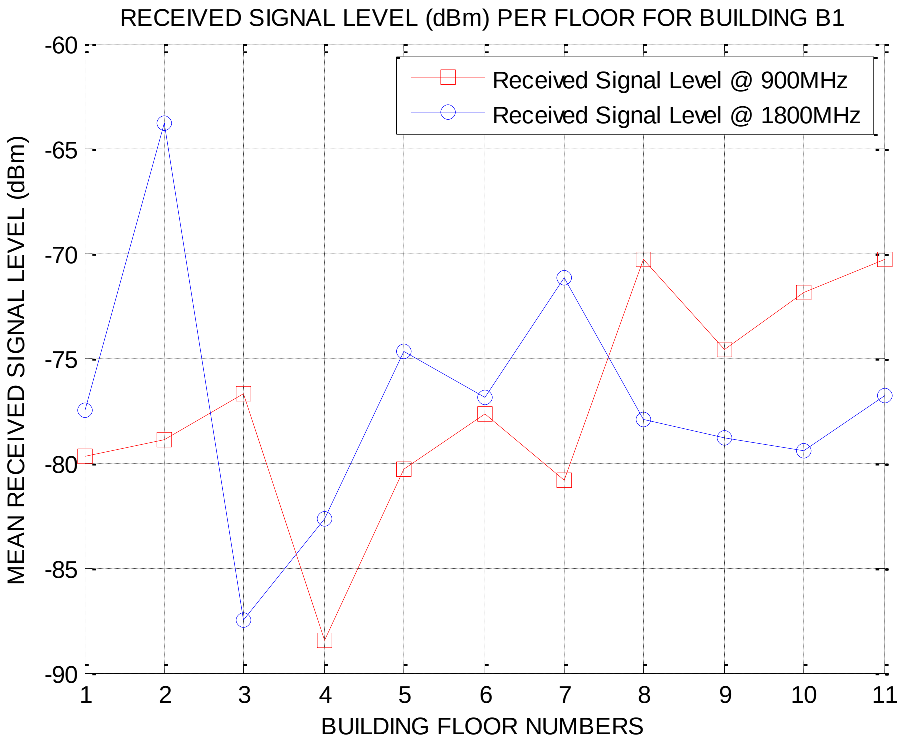

Fig. 3. Mean received level measurements for building B1 at 900 and 1800MHz

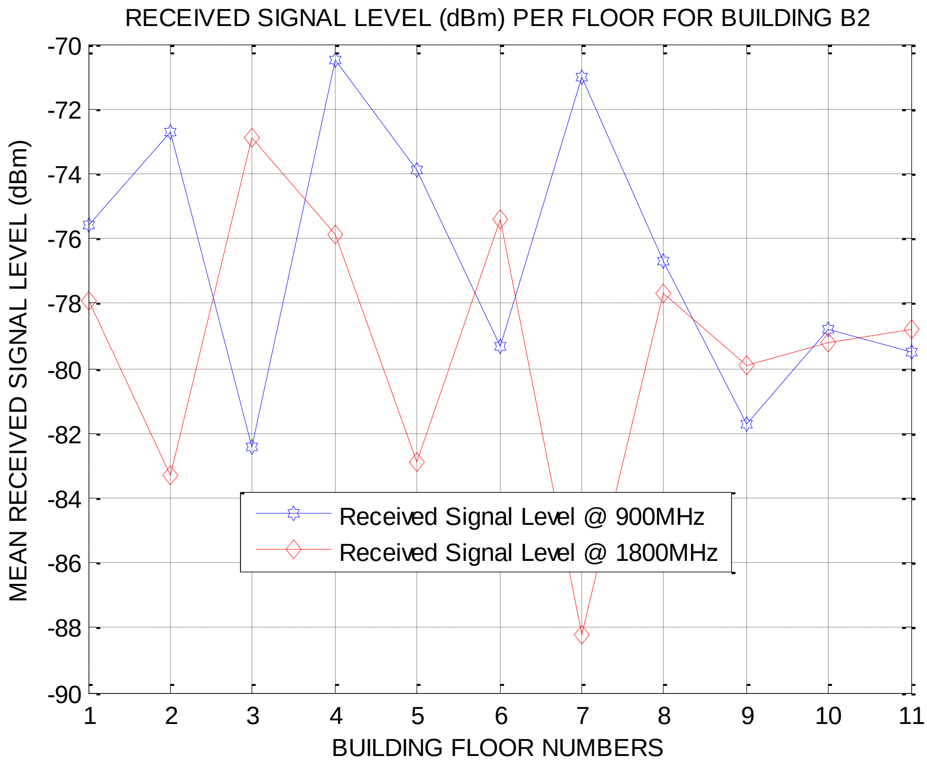

Fig. 4. Mean received level measurements for building B 2 at 900 and 1800MHz

