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In-depth study of path loss and coverage areas of selected GSM signals over a typical Sudan Savannah environment

Bolanle T. Abe[1], Akinsanmi Akinbolati[2*]
[1,2]Department of Electrical Engineering, Tshwane University of Technology, eMalahleni Campus, 1034, South Africa; abebt@tut.ac.za (B.T.A); AkinbolatiA@tut.ac.za (A.A.)

Abstract: Studies on path loss and coverage areas are essential in GSM technology to ensure Quality of Service (QoS). This research was conducted on MTN and 9-Mobile 4G signals over Zaria City, Nigeria, using the COST-231 model. The measurement campaign was conducted using a drive test; Line of Sight (LOS) from the Transmitting Base Station(s) (TBS), Received Signal Strengths (RSS), elevation, longitude, and latitudes of data points were recorded. Data were collected at 100 m intervals along two routes from the TBS up to 1 km and then at 1 km intervals up to 5 km. The Spectrum Analyzer was used to measure the RSS while the GPS was used to capture the geographic parameters (latitude, longitude, elevation) for the data points. Path losses for the two routes and channels were evaluated with digital maps of coverage areas generated using GIS. Other key findings show strong RSS from TBS until about 4.0 km for both signals; beyond this range, RSS reduces drastically, approaching the sensitivity value. For GSM 4G, an Inter-TBS link of around 4 km is suggested for the study area and any similar city to improve QoS. Furthermore, a strong negative correlation coefficient (R) of -0.83 (mean value) exists between path loss and RSS, while a low R of -0.09 exists between it and elevation. A low level of signal enhancement by elevation is observed with R of +0.06 between it and RSS, and a low negative R of -0.09 between elevation and path loss. The COST-231 was optimized by generating a modified model (ZCOST-231) that incorporates some of the location-based transmission parameters. The optimized model presents valuable applications in the accurate prediction of path losses for GSM 3&4 G channels and Radio Link Design (RLD) over the study areas or any similar Sudan Savannah environment of Africa. The overall findings will significantly benefit radio link appraisal of existing GSM channels, power budgeting, and coverage area assessment in a typical Sudan Savannah City of Africa.
Keywords: *Coverage areas, GSM signals, Pathloss, Quality of service (QoS), Radio-link-design, Sudan savannah.*

1. Introduction

Radio communication simply means 'wireless' communication. It is the type of communication (sending signals or information from one point to the other) that does not require connecting wires directly from the transmitter to the receiver [1]. Instead, it is the transmission of the radio signal from the transmitter through space (atmosphere) to the receiver. A transmitter is an electronic device that processes, modulates, and amplifies a radio frequency energy and transmits it via the transmitting antenna [1]. A receiver is a radio signal (RF) processing device that periodically scans a given frequency range by performing a frequency ramp on the local oscillator [2] and delivers the inherent message. The signal of interest (data, voice, visual/picture, audio, etc) is generated at the source, processed (filtered, amplified, modulated) and transmitted through the transmitter via the transmitting antenna in the case of terrestrial transmission [1]. In the case of satellite communication, the signal is processed at the source and transmitted using the uplink satellite earth station, which beams the signal to the spacecraft/space station. The space station beams the signal back to the Earth with its coverage area equal to the transmitting

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* Correspondence: AkinbolatiA@tut.ac.za

satellite's footprint. Radio communications include radio and television broadcasting, telephone, walkie-talkie, internet, data transmission, microwave link, etc. Path loss and coverage areas assessment are critical in wireless communications. This helps communication operators and regulatory government agencies appraise existing communication networks and make good link designs and power budgets for future networks to ensure efficient service delivery. This is why studies on coverage areas, path loss assessment, prediction, modelling and investigation of error margins of existing models for suitability in other environments find relevance in wireless communication research. Thus, the need for radio scientists and engineers to conduct studies in this regard becomes imperative [3]. This is the problem, and there is a shortage of such related studies in the selected City. This study will provide the quantitative attenuation profile for the studied GSM networks (MTN&9 Mobile) so that the service providers will be guided towards ensuring quality of service for their subscribers. Friis [4] introduced the Friis or free space equation, a propagation model to predict wireless signals' received power in unobstructed space. However, this model is limited in applicability to other environments beyond free space. Okumura, et al. [5] conducted extensive field strength measurements in Tokyo, Japan, resulting in an empirical formula for predicting power loss in urban areas. This formula considered factors like distance, transmission frequency, and antenna heights. Hata [6] modified Okumura's model to create the Okumura-Hata model, which is widely accepted over the UHF channel [7]. This model considers antenna height, frequency, and environmental conditions and is suitable for predicting path loss in urban, suburban, and rural environments. Other models were also proposed, such as those by COST- 231 [8] and Walfisch and Bertoni [9]. The authors in Sarkar, et al. [10] introduced numerical methods as a third alternative for predicting path losses alongside empirical and site-specific approaches. While empirical models' applications are simple, site-specific models offer greater accuracy at the cost of requiring specific information about the area. The authors in Ajewole, et al. [11] examined UHF signal strength and its relationship with precipitation in Nigeria. A high negative correlation coefficient was established between UHF TV signal and precipitation. The authors in Prasad and Ahmad [12] conducted field strength measurements over the Indian subcontinent but didn't propose specific models based on the results. Armoogum, et al. [13] studied propagation models in digital television broadcast network design using Mauritius as a case study. They found that Okumura-Hata and COST-231 models gave better agreement. Nisirat, et al. [14] presented a novel terrain correction factor for the Okumura-Hata model, specifically at 900 MHz in Jordan. RMSE shows the predicted improvement by up to 3 dB compared to the Hata suburban model in most areas under study. Authors in Akinbolati and Ajewole [15] worked on investigating path loss and modelling over digital terrestrial television channels in Nigeria. The research areas covered Ikorodu-Lagos, Kaduna, and Katsina. Calculations and comparisons were based on Hata models. Modified- Hata models that incorporate some tropospheric parameters were proposed. The work in [1] analyzed UHF signal strength variations in Ondo State, Nigeria. The results show that elevation above ground level is crucial for UHF transmission and reception (location of transmitters, transmitting antenna's height, directivity and gain). Akinbolati, et al. [16] worked on the assessment of the error margin of some path loss models over the Digital Terrestrial Television (DTTV) channel using the Star Times DTTV channel within the Katsina metropolis. The predicted COST-231 and ECC models are preferred for path loss prediction over the study areas and channels. Abiodun, et al. [17] evaluated path loss prediction models in microcellular environments of Ekiti State, Nigeria. They proposed a two-slope model that exhibited good agreement with measured values. The study concluded that the COST 231-Hata model could predict path loss in mobile microcell coverage.

