Empirical model of cellular signal propagation loss for smart grid environment

Okumbor N. Anthony^a, Okonkwo O. R^b

^a Department of Computer Science, Delta State Polytechnic, Otefe-Oghara, Nigeria

^b Department of Computer Science, Nnamdi Azikiwe University, Awka Nigeria.

Abstract

Wireless communication technologies in smart grid covers a variety of environments such as indoor, outdoor, and electric-power-system facilities. The characteristics of wireless and power line communication channel in smart grid networks are usually in terms of several parameters such as propagation (path) loss and attenuation, time dispersion and so on. Today, a number of empirical propagation prediction models for mobile radio communication systems are available in the literature. However, the accuracy of these models suffers when they are used in an environment other than that for which they have been developed. In this research work, the log-normal shadowing method was used to model mobile cellular signal propagation loss in a smart grid environment. The data used for this analysis were gathered between 2012 and 2013 in a suburban area cellular link in Niger-delta Nigeria. The measured data were applied to some propagation loss model equation and analyzed using linear regression method to obtain the link parameters such as the propagation loss exponent $n = 3.38$, the standard deviation $\sigma = 9.2\text{dB}$, to formulate the model equation $PL (dB) = 75.16 + 33.8\log d$ for the design of a mobile radio link in the test bed areas. The knowledge shared here will assist researchers apply the concept to other geographical environments, it will assist system engineers determine signal strength in error and as efficient propagation loss prediction tool thus improve the quality of wireless signal and also the model can be use as validation tool where measurement is done in different geographic areas.

Keywords: Average signal level, linear regression, log-normal shadowing, propagation loss, models, radio link, smart grid

1. Introduction

The communication technologies in which smart grid communication infrastructure is envisioned to be built are likely to be wireless, power line communication Plc, fiber optic, Ethernet and so on. Among these, wireless and PLC (Power line communication) based solutions are attractive considering the cost of initial deployment. Wireless communication deployment in smart grid covers a variety of environments such as indoor, outdoor, and electric-power-system facilities.

Understanding of the communication channels and signal propagation characteristics in smart grid environment is necessary prior to the development of optimal communication solutions. However, being more favourable compared to other technologies, emphasis is to be given to wireless communication channels in this paper and their corresponding signal propagation characteristics. Therefore the characteristics of wireless and PLC channel in smart grid networks are usually in terms of several parameters such as propagation (path) loss and attenuation, time dispersion, time selectivity, amplitude statistics, and noise characteristics which are of vital importance considering the communication system performance; hence our objective here is to focus on the propagation loss modelling.

The mechanism that governs the signal propagation within wireless and power line communication channels is diverse, but they are characterized by reflection, refraction, path loss, fading, scattering and shadowing. Communication System engineers are generally concern with the application of two main

* Manuscript received April 15, 2016; revised October 20, 2016.

Corresponding author. Tel.: +234-08-056771010; E-mail address: aokumbor@yahoo.com

doi: 10.12720/sge.5.4.272-279

radio channel links. These channel links are the mobile radio link parameters and time dispersion nature of the channel. The mobile radio link parameters consist of the path loss exponent (n) and the standard deviation (σ). The Path loss exponent indicates the rate at which a signal depreciates with increase in distance while the standard deviation accounts for the random shadowing effects which occur over a large number of measurement locations which have the same transmitter-receiver separation, but have different levels of clutter on the propagation path. However, an accurate estimation of path loss is useful for predicting coverage areas of base stations, frequency assignments, and proper determination of electric field strength, interference analysis, handover optimization, and power level adjustments. In this paper, we present a practical seasonal measurement of signal strength over a wireless network in suburban town of Niger-Delta environment of Nigeria and determination of the signal attenuation by statistical analysis of measured data, using these parameters to develop a model that appropriates for certain geographical areas, that would assist system engineers anywhere in the world determine signal strength in error and efficient path loss prediction thus enhances proper network design to improve the quality of signal strength for transformation.

1.1. Background

A transmit signal goes through various distortions on its way to receiver in both wireless and PLC channels. A variety of parameters is employed while quantifying these distortions in communication channels. In wireless communications, the concept of path loss is used to capture how the power of the transmit signal varies as a function of distance. It is defined as the dB (decibel) value of the ratio of the transmit power to the received power. Presence of the obstacles between transmitter and receiver gives rise to random fluctuations of path loss called shadowing. Since variations due to path loss and shadowing take place over relatively large distances, these two variations are traditionally referred to as large-scale propagation effects by wireless communication community.