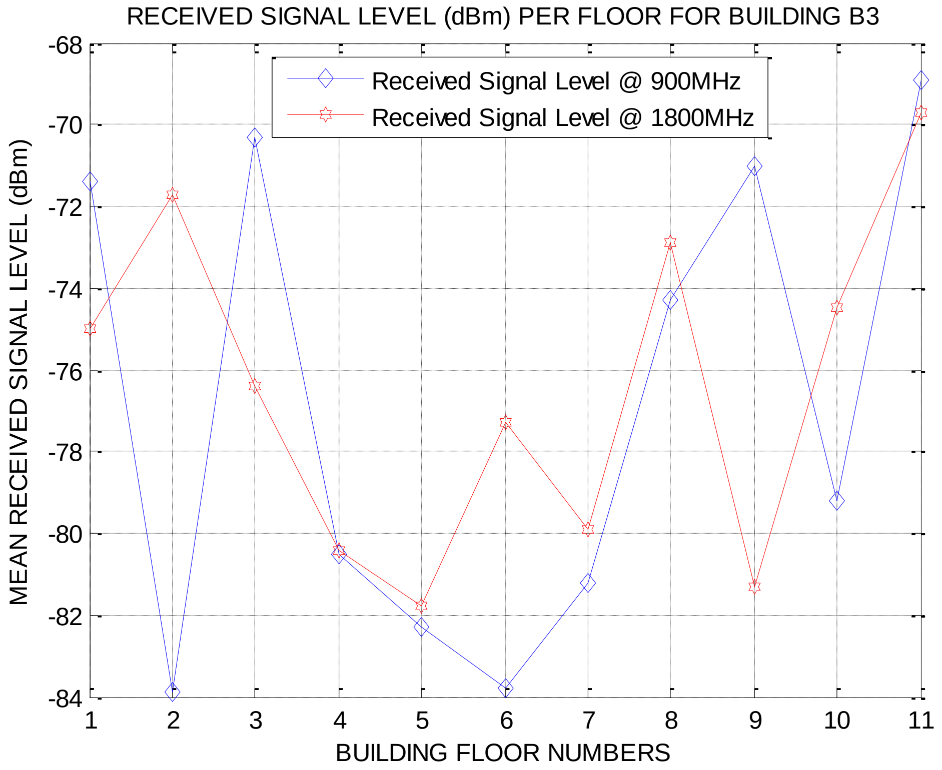

Fig. 5. Mean received level measurements for building B 3 at 900 and 1800MHz

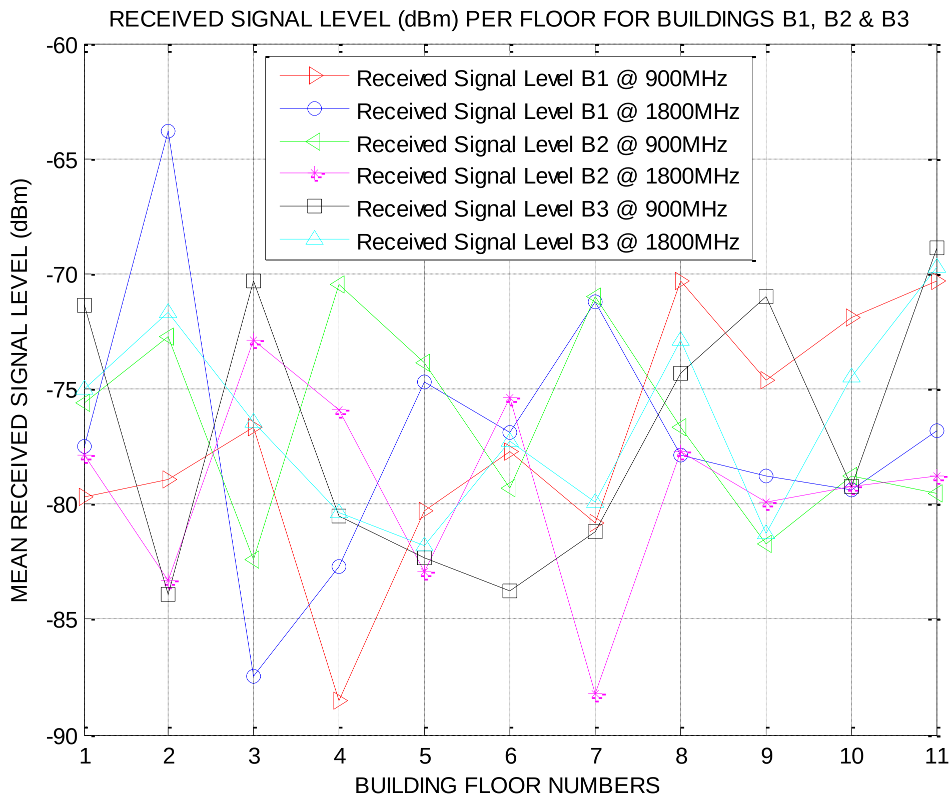

