Calibrating the Standard Path Loss Model for Urban Environments using Field Measurements and Geospatial Data

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Abstract— **Path loss model is essential to achieving a successful cellular network planning and deployment. Despite the benefits derived from models that have become standard and are widely adopted, the actual applicability of these models depends on the local ambient characteristics of the environment. This means that environments that substantially differ from those used to create the models will not be adequately characterized, and so the resulting cellular planning fails to some extent. Therefore, the models used may substantially benefit from calibration to ensure fitness with the actual measurements collected over a given area. This paper presents a calibration procedure based on the Standard Propagation Model (SPM), and applies to the 900 MHz and 1800 MHz bands. In particular, signal strength data were collected along four routes in residential areas, and the results were then processed using the ATOLL network planning tool. Overall, we find that, after a proper calibration, the SPM provides a much better fitness, achieving average Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and Standard Deviation (SDE) values of 5.40 dB, 6.90 dB and 4.29 dB, respectively, which are significantly better than the reference values without calibration (18.32 dB, 21.55 dB and 11.34 dB, respectively).**

Index Terms— **standard propagation model; path loss; received signal strength; digital cellular network; ATOLL.**

I. Introduction

THE phenomenon of electromagnetic wave (EM) propagation through space introduced additional modeling complexity for telecommunication systems due to mobility support requirements. Additionally, the radio channel used by the Global System for Mobile Communications (GSM) and the Digital Cellular Systems (DCS) also experiences signal propagation in Non-Line of Sight (NLOS). Specifically, at the frequency bands of 900 MHz and 1800 MHz, propagation mechanisms occur through phenomena including reflection, scattering, refraction, polarization and diffraction of EM waves, over and around the edges and surfaces of the obstacles and obstructions within the propagation environment. This causes multiple copies of the transmitted signal reaching the mobile station from different directions, and with varying time delays. Hence, the radio channel is a multipath propagation channel [1]. The propagation paths are of different amplitudes, phases, path lengths, and angles of arrival. Consequently, the received signal strength varies significantly with the location of the mobile receiver in a very complex manner. Therefore, the radio channel is considered a random and linear time-varying channel [1].

Multipath propagation characteristics usually cause the transmitted signals to experience fading. The mobile radio channel is also highly susceptible to noise, interference and data corruption. In fact, the vulnerability of the mobile radio channel to both signal fading and interference has made efficient radio network planning a vital part of the pre-deployment process of cellular systems. Thus, cellular network operators and vendors have acknowledged the need for an efficient network providing a better Quality of Service (QoS) through a systematic design process. This highlights the importance of an adequate radio network planning & optimization [2].

The reliability of the radio network planning for optimal network coverage largely depends on the accuracy of the path loss prediction models included in the network planning tools adopted, as these will show the non-linear relationship between the Received Signal Strength Level (RSSL) and the distances between the BTS and the mobile station, given the necessary radio network parameters. This way, the accuracy of the propagation prediction models becomes essential to correctly determine the best possible sites for the Base Transceiver Stations (BTSs) that conform the radio access network.

Previously, efforts have been made [3-7] to evaluate the suitability of various empirical path loss models for different propagation terrains in Nigeria. The findings of these research works highlight that the prediction results of traditional path loss models do not match, in general, the field measurement data collected on local terrains. In fact, for our particular target region, which is the city of Lagos in Nigeria, we find that these models lack accuracy when used for radio network planning purposes. This occurs because

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the performance of the communications system depends on network parameters whose values are predetermined by the system engineer, and also by environmental parameters over which the network planners have no control, thus requiring a proper calibration.

Model calibration is a process where an existing path prediction model is tuned (or adjusted) to accurately fit the actual measurements collected over the part of the network already deployed. This process is targeted at improving the degree of accuracy of the model so as to truly represent the actual signal propagation behavior of the target environment [2].