In propagation loss modelling, a parameter of n , which is called path loss exponent, is used to characterize how fast the signal attenuates with respect to the communication distance [1]. The *Path loss*, which represents signal attenuation as a positive quantity measured in dB, is defined as the difference (in dB) between the effective transmitted power and the received power, and may or may not include the effect of the antenna gains. The loss for the free space model when antenna gains are included is given by

$$20 \log \sqrt{\frac{4\pi f d}{c}} \quad (1a)$$

where π is constant, f is frequency, d is distance and c is the speed of light. When antenna gains are excluded, the antennas are assumed to have unity gain, and path loss is given by [2].

$$PL (dB) = 10 \log \frac{P_t}{P_r} = -10 \log \left[\frac{\lambda^2}{(4\pi)^2 d^2} \right] \quad (1b)$$

The Friis free space model is only a valid predictor for P_r for values of d which are in the far-field of the transmitting antenna. The far-field, or Fraunhofer region, of a transmitting antenna is defined as the region beyond the far-field distance d_f , which is related to the largest linear dimension of the transmitter antenna aperture and the carrier wavelength. The Fraunhofer distance is given by

$$d_f = \frac{2D^2}{\lambda}$$

where, D is the largest physical linear dimension of the antenna. Additionally, to be in the far-field region, d_f must satisfy

$$d_f \gg D$$

and

$$d_f \gg \lambda$$

Furthermore, it is clear that equation (1.a) does not hold for $d = 0$. For this reason, large-scale propagation models use a close-in distance, d_0 , as a known received power reference point. The received power, $P_r(d)$, at any distance $d > d_0$, may be related to P_r at d_0 . The value $P_r(d_0)$ may be predicted, or may be measured in the radio environment by taking the average received power at many points located at a close-in radial distance d_0 from the transmitter. The reference distance must be chosen such that it lies in the far-field region, that is, $d_0 \geq d_f$, and d_0 is chosen to be smaller than any practical distance used in the mobile communication system. Thus the received power in free space at a distance greater than d_0 is given by [3].

$$P_r(d) = P_r(d_0) \left(\frac{d_0}{d} \right)^2 \quad d \geq d_0 \geq d_f \quad (1c)$$

By using path loss models to estimate the received signal level as a function of distance, it becomes possible to predict the signal strength for a mobile communication system. A practical path loss estimation technique is presented in this work.

2. Log Distance Path Loss Model

Both theoretical and measurement-based propagation models indicate that average received signal power decreases logarithmically with distance, whether in outdoor or indoor radio channels. The average large-scale path loss for an arbitrary T-R separation is expressed as a function of distance by using a path loss exponent, n .

$$P_L(d) \propto \left(\frac{d}{d_0} \right)^n \quad (1d)$$

or

$$\hat{P}_L(dB) = \hat{P}_L(d_0) + 10n \log \left(\frac{d}{d_0} \right) \quad (1e)$$

where:

n is the path loss exponent, which indicates the rate at which the path loss increases with distance, d_0 is the close-in reference distance which is determined from measurement close to the transmitter, and d is the T-R separation distance. The bars in equation (1.d) and (1.e) denote the ensemble average of all possible path loss values for a given value of d . When plotted on a log-log scale, the modeled path loss is a straight line with a slope equal to $10n$ dB per decade. The value of n depends on the specific propagation environment. For example, in free space, n is equal to 2, and when obstructions are present, n will have a larger value. Table 1 lists typical path loss exponents obtained in various mobile radio environments [4].

Table 1. Path loss exponents for different environments

Environment	Path Loss Exponent, n
Free Space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

2.1. Link budget design using loss model

Most radio propagation models are derived using a combination of analytical and empirical methods. The empirical approach is based on curve fittings whereas analytical is based on a set of measured data. However, the validity of an empirical model at transmission frequencies or environment other than those used to derive the model can only be established by additional measured data in the new environment at the required frequency. The two practical mobile radio link design estimation techniques are: The log-distance path loss model and the log-normal shadowing model [5].