Fig. 6. Average received level measurements per floor for buildings B1, B2 and B3 at 900 and 1800MHz

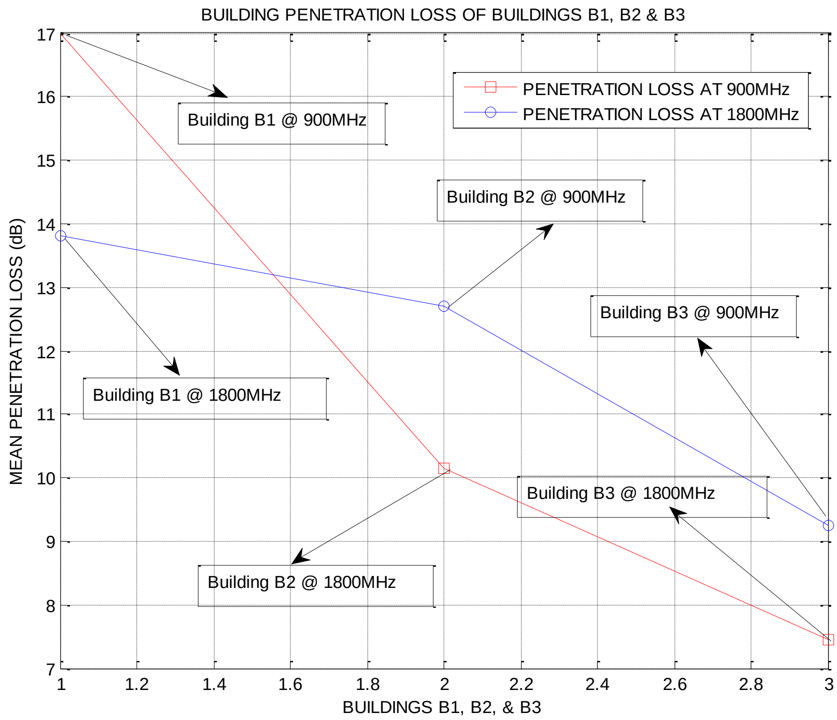

Fig. 7. Average penetration loss computed for buildings B1, B2 and B3 at 900 and 1800MHz