The statistical calibration approach is perhaps the most widely used method to achieve model calibration. It is based on the modification of the coefficients of the propagation prediction models in order to achieve the reference behavior. Notice that these coefficients are the parameters that have been found, through statistical analysis, to be the ones responsible for the relationship of the models with the values to be predicted [2]. Statistical calibration implicitly takes all the environmental factors into account regardless of whether they can be separately recognized. The accuracy of the approach depends not only on the accuracy of the collection procedures of the field measurement data, but also on the similarities between the environment under study and the environment where the measurements were taken. Nevertheless, the statistical calibration method is widely used because of its simplicity, flexibility and computational efficiency. With the recent development of automated received signal measurement devices that include the logging of Global Positioning System (GPS) information, it has become relatively easy to record large amounts of measurement data in a straightforward manner.

This research work is aimed at improving the prediction accuracy of the Standard Propagation Model (SPM) to the specific case of Lagos, Nigeria, by adequately accounting for the effect of local geographic features within the path loss predictions for urban propagation environments. Radio network data were collected over DCS 1800 in four different locations (A, B, C, and D). Locations A and B represent a dense suburban area, while locations C and D represent dense urban areas.

In this work we focused on the RSSL, in particular those values collected at locations A and C. The RSSL data of BTS B and BTS D were used for model verification to ensure good generalization, meaning that these data sets that were not included in the calibration process. Regarding the model calibration process, it was automated using the ATOLL network planning tool.

The rest of the paper is summarized as follows: Section II provides an overview of SPM; Section III presents the materials and methodology employed in this work; Section IV presents and discusses the results of the experiments; finally, Section V concludes the paper by summarizing the main findings.

II. Standard Path Loss Model

SPM was developed based on the Hata path loss formulas [8, 9]. This empirical model is suitable for path loss predictions in the 150–1500 MHz frequency band. It determines the large-scale fading of received signal strength over a distance range of 1–20 km. Therefore, it is appropriate for mobile channel characterization of popular cellular technologies such as GSM [8].

The received signal strength is given by equation (1):

$$P_r = P_t - \{K_1 + K_2 \log(d) + K_3 \log(h_t) + K_4 . Diffraction\,Loss + K_5\, log(d). log(h_t) + K_6 . h_r + K_7 \log(h_r) + K_{clutter} . f_{clutter} + K_{hill}\} \quad (1)$$

The model parameters are defined as follows:

P_r = Received power in dBm
P_t = Transmitted power (EIRP) in dBm
K_1 = Constant offset in dB
K_2 = Multiplying factor for $\log(d)$
d = Separation distance (in meters)
K_3 = Multiplying factor for $\log(h_t)$
h_t = Effective transmitter antenna height (in meters)
K_4 = Multiplying factor for diffraction calculation
K_5 = Multiplying factor for $log(d). log(h_t)$
K_6 = Multiplying factor for h_r
K_7 = Multiplying factor for $\log(h_r)$
h_r = Effective mobile receiver antenna height (in meters)
$K_{clutter}$ = Multiplying factor for $f_{clutter}$
$f_{clutter}$ = Average of the weighted losses due to clutter
K_{hill} = Corrective factor for hilly regions

The Hata path loss model is represented by equation (2) [8]:

$$PL\,(dB) = A_1 + A_2 log(f) + A_3 log(h_t) + [B_1 + B_2 log(h_t) + B_3 . h_t][log(d)] - a(h_r) - C_{clutter} \quad (2)$$

The definition of parameters is as follows:

A_1 ... B_3: Hata parameters
f : Frequency in MHz
h_t: Effective transmitter antenna height in metres
d : Separation distance in km
h_r : Mobile receiver height in meters
$a(h_r)$: Mobile receiver antenna height correction factor in dB
$C_{clutter}$: Clutter correction function

Although distance is usually expressed in *km* in Hata formulas, SPM accepts distance values in meters. The generic values of the Hata model parameters are the ones stated below:

$$A_1 = \begin{cases} 69.55 & for\ 900\ MHz \\ 46.30 & for\ 1800\ MHz \end{cases}$$
$$A_2 = \begin{cases} 26.16 & for\ 900\ MHz \\ 33.90 & for\ 1800\ MHz \end{cases}$$
$$A_3 = -13.82$$
$$B_1 = 44.90$$
$$B_2 = -6.55$$
$$B_3 = 0$$

Therefore, the path loss model for GSM technologies that operate in the 900 MHz band becomes equation (3)

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$$PL\ (dB) = 69.55 + 26.16\ log(f) - 13.82\ log(h_t) + [44.9 - 6.55\ log(h_t)][log(d)] - a(h_r) - C_{clutter} \quad (3)$$