The focus of this study included the determination of the propagation curves that are useful in the prediction of coverage areas and assessments of the GSM signals. The evaluation of path loss (micro and macro cells) using the widely acceptable COST-231 model and the degree of relationship between path loss and the transmission variables was also carried out. The study also generated digital contour maps of the coverage areas of the two GSM service providers, providing functional parameters and solutions that will enhance QoS over the study area. Furthermore, the Modified COST-231 Model (ZCOST-231

Model) that incorporates selected location-based transmission parameters of the environment was developed.

2. Theoretical Analysis

2.1. Path Loss Over the Radio Channel

Path loss in radio communication signifies the decline in the intensity of a signal, brought about by an array of elements such as terrain characteristics and atmospheric circumstances encountered along the transmission route or channel. This diminishment can be gauged by the disparity in decibels between the power at the point of transmission and the power upon reception, as expressed in (1)

$$P_L\ (\mathrm{dB}) = 10Log\frac{P_t}{P_r} \quad (1)$$

where P_t *and* P_r are the transmitted and received power, respectively.

This phenomenon illustrates the reduction in signal magnitude due to several factors, including the dissipation of energy as radio waves travel through open space, the reflection of surfaces, the bending of waves around obstacles, and the scattering of waves due to objects in the environment, amongst others [18]. Path loss refers to the typical reduction in signal strength encountered by a transmitted Radio Frequency (RF) signal during its propagation. This reduction becomes evident as the signal covers a distance equivalent to several wavelengths and ultimately arrives at the receiver. Path loss is helpful in the calculation of the link budget of communication systems. It serves as a tool for forecasting and enhancing coverage areas in radio communication [19].

Furthermore, it finds utility in anticipating spatial areas for TV and accommodating secondary users, as highlighted by Faruk, et al. [20]. Path loss prediction encompasses the capability to accurately predict the attenuation of a radio signal as it traverses a communication channel. This entails the computation of the power reduction that occurs from the point of transmission, usually at a base station, to the reception point at the receiver. Path loss prediction quantifies the power dissipation the transmitted signal encounters during its journey between the origin and destination.

Diverse prediction models have been formulated for wireless channels. Some are established through statistical analyses of field measurements, while others are developed analytically, considering factors like diffraction effects. These models are equipped with specific parameters tailored to achieve reasonable accuracy in their predictions.

2.2. Path Loss Prediction Models

Path loss prediction involves accurately forecasting the impact of channel features on a radio signal, precisely the attenuation effect. It refers to accurately estimating the attenuation impact caused by the propagation channel on a radio signal. It involves predicting, modelling, or calculating the power losses between the transmission at the base station and the reception at the receiver. In wireless communication, various models have been developed to predict path loss. Some are derived statistically based on field measurements, while others are formulated analytically, considering the consequences of diffraction.

Friis Transmission Equation or Free Space Model (FSPL): The Friis transmission equation [4] is a streamlined model for predicting path loss in radio wave propagation. Equation 2 is used to estimate path loss (L) between two isotropic antennas in an unobstructed space.

$$L = 20\log_{10}\left(\frac{4\pi d}{\lambda}\right) \quad (2)$$

Where is the distance (Line of Sight, LOS) from a transmitter in meters, and λ is the wavelength in m. Plane Earth Model: The free space model simplifies by not accounting for the impact of ground reflection on signal propagation. When a radio wave travels over the ground, a portion of its energy is reflected due to the presence of the ground surface, eventually reaching the receiver. In this scenario, significant factors include the heights of the transmission and reception apparatus, the separation distance between them, and the specific attributes of the ground's reflective properties. The path loss equation in the context of the plane earth model is expressed as follows [18]:

$$L_{PE} = 40log_{10}(d) - 20log_{10}(h_1) - 20log_{10}(h_2) \quad (3)$$

Where the distance between the transmitting and receiving antenna in (km), h_1 and h_2 (m) are the height of the transmitting base station and receiving antenna, respectively.

Okumura Model: Okumura's widely employed macroscopic propagation model was formulated during the mid-1960s following comprehensive investigations conducted within Tokyo and its environs. This model was tailored to function within the frequency spectrum from 200 to 1920 MHz, predominantly catering to urban propagation scenarios [5]. Okumura's model posits that the loss of signal strength between the transmitting and receiving ends within a terrestrial propagation environment can be effectively represented by:

$$L_{50\%} = L_{FSL} + A_{mu}(f,d) - G(h_{re}) - G_{area} \quad (4)$$

Where:

$L_{50\%}$ is the median (i.e., 50th percentile) value of propagation path loss expressed in dB. L_{FSL} is the free space propagation loss in dB. A_{mu} (f,d) is the essential median attenuation relative to free space in dB. $G(h_{te})$ and $G(h_{re})$ are the base station and receiver antenna height gain correction factor in dB, respectively, and G_{AREA} is the gain dB due to the type of environment.

Hata [6]: The Hata Model for Urban Areas, also called the Hata [6] model, represents an evolved iteration of the Okumura Model and is the most widely adopted radio frequency propagation model. This model is a robust tool for projecting the behaviors of cellular transmission in densely constructed regions [13]. The Hata model comprises distinct variants tailored for specific scenarios: one for sub-urban contexts and another for open areas. With a primary focus on terrestrial microwave communication, the model furnishes insights into the cumulative path loss experienced along a transmission link. The Hata model accommodates micro and macro cell outdoor prediction, rendering it a valuable tool for forecasting radio wave propagation across various scales. Its suitability extends to point-to-point and broadcast transmissions, making it versatile for multiple communication scenarios.