For building B1 at 900MHz with $Norm = 10.855$,

$$PL_{B1\_900MHz} = -0.042308n^3 + 0.9669n^2 - 5.215n - 73.679 \quad (5)$$

For building B1 at 1800MHz with $Norm = 18.649$,

$$PL_{B1\_1800MHz} = -0.045882n^3 + 0.87051n^2 - 4.8533n - 69.773 \quad (6)$$

For building B2 at 900MHz with $Norm = 11.775$,

$$PL_{B2\_900MHz} = 0.0012044n^3 - 0.12786n^2 + 0.91639n - 76.648 \quad (7)$$

For building B2 at 1800MHz with $Norm = 12.84$,

$$PL_{B2\_1800MHz} = 0.042347n^3 - 0.71235n^2 + 3.0574n - 81.627 \quad (8)$$

For building B3 at 900MHz with $Norm = 14.854$,

$$PL_{B3\_900MHz} = -0.018609n^3 + 0.68054n^2 - 5.4372n - 68.294 \quad (9)$$

For building B3 at 1800MHz with $Norm = 9.2151$,

$$PL_{B3\_1800MHz} = 0.016414n^3 + 0.0053613n^2 - 1.9701n - 71.371 \quad (10)$$

where PL =Pathloss in dB and n = Building floor numbers.

Table 1: Mean and standard deviations of measured penetration loss

Buildings	Frequency (MHz)	Data Statistics	Signal Level Within (dBm)	Signal Level Outside (dBm)	Building Loss (dB)
B1	900	Mean	-77.25	-62.3	17
		Standard Deviation	5.385	5.6	5.2
	1800	Mean	-77.02	-56.9	13.8
		Standard Deviation	6.05	0.95	7.8
B2	900	Mean	-76.55	-64	10.15
		Standard Deviation	4.15	7.2	8.65
	1800	Mean	-79.28	-67.9	12.7
		Standard Deviation	4.255	1.3	1.4
B3	900	Mean	-76.98	-70.2	7.45
		Standard Deviation	5.847	4.7	1.55
	1800	Mean	-76.45	-64.1	9.25
		Standard Deviation	4.087	8.20	6.55

Table 2: Building description and measured penetration loss

Buildings Measured	Building Description	Standard Deviation of Penetration Loss (dB)	
		900MHz	1800MHz
UNILAG Senate Building B1	Heavy Reinforced Concrete with Steel Rods Embedded	5.2	7.8
Mike Adenuga Towers B2	Reinforced Concrete coated with Gold Colour	8.65	1.40
Sapetro Towers B3	Glassy Front View Heavy Walls at the Back end	1.55	6.55
Buildings Measured	Building Description	Mean Values of Penetration Loss (dB)	
		900MHz	1800MHz
UNILAG Senate Building B1	Heavy Reinforced Concrete with Steel Rods Embedded	17	13.8
Mike Adenuga Towers B2	Reinforced Concrete coated with Gold Colour	10.15	12.7
Sapetro Towers B3	Glassy Front View Heavy Walls at the Back end	7.45	9.25

Table 3: Comparative analysis of measured penetration loss with related reports

Average Measured Penetration Loss		Martijn and Herben [18] at 1800MHz			Antonio et al. [62] at 900, 1800 and 2300 MHz				NYU Model [38] [59]	3GPP Model [59] [60]
900MHz			Mean (dB)	SD (dB)	Atlantic Telecom	9.26	Computer Lab	14.41	Std Dev. (dB)	Std Dev. (dB)
B1	17	Building 1 F1	13	2	Lloyds Bank	14.70	Barclays Bank	26.03	Low-loss model	Low-loss model
B2	10.15	Building 2 F1	5	4	Pykes	8.66	News Agent	17.58	4.0	4.4
B3	7.45	Building 3 F1	4	7	British Telecom I	30.14	Alsop Building	20.85	High-loss model	High-loss model
1800MHz		Building 4 F1	12	4	British Telecom II	23.94	Parrys Bookshop	14.73	6.0	6.5
B1	13.8				City Council	15.92	Old Student Union	18.75		
B2	12.7				Royal Bank of Scotland	10.12	New Student Union	18.60		
B3	9.25				General Accident	16.19	Catholic Chaplaincy	16.25		
					Birm. Mildshires	12.85	Ashton Building	10.56		
					Queen Avenue	15.80	Victoria Building	9.38		
					Elsmore Travel	10.59				
					Derbyshire	2.96				
					Barclays Banks	21.68				
					Average	14.83	Average	16.71	5.0	5.45

4.2 Discussion of Results

As shown in Figure 3 for building B1, the received level at 900MHz for the first floor was found to be -77.5dBm, and it increased sharply to -61.5dBm at the second floor, and fell back to as low as -87.5 and -83.5dBm at the third and fourth floors, respectively. A steady increase was seen from the fourth floor up to the fifth floor and this fall slightly to -77dBm at the sixth floor. A gentle fall in the value of the received level was observed from the eight floor to the tenth floor and a further rise at the eleventh floor. For the same building at 1800MHz, the behaviour was quite different with the lowest received level seen at floor four and the highest value of -70dBm found at floors nine and eleven.