On the other hand, the path loss predictions for the DCS 1800 counterpart is given by equation (4) [9]:

$$PL\ (dB) = 46.3 + 33.9\ log(f) - 13.82\ log(h_t) + [44.9 - 6.55\ log(h_t)][log(d)] - a(h_r) - C_{clutter} \quad (4)$$

SPM ignored the effects of diffraction, clutter, and terrain to produce equation (4). It assumed that appropriate settings of A_1 and K_1, which account for only one clutter class, will cater for the influence of these external factors on signal propagation. The correction function for the mobile receiver antenna height was also ignored for $h_r \leq 1.5$ m since it has negligible values for an average mobile antenna height. The resulting path loss model is given in equation (5):

$$PL\ (dB) = A_1 + A_2 log(f) + A_3 log(h_t) + [B_1 + B_2 log(h_t)][log(d)] \quad (5)$$

The SPM formula can be further reduced to equation (6):

$$PL\ (dB) = K_1 + K_2 \log(d) + K_3 \log(h_t) + K_5\ log(d).log(h_t) + K_6.h_r + K_7 \log(h_r) \quad (6)$$

Presenting the reduced Hata equation as a model which accepts distance input in *m* as in SPM, we have equation (7):

$$PL\ (dB) = A_1 + A_2 log(f) - 3B_1 + [A_3 - 3B_2][log(h_t)] + B_1 log(d) + B_2 log(h_t).log(d) \quad (7)$$

Equating the coefficients of equations (6) and (7):

$$K_1 = A_1 + A_2 log(f) - 3B_1$$
$$K_2 = B_1$$
$$K_1 = A_3 - 3B_2$$
$$K_5 = B_2$$
$$K_6 = K_7 = 0$$

Hence, the SPM mathematical representation of the GSM 900 mobile channel is given by equation (8):

$$PL\ (dB) = 12.5 + 44.9\ log(d) + 5.83\ log(h_t) - [6.55\ log(d).log(h_t)] \quad (8)$$

For DCS 1800, we have equation (9):

$$PL\ (dB) = 22 + 44.9\ log(d) + 5.83\ log(h_t) - [6.55\ log(d).log(h_t)] \quad (9)$$

III. Materials and Methods

A. Field Measurement Propagation Environment

Lagos is a popular urban center in Nigeria, located on coordinates 6°31'28.22" N, 3°22'45.17" E. The metropolis has a land area of 385.9 square miles. 90.75% of the land area is categorized as urban [10]. It is composed of high-rise residential apartments built close to each other. Areas within the urban perimeter, with building height above 40 m, were classified as dense urban. Dense residential areas, with a mix of residential and commercial zones, and building heights of between 2–4 floors, were regarded as dense suburban.

Extensive field campaigns were conducted in the dense suburban and dense urban areas of Lagos. These measurements were carried out under good climatic conditions.

B. Selection of Base Transceiver Stations

In each of the dense suburban and dense urban areas under investigation, two commercial Base Transceiver Stations (BTSs) operating at the DCS 1800 MHz band were selected. This was done to sufficiently represent the clutter classes within the propagation environments. Selected BTSs have good Radio Frequency (RF) clearance such that they are not obstructed in any direction. The antennas on the sites of the live radio access networks under study represent the full variation of antenna heights (typically 20 m to 50 m) in the areas. The terrains within the network coverage areas are representative of the entire area covered by the measurement campaigns. Also, good vehicular accessibility to site locations were considered for a smooth test drive. This work accounted for the influence of the propagation environments.

C. Drive Test Routes

The transmitters were located and the best driving routes identified were planned. Distances covered by the drive routes are considered long enough to allow the noise floor of the receiver to be reached. A distance of approximately 2 km was planned for the suburban areas, while a distance of 1 km was planned for the urban areas. The routes were laid out such that an equal number of samples was taken in both near-field and far-field scenarios. Clutter classes outside the scope of our study were carefully mapped out. Even profiles between the transmitter and the receiver were monitored. Extraneous measurement points were detected and filtered using ATOLL. The maps used in planning the survey routes were of the same projection system (WGS84 UTM Zone 32N) as the scanned maps in ATOLL. This allowed the validation of the survey routes.