Okumura-Hata models for urban and suburban areas are formulated as follows:

$$L_{(Urban)} = [69.55 + 26.16logF - 13.82logh_b - \alpha(h_m) + 44.9 - 6.55logh_b)logd]\ (dB) \quad (5a)$$

For a large city with the wave frequency of transmission f ≥ 400 MHz,

$$\alpha(h_m) = 3.2[\log(11.75h_m)]^2 - 4.97 \quad (5b)$$

Where $L_{(urban)}$ is the path loss in Urban Areas in dB, h_b is the height of the base station antenna in meters, h_m is the height of the mobile station antenna in meters, f is the frequency of transmission in MHz, $\alpha(h_m)$ the antenna height correction factor and d, is the line-of-sight distance between the base and mobile stations in (km). By specifications, the Okumura-Hata model has the following range for optimal results: Carrier frequency: 150MHz ≤ f ≤ 1500MHz; Base station height: 30m ≤ h_b ≤ 200m; Mobile station height: 1m ≤ h_m ≤ 10m; Distance between mobile and base station: 1km ≤ d ≤ 20km [14, 16]. For suburban areas, it is given by:

$$L_{(sub-urban)} = (L_{(urban)} - 2[\log\ (\frac{f}{28})^2 - 5.4\ (dB) \quad (5c)$$

The European Committee for Scientific and Technical Research Team (COST-231) Model: The COST-231 Hata model, also recognized as the Personal Communication System (PCS) Extension, is a prevalent tool for forecasting path loss within mobile wireless systems. Crafted by the European Co-operative for Scientific and Technical Research Team, this model has garnered substantial recognition in wireless communications. It represents an expanded version of the Okumura-Hata model, encompassing an extensive frequency spectrum from 0.5 to 2 GHz and suitable for medium to small cities [21]. It is a widely acceptable model for path loss and coverage assessment over wireless communication channels. The model's formulation is as presented in (6):

$$L_{(dB)} = \begin{array}{l} 46.3 + 33.9\, log_{10}(f) - 13.82\, log_{10}(h_b) + \\ [44.9 - 6.55\, log_{10}(h_b)]\, log_{10}(d) - \alpha(h_m) + C_m \end{array} \quad (6)$$

$a(h_m)$ is the receiver antenna correction factor as presented in (5b), while $C_m = 0\ dB$ for medium-sized city and suburban areas and $3\ dB$ for urban areas.

The parameters h_m h_b f_c are presented in Table 1.

This model was used for computation in this study. Its choice was because most results of similar studies in Nigeria predicted the COST- 231 model as the most preferred to be used on 3G/4G frequencies [22-28]. Internationally, COST-231 is gaining acceptability for path loss prediction over microcell outdoor prediction [29, 30].

3. Materials and Methods

The study was conducted in the urban city of Zaria, Nigeria (Latitude 11.085° N and Longitude 7.720° E). In terms of total land area, Zaria covers about 563 km² with a population of 736,000 people as of 2006 [31]. Zaria has a tropical savannah climate with warm weather year-round, a wet season lasting from April to September, and a drier season from October to March. The experimental study was conducted on two GSM operators: MTN and 9-Mobile signals. Table 1 presents the transmission characteristics of experimental stations.

Table 1.
Transmission characteristics of the experimental Transmitting Base stations.

S/N	Parameters	MTN Transmitting Base Station (TBS)	9-Mobile Transmitting Base Station (TBS)
1	Base station geographical coordinates	(Lat.11.108°N, Long. 7.718° E)	(Lat.11.158°N, Long. 7.652° E)
2	Base station rated power/transmitted output	36 dBm	36 dBm
3	Transmitting antenna's gain	17 dBi	17 dBi
4	TBS frequency (f_c)	2115 MHz	2175 MHz
5	Height of receiving/mobile antenna, h_m	1.5 m	1.5 m
6	Height of transmitting/ base station antenna, h_b	55 m	55 m
7	GSM band/ Technology	(2100-2300 MHz)/3-4G	(2100-2300 MHz)/3-4G

3.1. Method of Data Collection

The Measurement of RSS from the Transmitting Base Stations (TBS) under investigation was conducted along various routes, with the transmitting station logged and served as the reference point throughout the measurement period using drive test protocol. Measurements were taken along two routes at 100 m intervals up to 1 km (microcell) and 1 km intervals up to 5 km (macro cell). The mean of the routes was taken and used for the study. Figures 1 and 2 present the Spectrum Analyzer (BK Precision2658A; 5 kHz-8.5 GHz) and GPS used to measure the RSS and geographic coordinates of data points, respectively. Figure 3 is the digital map indicating data location points.

Figure 1.
Spectrum Analyzer Used for RSS.

Figure 2.
GPS Garmin map 78s.

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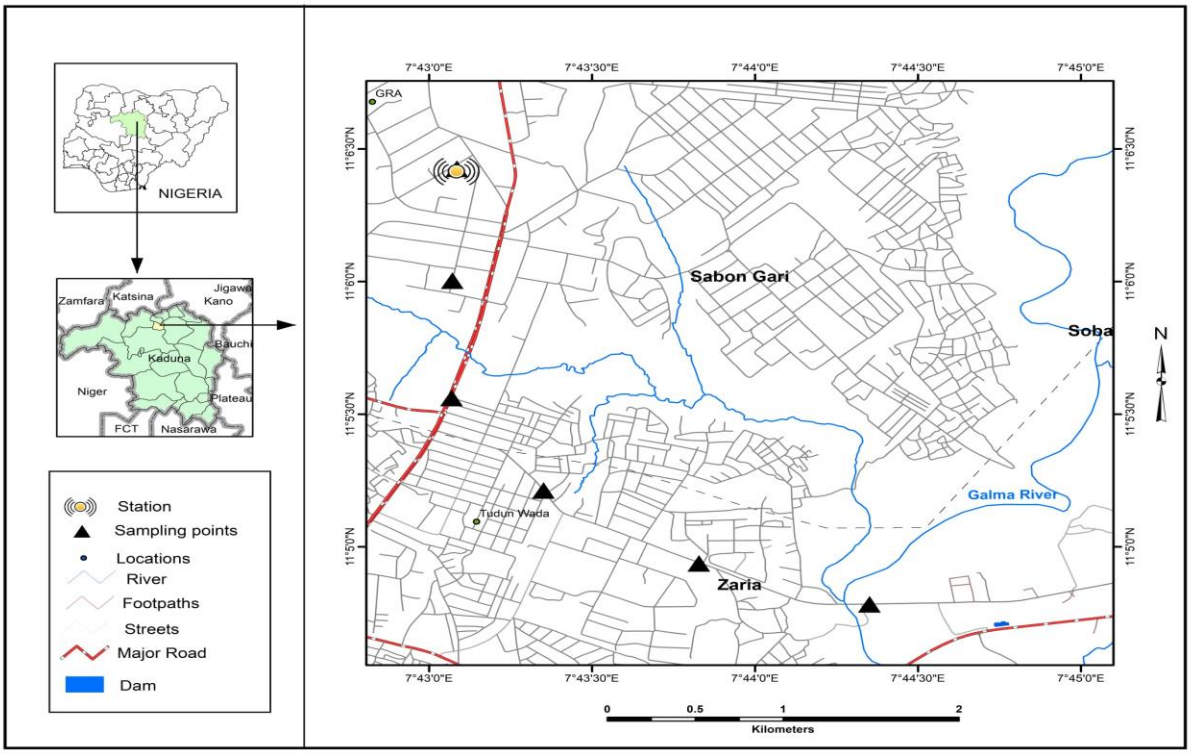