The received level for building B2 at 900 and 1800MHz as shown in Figure 4 showed a rather similar trend except at the seventh floor when the received level was found to be -71dBm at 900MHz and -80.5dBm at 1800MHz. For the third building B3, the received level as depicted in Figure 5 shows very high variations at 900 and 1800MHz for floors 2 and 9, while the received level was the same for floor 4 at the 900 and 1800MHz bands.

A closer look at the results presented in Table 1 show mean penetration loss of 17dB, 10.15dB, and 7.45dB at 900MHz, and 13.8dB, 12.7dB, and 9.25dB at 1800MHz for buildings B1, B2, and B3, respectively. Smilarly, the average standard deviations are; 5.2dB, 8.65dB, 1.55dB at 900MHz, and 7.8dB, 1.40dB, 6.55dB at 1800MHz for B1, B2, and B3, respectively. The standard deviation of penetration losses shows an increase from 5.2dB at 900MHz to 7.8dB at 1800MHz for building B1, whereas it fell drastically from 8.65dB at 900MHz to 1.40dB at 1800MHz for B2, and a similar behaviour observed for B1 is seen for building B3 where it rises sharply from 1.55dB at 900MHz to 6.55dB at 1800MHz. This is in conformity with the general trend of increasing penetration loss with increase in frequency except for B2 where an anomaly is observed, and for concrete materials, penetration loss increases sharply with a corresponding rise in frequency [56].

Generally, results revealed that the penetration losses of 17.0dB and 13.8dB obtained from building B1 at 900 and 1800MHz, respectively are higher than those of buildings B2 and B3 (as shown in Tables 1 and 2). Perhaps, this is due to the heavy masonry work on the building, and the fact that penetration loss is dependent on the building wall type. In addition, the loss of concrete with embedded steel rod could be very high when compared with buildings constructed with hollow blocks.

Furthermore, the heavy concrete structure is more compact in comparison with the gold-coated and the glassy buildings. The porous nature of the block building with glass cover ensures that radio waves penetrate better, thereby limiting the penetration loss. The conductive nature of the embedded steel rods (which tends to cause a reflection of the electromagnetic waves and lowers the forward energy, which aids easy penetration through the wall) may have also contributed to the higher loss occurring in the building with heavy concrete walls.

There were variations with the results of this study when compared with related reports as shown in Table 3. This may be due to the origination of radio waves from different base stations at different locations, which must have entered the tested buildings from different directions, as the direction of incident wave is known to influence penetration loss. The limitation of the measurements equipment and other dynamic factors may also contribute to the variations in the values of the penetration losses.

5. CONCLUSION

Measurements campaign assessed the behaviour of radio waves transmission into three distinct multi-storey buildings at different locations. Results indicate that the signal statistics within the investigated multi-storey buildings can be represented in the form of small-scale signal variations characterized by multipath superimposed on large-scale variations. The small-scale variations assume the Rayleigh distribution pattern whereas the large-scale variations depict lognormal distribution, having standard deviations relative to the conditions of transmission. The results reported in this study will ease the development of novel and robust building penetration loss models that would best predict radio coverage into and within multi-storey buildings with greater accuracy. Network providers could leverage on these models to further improve on radio coverage in high-rise buildings, especially in densely populated environments. This will further help to improve on the current quality of service, and enhance user experience. Future works would investigate propagation pattern into multi-floored buildings at different radio frequency bands such as LTE at 2300MHz and mmWave at 28, 38, and 74 GHz. Furthermore, focus could be directed towards the determination of the path loss exponent n, which characterizes how rapidly fading occurs in the tested high-rise buildings.

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