D. Field Measurement Data Collection

The data collection process was performed with the use of the Transmission Evaluation and Monitoring System (TEMS) network performance investigation software [11]. TEMS Investigation has data collection, real-time network data analysis, and post-data processing capabilities. This network testing software ran on an Intel Core i5-3210MCPU@2.50GHz speed with 4 GB RAM and 64-bit Windows 7 operating system. A TEMS mobile station, the software USB dongle, and a Garmin Global Positioning System (GPS) were connected to the laptop. The whole set-up was carefully placed in a vehicle, and the vehicle was driven at an average speed of 40 km/h. This speed was maintained to minimize Doppler effects.

A single frequency channel was monitored at a time using the Broadcast Control Channel (BCCH). The drive test mode enabled data collection while the inspection and analysis were done in replay mode. Collected data were recorded in log files for post-field analysis.

Radio network data were collected over DCS 1800 in four different locations (A, B, C, and D) in Lagos, Nigeria. Locations A and B represent a dense suburban area, while locations C and D represent dense urban areas. This work focused on the Received Signal Strength Level (RSSL). The model calibration was performed with RSSL data collected in locations A and C. The RSSL data of BTS B and BTS D were used for model verification to ensure good generalization for data sets that were not included in the calibration process.

E. *Model Calibration*

Automatic model calibration was performed in ATOLL. The result of this tuning process is a purely mathematical solution.

Geographic data used in this work include Digital Terrain Model (DTM), clutter classes, and clutter heights. Scanned maps and online maps were used for visualization. DTM describes the elevation of the ground over the sea level, while the clutter classes geodata file describes the land cover or land use. Each pixel in the clutter class file contains a code which corresponds to a clutter class. Clutter height maps described the altitude of the clutter over the DTM with one altitude defined per pixel. This offered more precise information than defining an altitude per clutter class because, in a clutter height file, it is possible to have different heights within a single clutter class. The actual physical objects were depicted by the scanned maps. They were used to provide a precise background for other objects, but have no effect on calculations. Online maps displayed various types of maps directly by specifying their server URLs.

In ATOLL, the transmission equipment used in the radio network is modelled along with the characteristics which influence the network performance. The field measurement data obtained were sorted and imported into ATOLL. The transmitter parameters (latitude, longitude, height, elevation, transmit power, antenna gain, and the azimuth) were properly configured in the ATOLL radio network planning tool [11]. The BTS transmit power and the gain of the directional antenna were 43 dBm and 18 dBi, respectively. The cable and combiner losses were also taken into consideration. The heights of the transmitters vary between 20 m and 36 m. ATOLL also allows network radio network planners to create and set the antenna parameters. These were imported into the ATOLL environment.

SPM is one of the path loss models available in ATOLL, and so we used to obtain the coefficients of the SPM expression. 70% of the data collected were used for calibration, while the remaining were used for result verification. The calibration process was aimed at reducing the mean error and the standard deviation of the path loss model.

In this work, both the automatic calibration method and the assisted calibration method were engaged. The model was first calibrated using the automatic calibration process. The results were then fine-tuned using the assisted calibration approach. It is worth mentioning that the actual quality of the calibrated path loss model depends largely on the quality of the field measurement data used in the calibration process.

F. *Model Performance Evaluation*

Two different approaches were employed to evaluate the performance of the model calibration. First, the model results were appraised based on the path loss data used for calibration. Second, the accuracy of the calibrated SPM was adjudged based on the results of path loss predictions on verification sites (locations B and D for dense suburban and dense urban, respectively). The performance of the SPM and the calibrated SPM were compared using the following statistical performance metrics: Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Standard Deviation (SDE). The mathematical expressions of these metrics are given by equation (10)-(12).

$$MAE = \frac{1}{n}\sum_{i=1}^{n}\left|RSSL_i^m - RSSL_i^p\right| \quad (10)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(RSSL_i^m - RSSL_i^p\right)^2} \quad (11)$$

$$SDE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\left|RSSL_i^m - RSSL_i^p\right| - \mu\right)^2} \quad (12)$$

where μ is the mean prediction error in dB.