Figure 3.
The Digital Map indicating sampling points for the macro cell over Zaria City

3.2. Empirical and Statistical Tools

The European Union Committee for Scientific and Technical Research Team model [32] a widely acceptable model for path loss prediction over the 3/4G-GSM channel, as presented in (6), was used for computation in this study. Karl Pearson's Product Moment Correlation Coefficient for continuous data, presented in (7), was used to determine the degree of relationship between the variables and path loss, where x and y are the variables of interest.

$$r = \frac{n\sum xy - \sum x \sum y}{\sqrt{\left[n\sum x^2 - \left(\sum x\right)^2\right]\left[n\sum y^2 \left(\sum y\right)2\right]}} = \frac{\text{cov}\,XY}{\sqrt{\text{var}\,X.\text{var}\,Y}} \tag{7}$$

4. Results and Discussions

4.1. Spatial Distribution of RSS And Evaluated Pathloss of the Two Signals

Tables 2 and 3 present the overall average of measured parameters (during the fieldwork) and the computed path loss based on the COST-231 model over the study areas for MTN and 9-mobile signals, respectively. From Tables 2 and 3, the mean values of the elevation, RSS, and path loss are 656.53 m, -75.47 dBm, and 133.841 dB, respectively, for MTN and 683 m, -71.68 dBm, and 132.175 dB, for 9-mobile networks.

Table 2.
Measured parameters and evaluated Path Loss for MTN 4 G.

S/N	LOS from TBS (km)	Lat. (°N)	Long. (°E)	Elevation (m)	RSS1 (dBm)	RSS2 (dBm)	Mean RSS (dBm)	Path loss (dB)
1	0.0	11.108	7.718	662	-55.89	-57.25	-56.57	100.305
2	0.1	11.065	7.431	639	-62.98	-64.03	-63.505	102.764
3	0.2	11.064	7.431	638	-75.52	-72.41	-73.965	113.212
4	0.3	11.156	7.719	637	-74.43	-78.3	-76.365	119.324
5	0.4	11.105	7.718	637	-73.82	-74.77	-74.295	123.659
6	0.5	11.104	7.719	634	-79.81	-80.75	-80.28	127.023
7	0.6	11.103	7.186	633	-77.7	-76.97	-77.335	129.771
8	0.7	11.103	7.718	932	-76.21	-75.63	-75.92	132.095
9	0.8	11.101	7.718	631	-78.79	-79.75	-79.27	134.107
10	0.9	11.100	7.718	630	-73.92	-76.56	-75.24	135.883
11	1.0	11.099	7.718	628	-75.84	-71.81	-73.825	137.471
12	2.0	11.093	7.718	636	-76.91	-73.95	-75.43	147.918
13	3.0	11.087	7.722	643	-79.01	-79.16	-79.085	154.029
14	4.0	11.082	7.732	640	-84.99	-86.2	-85.595	158.366
15	5.0	11.080	7.739	628	-85.94	-84.91	-85.425	161.729
		Mean		656.53	-75.45	-75.45	-75.47	133.841

Table 3.
Measured parameters and evaluated Path Loss for 9-Mobile 4G.

S/N	LOS from TBS (km)	Lat. (°N)	Long. (°E)	Elevation (m)	RSS1 (dBm)	RSS2 (dBm)	Mean RSS (dBm)	Path loss (dB)
1	0.0	11.158	7.652	683	-51.34	-54.8	-53.07	99.520
2	0.1	11.159	7.651	684	-59.65	-53.69	-56.67	103.175
3	0.2	11.159	7.650	685	-62.87	-64.74	-63.805	113.622
4	0.3	11.159	7.650	684	-68.91	-72.87	-70.89	119.734
5	0.4	11.160	7.649	686	-73.68	-70.94	-72.31	124.070
6	0.5	11.160	7.648	685	-73.76	-75.86	-74.81	127.433
7	0.6	11.161	7.648	685	-64.56	-64.61	-64.585	130.181
8	0.7	11.161	7.648	684	-70.37	-67.81	-69.09	132.505
9	0.8	11.161	7.646	685	-78.82	-78.22	-78.52	134.518
10	0.9	11.161	7.645	685	-73.32	-74.75	-74.035	136.293
11	1.0	11.162	7.644	684	-74.23	-72.49	-73.36	137.881
12	2.0	11.150	7.666	679	-76.16	-76.42	-76.29	148.329
13	3.0	11.146	7.673	676	-79.61	-78.58	-79.095	154.440
14	4.0	11.141	7.681	682	-82.82	-83.23	-83.025	158.776
15	5.0	11.138	7.689	678	-85.00	-86.32	-85.66	162.140
		Mean		683.01	-71.67	-71.69	-71.68	132.175