- The Log-distance path loss model:-This model indicates that the average receive signal power decreases logarithmically with distance; the average large-scale path loss for an arbitrary Transmitter-Receiver (T-R) separation is expressed as a function of distance(d) by using a path loss exponent(n) as in equation (1.e)
- The log-normal shadowing model: - The log-distance path loss model does not consider the fact that the surrounding environmental clutter may be vastly different at two difference locations having the same T-R separation. This leads to measured signals, which are vastly different from the average value predicted by equation (1.e).

The log-normal distribution describes the random shadowing effects which occur over a large number of measurement locations which have the same T-R separation, but have different levels of clutter on the propagation path. This phenomenon is referred to as log-normal shadowing. Log-normal shadowing implies that measured signal levels at a specific T-R separation have a Gaussian (normal) distribution about the distance-dependent mean of equation (1.e); where the measured signal levels have values in dB units. The standard deviation of the Gaussian distribution that describes the shadowing also has units in decibel dB. Measurement have shown that at any value of d , the path loss $PL(d)$ at a particular location is random and distributed log-normally (normal in dB) about the mean distance dependent value, that is:

$$PL(d)[dB] = \overline{PL}(d) + X_{\sigma} = \overline{PL}(d_0) + 10n \log\left(\frac{d}{d_0}\right) + X_{\sigma} \quad (2)$$

where X_{σ} is a zero-mean Gaussian distributed variable (in dB) with standard deviation σ also in dB. The close-reference distance d_0 , the path loss exponent (n), and the standard deviation (σ) statistically describe the path loss model for an arbitrary location having a specific T-R separation and this model may be used in computer simulation to provide received power levels for random locations in communication system design and analysis [5].

3. Materials and Method

Measurement provides that reports over the GSM (Global System for Mobile Communication) network are transmitted periodically (480ms) from the Mobile Terminal (MT) to the Base Transceiver Station (BTS) on the Stand Alone Common Channel (SACCH) assigned to each communication, according to which the measured received signal Level (RXLEVs) from the serving BTS and from a neighbor BTS (in situations requiring handover) are submitted [6]. In this work, RXLEV data or signal strength data measurement was done with data acquisition software. The losses in signal strength that do occur during transmission from the Transmitting antenna TX (Transmitter) to the Receiving antenna RX (Receiver) are given by the path loss, while the receive power is the result of the path loss phenomenon.

The Field test measurement in the environment explicitly, has the advantage of taking into account all the environmental effects. Using the NOKIA 1265 test phone systems operated in the active mode which was provided by the a network service provider, to measure received signal from the serving BTS, accompanied with an HP portable laptop and a GAMIN GPS (is a device for Global positioning system, receiver for accurate location), measurement survey was conducted on received signal strength propagation level, transmitting in 13000MHz. The system links compromises of five BTS site cells the links characteristics is shown in Table 1 and schematic diagram of measurement setup in Fig. 1.

Table 2. System link characteristics

System Parameters	Stations
Latitude and Longitude	05° 53.961' / 005° 41.139'
Antenna Type	Sectoral
BS Antenna Height	30m
Transmitting Frequency	13Ghz
Tx Pwr	15.0 (dBm)
Path Length	1km – 10km

The cells in the environment investigated have sectoral antenna placed at 30 meters above ground level.

Fig. 1. A schematic diagram of measurement setup.

3.1. Methods

The measurement setup is shown in Fig. 1. A NOKIA handset equipped with net-monitor software (Transmission Evaluation Monitoring System TEMS) was used to measure the received signal strength level (power received) at a distance (d) from the base station. The software comprises of a scale, which represent the power received in dBm. For every cell in the environment investigated, power received at a distance 1000 meters from the base station was measured. Power received at a distance interval of 1000 m from the initial test point up till the distance of 10km was measured. The global positioning system GPS was used to determine the geographic coordinate and distance. The field test was done between November 2012 and March 2013 in suburban area in Niger-Delta Nigeria using existing network and five BS cell sites selected in the locations of study. With the aid of testing tool (i.e. NOKIA mobile handset) running on the software mode, calls were initiated at each test point until it is established and the signal strength information sent over the air interface between the base and the mobile station were read and recorded with the laptop computer. For every site, received signal strength was measured at a reference distance of 1000m from the base station and at subsequent interval of 1000m up to 10000m. All measurements were taken in the mobile active mode and in three sectors of each base station. This was to ensure that the mobile phone was in constant touch with the base station. Averaging is done to compensate for variation in signal strength at a given location over time.