IV. Results

Generally, the RSSL decreased as the distance between the BTS and the mobile station increased, as expected. The RSSL varies randomly between -43 dBm and -100 dBm. The calibration process significantly changed the model parameters, as shown in Table 1. In fact, the calibrated SPM accounted for additional path losses of 25 dB in the urban environments. The resulting calibrated SPM formula is clearly expressed in equation (13).

Table 1: Calibration Result of SPM for Urban Environments

Parameter	Description	Before	After
H_t Method	-	Abs Spot H_t	Slope at receiver
Diffraction Method	-	Deygout	Deygout
K_1	-	22	51.4
K_2	log (d)	44.9	20
K_3	log (h_t)	5.83	20
K_4	Diffraction	1	0
K_5	log (d) .log (h_t)	-6.55	-4.97
Additional Losses	Clutter Losses	0	25

$$PL\ (dB) = 51.4 + 20\ log(d) + 20\ log(h_t) - [4.97\ log(d).log(h_t)] \quad (13)$$

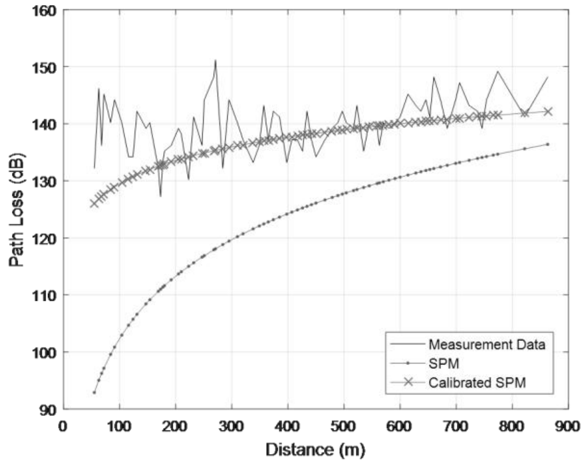

Figure 1: Path Loss Predictions in Location A (Dense Suburban)

The calibrated SPM provided better fits to field measured path loss data when applied to all four cases under investigation. Figure 1 and 2 shows the non-linear relationship between the path loss and the distance between the transmitter and the receiver in the two selected dense suburban areas. Figure 3 and 4 shows a similar relationship for data collected in selected dense urban areas.

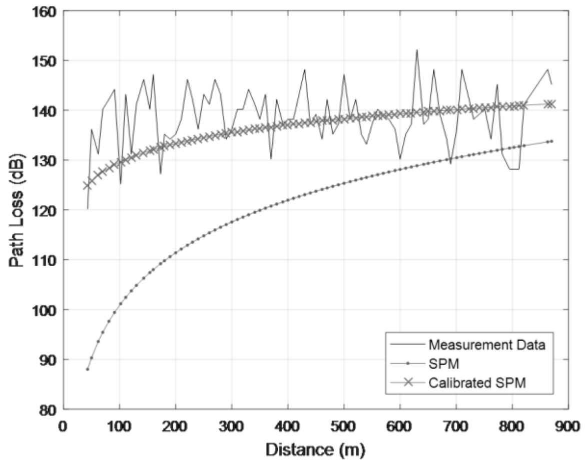

Figure 2: Path Loss Predictions in Location B (Dense Suburban)

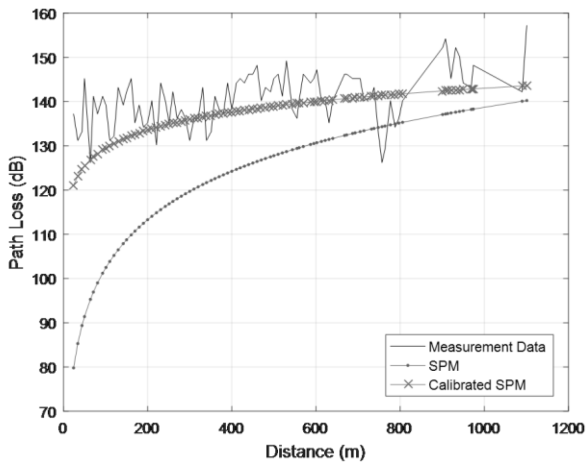

Figure 3: Path Loss Predictions in Location C (Dense Urban)