4.2. Propagation Curves of The Signals and Digital Map Indicating Coverages

Figure 4 shows the propagation curves of the two signals over the distance investigated. It could be observed that both signals depreciated gradually with distance. However, within the micro-cell (0-1km), the signals depreciated and improved again between 1-3 km of the macro cell and later depreciated around 4 km. The reason could be that line-of-sight was not adequately established between the transmitting antenna and the receiver in the micro-cell for this location. Perhaps it was due to some high-rise terrestrial features close to the TBS. From 1-3 km, LOS could now be established appropriately, thus improvement in the signal received. Beyond 3 km from the base station, both signals depreciated. The effects of wave divergence and the line-of-sight distance are manifesting. It can equally be observed that both signals from the two operators are nearly the same in their propagation trajectory. This indicates that the two operators operate within the same transmission characteristics permitted by the Communication's regulator. One of the critical applications of this result is that an approximate distance of 4 km could be used for inter-TBS-link design in the study area or any similar city. This assertion is based on the propagation curves and the standard quality of 4G presented in Table 4 [33]. The signal is considered fair when RSS ≤ -85 dBm and poor when RSS ≤ -86 dBm. Here, the distance corresponding to -86 dBm is 4 km. The sensitivity value for a 4G signal at which no signal will be received is RSS ≤ -120 dBm.

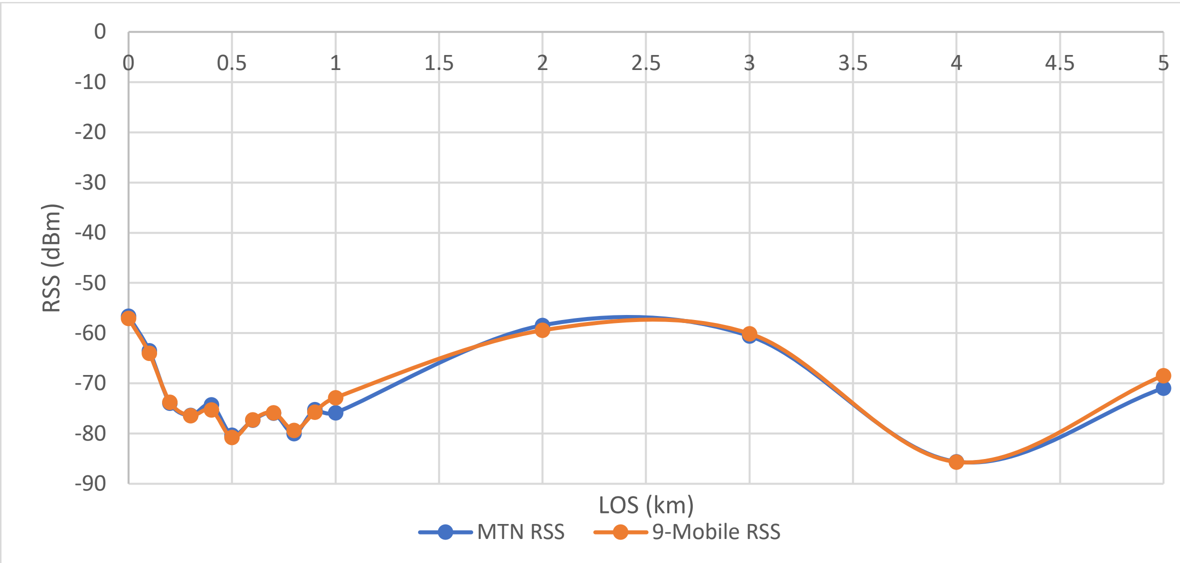

Figure 4.
Propagation curves for the two 4G-GSM signals.

Table 4.
Classification of signal qualities according to 3G and 4G GSM [33].

S/N	RSSI 3G (dBm)	RSSI 4G (dBm)	Signal Strengths Quality	Description
1	≥ -70	≥ -65	Excellent	Strong signal with maximum data speed
2	-86 ≤ RSS ≤ -70	-75 ≤ RSS ≤ -65	Good	Strong signal with good data speed
3	-100 ≤ RSS ≤ -86	-85 ≤ RSS ≤ -75	Fair	Fair, fast and reliable data speed could be achieved, but drop-out is possible
4	-110 ≤ RSS ≤ -100	-119 ≤ RSS ≤ -85	Poor	Performance drops drastically
5	RSS≤ -110	RSS ≤ -120	No signal	Sensitivity value (Disconnection)

The collected data were interpolated using GIS software to create contour maps. Kriging interpolation techniques generated smooth, continuous surfaces representing the different grades of coverage-areas across the city. The resulting maps show regions of poor, weak, and strong signal strengths, this will find valuable applications for planning signal enhancement and the choice of quality of reception by GSM operators and subscribers. Figures 5 and 6 present the digital map for MTN and 9-mobile coverage profiles, respectively.

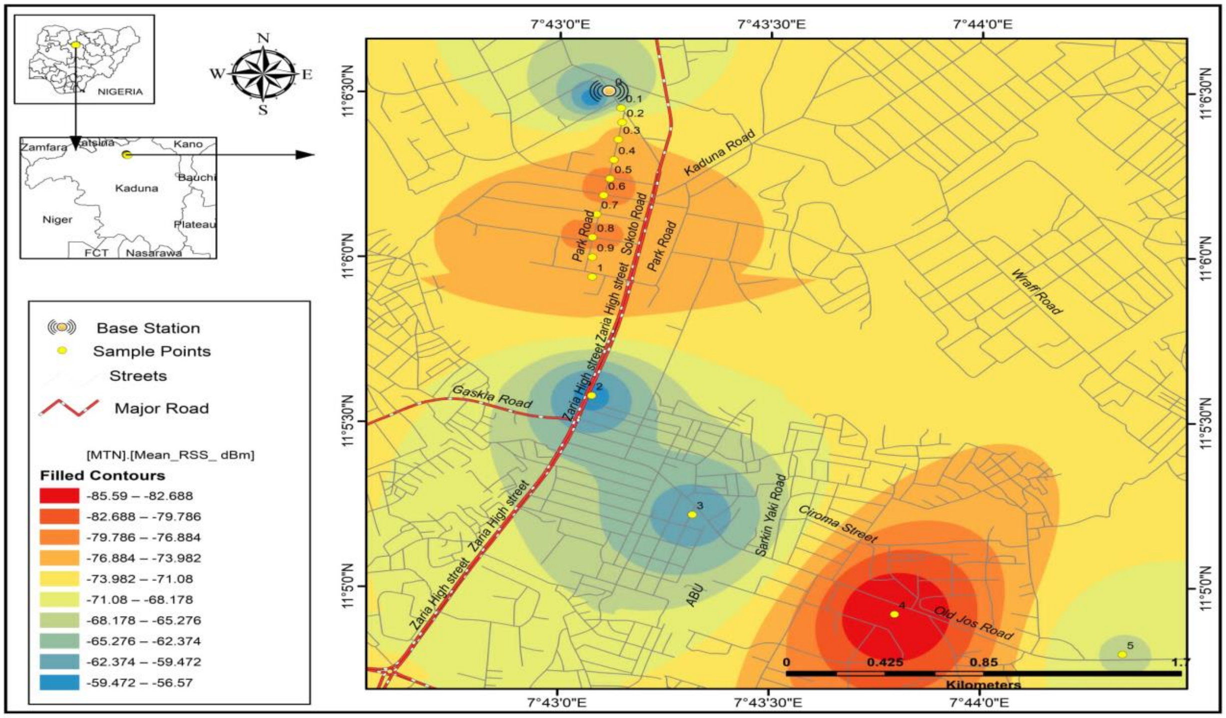

Figure 5.
Digital Map for MTN 4 G indicating the coverage profiles.

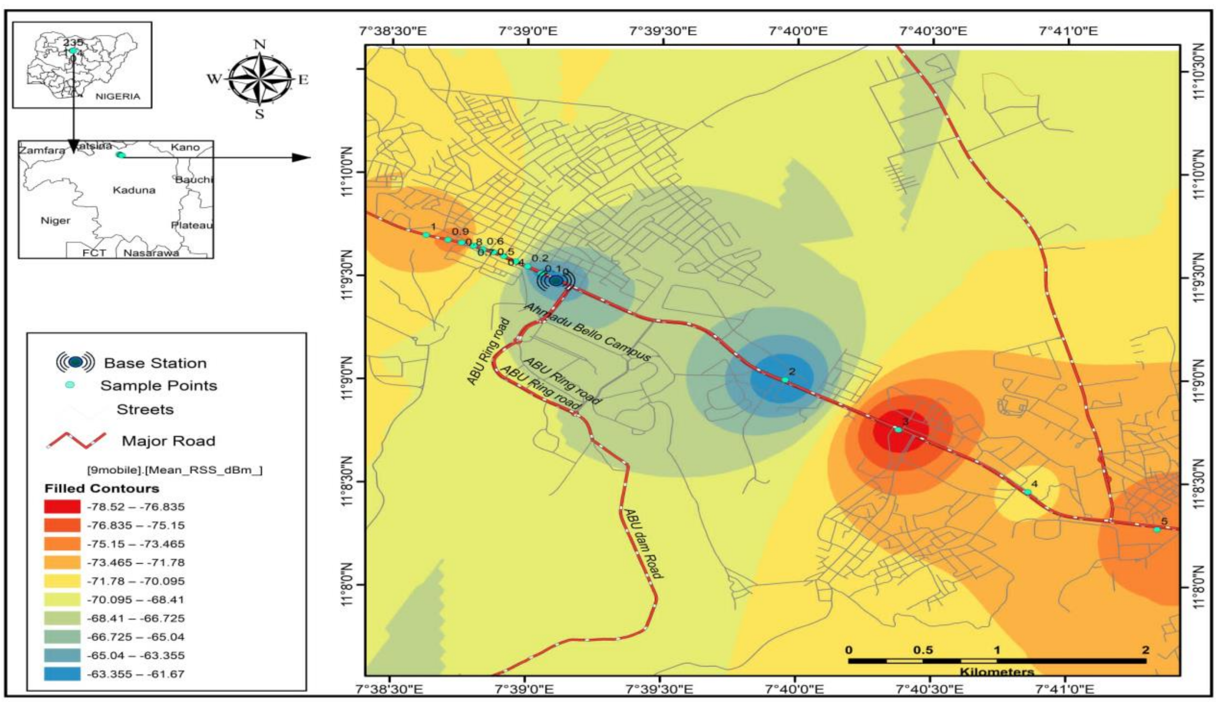

Figure 6.
Digital Map for 9mobile 4 G indicating the coverage profile.

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4.3. The Path Loss Assessment and Modeling over the Study Area

For the path loss analysis, Figure 7 depicts the comparison plots of the path loss associated with the two signals with distance. Mean values of 133.841 and 132.175 dB were obtained for MTN and 9-Mobile, respectively, while an overall mean of 133.008 dB was determined. The path-loss follows the conventional pattern of increase as distance increases, and the two are nearly the same. The path loss profiles justify the need for another transmitting base station at around 4 km intervals to ensure reception quality over the study locations. Figs. 8 and 9 present the variation of RSS and Path loss with LOS for MTN and 9-Mobile signals, respectively. It could be clearly seen that as the transmitter-receiver distance (LOS) increases, RSS reduces, and path loss increases for both signals.