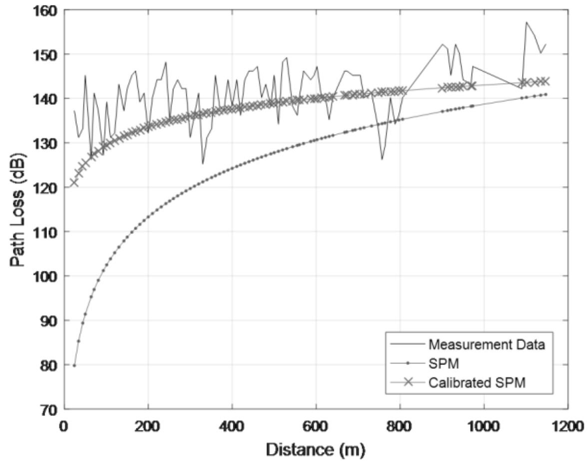

Figure 4: Path Loss Predictions in Location D (Dense Urban)

The results of the model performance evaluation in dense suburban areas are presented in Table 2. From this table, we can observe that the calibrated SPM outperforms the conventional SPM across all the performance metrics applied in this study. On calibration sites, the new model reduces the MAE, RMSE, and SD values by 13.79 dB, 14.99 dB, and 6.41 dB, respectively. Similarly, better performance metrics are recorded when the calibrated SPM was applied to verification sites. The reduction in MAE, RMSE, and SDE values is of 13.04 dB, 14.78 dB, and 7.09 dB, respectively.

Table 2: Performance Evaluation of the Model Calibration for Dense Suburban areas.

	Location A (Calibration Site)		**Location B (Verification Site)**	
	SPM	**Calibrated SPM**	**SPM**	**Calibrated SPM**
Mean Absolute Error (MAE) (dB)	18.28	4.49	18.60	5.56
Root Mean Square Error (RMSE) (dB)	21.16	6.17	21.81	7.03
Standard Deviation (SDE) (dB)	10.65	4.24	11.40	4.31

On the other hand, the results of the model performance evaluation in dense urban areas are presented in Table 3. From this table, we can observe that the calibrated SPM outperforms the conventional SPM across all the performance metrics applied in this investigation. On calibration sites, the new model reduces the MAE, RMSE, and SDE values by 12.66 dB, 14.53 dB, and 7.22 dB, respectively. Similarly, better performance metrics are recorded when the calibrated SPM is applied to verification sites. The reduction in MAE, RMSE, and SDE values is of 12.19 dB, 14.29 dB, and 7.50 dB, respectively.

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Table 3: Performance Evaluation of the Model Calibration for Dense Urban areas.

	Location C (Calibration Site)		Location D (Verification Site)	
	SPM	**Calibrated SPM**	**SPM**	**Calibrated SPM**
Mean Absolute Error (MAE) (dB)	18.15	5.49	18.26	6.07
Root Mean Square Error (RMSE) (dB)	21.49	6.96	21.75	7.46
Standard Deviation (SDE) (dB)	11.51	4.29	11.83	4.33

V. Discussions and Conclusion

Path Loss propagation models are the key to successful coverage planning and deployment of radio access networks. The applicability of these models is constrained by local environment features such as the terrain elevation, clutter cover, and other ambient characteristics, making it difficult to use a single model for all types of locations. Therefore, there is a need for the continual calibration of the model to ensure fitness with the actual measurement data collected over a given area. In this paper we present a calibration procedure of the Standard Propagation Model (SPM), commonly referred to as the Hata Model. The optimization was conducted for the 900 MHz and 1800 MHz bands within the ATOLL network planning tool. Driving tests were carried out to collect signal strength data along predefined routes in residential areas of Lagos, Nigeria. Our finding shows that the calibrated SPM provides a significantly better fitness with the measured data collected. The average MAE, RMSE and SDE across all the routes was of 5.40, 6.90 and 4.29, respectively. These values are quite lower when compared with default values obtained with SPM (18.32 dB, 21.55 dB and 11.34 dB, respectively). In detail, we found that the calibrated SPM accounted for additional path losses of 25 dB in the urban environments. Thus, a generic and optimized model equation was provided for path loss prediction in the study area.

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