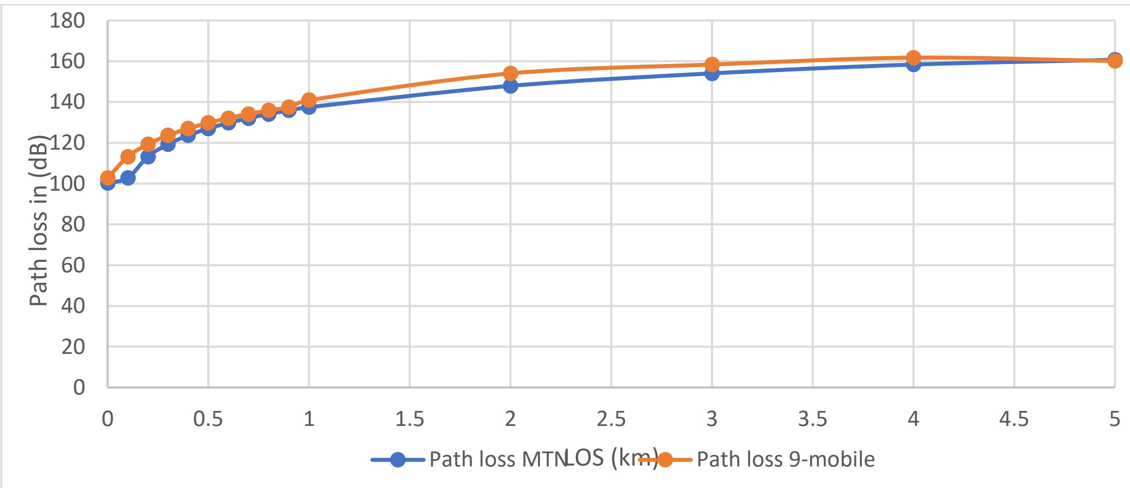

Figure 7.
Variation of Path Loss over distance for both MTN and 9-mobile GSM Networks.

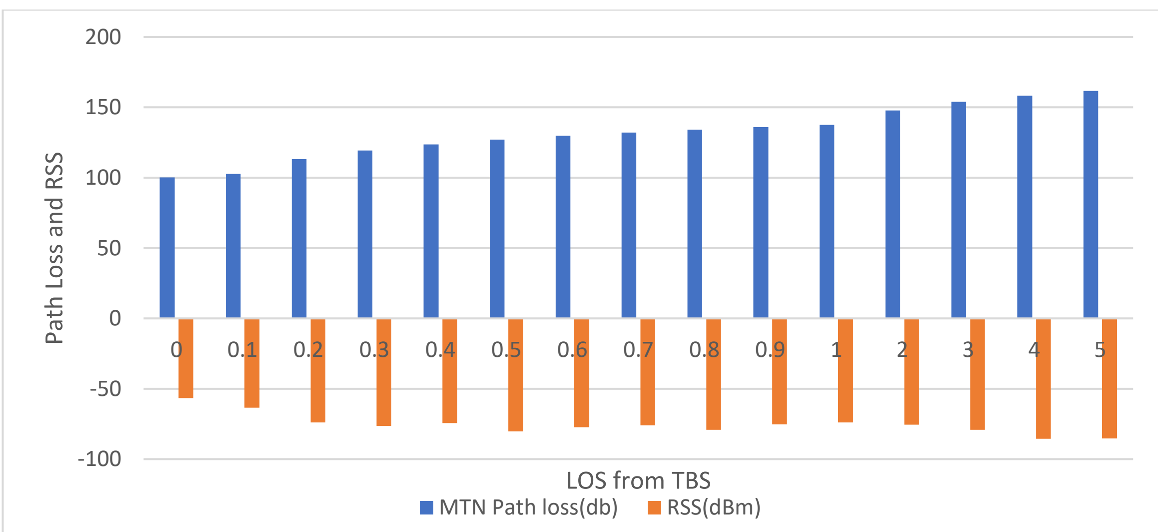

Figure 8.
Variation of Path Loss and RSS over distance for MTN signal.

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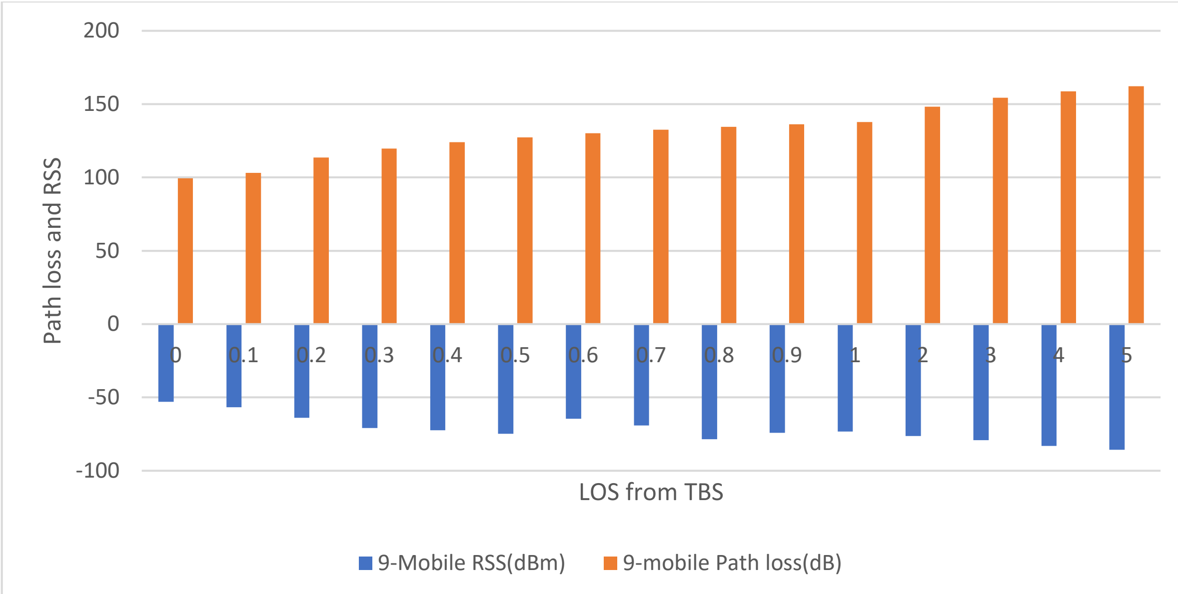

Figure 9.
Variation of Path Loss and RSS over distance for 9-Mobile signal.

4.4. The Correlation Coefficient Between Path Loss and Some Location-Based Parameters

The degree of relationship between path loss and some of the location-based transmission parameters (LOS, Elevation and RSS) for MTN and 9-Mobile were determined and presented in Tables 5 and 6, respectively. Correlation coefficient (R) of +0.88, -0.05 and -0.83 exists between path loss and LOS, elevation and RSS, respectively, for MTN. Similarly, correlation coefficient (R) of +0.95, -0.13 and -0.83 exists between path loss and LOS, elevation and RSS, respectively, for 9-mobile. This shows a strong positive R of **0.92** (mean value) between GSM Path loss and LOS, meaning that path loss increases by about 92% over the Sudan Savannah City as LOS increases. This result will serve as a good guide for wireless link design over the study area.

Table 5.
Degree of the relationship between path loss and some location-based transmission parameters for MTN 4 G.

	LOS (km)	Elevation (m)	RSS (dBm)	Path Loss (dB)
LOS (km)	1			
Elevation (m)	-0.13	1		
RSS (dBm)	-0.66	0.06	1	
Path Loss (dB)	0.88	-0.05	-0.83	1

Table 6.
Degree of the relationship between path loss and some location-based transmission parameters for 9-Mobile 4 G.

	LOS (km)	Elevation (m)	RSS (dBm)	Path Loss (dB)
LOS (km)	1			
Elevation (m)	-0.13	1		
RSS (dBm)	-0.87	0.05	1	
Path Loss (dB)	0.95	-0.13	-0.83	1

In addition, a strong negative R of -0.83 (mean value) exists between path loss and RSS, while a low R of -0.09 exists between it and elevation. The implication is that the higher the RSS, the lower the path loss. A low level of signal enhancement by elevation is observed in this study, with a low +0.06 (mean value) between it and RSS and a low negative R of -0.09 between elevation and path loss. The study area has a balanced land terrain, with an averagely high elevation with mean values of 669.5 m and a low deviation from one location to the other.

4.5. Optimization of COST-231 Model by Incorporating Local Transmission Parameters of the Environment

COST-231 model was optimized by generating a local path loss model that incorporates some of the location-based transmission parameters to serve as enhanced alternative to the COST-231 model, a linear regression was generated, using the path loss as the dependent variable and the parameters of RSS, LOS, and Elevation as independent variables. Thus, a modified COST-231 model was obtained. Table 8 presents the parameters used for modelling.

Table 8.
Mean values of dependent and independent variables used for modelling.

S/N	Path Loss (dB)	LOS (km)	RSS (dB)	Elevation (m)
MTN				
1.	102.76	0.1	- 63.50	639
2.	127.50	0.5	- 80.28	634
3.	137.471	1.0	-73.825	628
4.	147.918	2.0	-75.43	636
5.	154.029	3.0	-79.085	643
6.	158.366	4.0	-85.595	640
7.	161.729	5.0	-85.425	628
9 – Mobile				
1.	103.17	0.1	-56.67	684
2.	127.43	0.5	-74.81	685
3.	137.881	1.0	-73.36	684
4.	148.329	2.0	-76.29	679
5.	154.440	3.0	-79.095	676
6.	158.776	4.0	-83.025	682
7.	162.140	5.0	-85.66	678

Equation 8 represents the general format of the expected path loss model developed in this study. It is the Modified COST -231 Path Loss (ZCOST-231Model) for Zaria City. Equations (9) and (10) represent the actual models for MTN and 9-mobile with coefficients of multiple determination (R^2) of 0.82 and 0.88, respectively. Equation (11) represents the mean model for the two, which is the real predicted model for the environment with R^2= 0.85. This indicates a strong and reliable relationship between the dependent and independent variables. This model (s) can be used for the accurate prediction of path loss of 3G ang 4G signals in the study area or any environment with similar terrain and climate.

$$\mathrm{ZCOST} - 231(\mathrm{dB}) = ß1LOS + ß2RSS + ß3Elev + k \quad (8)$$

Where:

- LOS (km) is Tx-Rx distance
- RSS (dBm) is Received Signal Strength
- Elev(m) is elevation
- β1, β1 and β3 are the model coefficients
- k is a constant

$$\mathrm{ZCOST} - 231(\mathrm{dB}) = 10.915LOS - 0.098RSS + 0.619Elev - 283.721k \quad (9)$$

$$\mathrm{ZCOST} - 231(\mathrm{dB}) = 9.335LOS - 0.132RSS - 1.416Elev + 1074 \quad (10)$$

$$\mathrm{ZCOST} - 231(\mathrm{dB}) = 10.125LOS - 0.115RSS - 0.399Elev + 395.15 \quad (11)$$

5. Conclusion

Path loss and coverage areas' assessment of 4G-9-mobile and MTN signals along a 5 km distance over Zaria, Nigeria, have been investigated successfully. The Received Signal Strength (RSS) and geographic parameters such as latitude, longitude, elevation, and line of Sight (LOS) for data points were measured using Spectrum Analyzer and Global Positioning System (GPS), respectively. Measurements were carried out along two routes within the range of 0 – 5 km (Line of Sight) from the transmitter's base station. These parameters were used to analyze path loss and generate the digital map for the coverage areas. The digital maps show regions of poor, weak, and strong signal strengths that are useful for planning signal enhancement and quality of reception by the GSM operators and subscribers, respectively. Other key findings show that strong RSS were recorded from the base station till about 4.0 km for both signals. Beyond these distances, the RSS reduces drastically, approaching the sensitivity value with greater path loss values recorded. The implication is that the signal quality would not always be reliable beyond this distance from the TBS. For GSM 3G and 4G, an inter-transmitting base station (TBS) link of around 4 km is suggested in the study area and in any environment with similar terrain and climate to improve signal quality. In addition, the mean values of the elevation, overall RSS and path loss are 656.53 m, -75.47 dBm and 133.841 dB, respectively, for MTN and 683 m, -71.68 dBm and 132.175 dB, for 9-mobile networks. In addition, a strong negative R of -0.83 (mean value) exists between path loss and RSS, while a low R of -0.09 exists between it and elevation. The implication is that the higher the RSS, the lower the path loss. A low level of signal enhancement by elevation is observed in this study, with a low +0.06 (mean value) between it and RSS and a low negative R of -0.09 between elevation and path loss. Furthermore, the Modified COST-231 Model, which incorporates selected location-based transmission parameters of the environment ZCOST-231 Model, was developed. This model presents valuable application in the accurate prediction of path losses and GSM Radio-Link-Design over the study areas or any similar Sudan Savannah environment of Africa. The overall findings of this study will be of great benefit at ensuring accurate appraisal, power budgeting, and coverage areas' assessment by all stakeholders, to ensure the quality of services of GSM transmission and reception in the study areas and in similar environments in general.

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The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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