The distances of these measurements points from the reference point of the base station were recorded using the Global Positioning System (GPS). The GPS showed the T-R separation distances. The GPS was first switched on at the foot of the BTS tower; before the ENTER button was pressed. We moved away from the reference BTS, and when the radial distance on the GPS becomes equal to the desired close-in reference distance, the radio propagation simulator was switched on to take the readings. Table 3 showcases the results obtained.

4. Data Presentation

Following the measurement procedures above the average of power received signal level at different months cum sites was computed and presented in Table 3.

Table 3. Mean received power (Pr) at different months Nov 12 – March 13

Cells	T-R Separation(m)	Months Nov 2012 – March 2013				
		Nov (dBm)	Dec (dBm)	Jan (dBm)	Feb (dBm)	Mar (dBm)
Cell1	1000	-51.3	-51.9	-51.5	-50.0	-50.1
Cell2	2000	-54.7	-54.9	-54.7	-49.5	-53.2
Cell3	3000	-58.6	-58.8	-58.7	-53.5	-57.2
Cell4	5000	-66.7	-66.4	-66.5	-61.5	-65.6
Cell5	10000	-98.5	-98.3	-98.8	-98.2	-97.5

Table 3 show case the average power received during the dry season between November, 2012 and March, 2013. On determination of the propagation loss given that:

$$Pl = Pt - Pr$$

where

Pl is Path loss, Pt is Power Transmitted and Pr is Power Received. The signal loss is shown in Table 4.

Table 4 Propagation loss at different months Nov. 12 – March 13 ($Pl = Pt - Pr$)

Cells	T-R Separation (m)	$(Pl = Pt - Pr)$				
		Nov (dB)	Dec (dB)	Jan (dB)	Feb (dB)	Mar (dB)
Cell1	1000	66.3	66.9	66.5	65	65.1
Cell2	2000	69.7	69.9	69.7	64.5	68.2
Cell3	3000	73.6	73.8	73.7	68.5	72.2
Cell4	5000	81.7	81.4	81.5	76.5	80.6
Cell5	10000	113.5	113.3	113.8	113.2	112.5

From the Table 4 the reference path loss (d_0) for the months is Cell 1. At a distance of 1000m (1km), for the month of November is 66.3 dB. The value of path loss is obtained from subtracting power received (Pr) from power transmitted (Pt) which is 15.0 dBm as shown in Table 2 of System Link characteristics. The data of the propagation loss versus distance at different months was plotted using Matlab 7.0 program as shown in Fig. 2.

Fig. 2. Plot of propagation loss vs. Distance for the months.

The variation of signal strength loss in the months as showcase in the plot of Fig 2 showed a trend of signal degradation in the environment generally increasing with distance

4.1. Data analysis and result

Knowing that the close-in reference distance (d_0), the path loss exponent(n), and the standard deviation (σ) statistically describe the propagation loss model of an arbitrary location; to truly characterize propagation path loss for the environment (location), values should be establish for these parameters Pl , n , d_0 , and σ . The path loss exponent n , which characterizes propagation environment of the Niger-delta suburban, is obtained from the measured data by the method of linear regression (LR) analysis [7]. In the LR analysis the difference between the measured and predicted pathloss values are usually minimized in a mean-square sense. The sum of the squared errors is given by [7]:

$$e(n) = \sum_{i=1}^K \{P_L(d_i) - \hat{P}_L(d_i)\}^2 \quad (3)$$

where $P_L(d_i)$ is the measured path loss as shown in Table 5 at distance d_i and $\hat{P}_L(d_i)$ is the estimated path loss obtained using equation (1). The value of n which minimizes the mean square error $e(n)$ is obtained by equating the derivative of equation (3) to zero and solving for n .

Table 5. Measured path loss at various distance

T-R Distance (m)	Average Received Power (Pr) dBm	Power Transmitted (Pt) dBm	Path loss Pl (dB) = Pt - Pr
1000	-50.96	15	65.96
2000	-53.4	15	68.4
3000	-57.36	15	72.36
5000	-65.34	15	80.34
10000	-98.26	15	113.26

Table 6. Mean square error

Distance (m)	$Pl(dB)$	$\overline{Pl}(dB)$	$Pl - \overline{Pl}$	$(Pl - \overline{Pl})^2$
1000	65.96	65.96	0	0
2000	68.4	$65.96 + 3.01n$	$2.44 - 3.01n$	$9.0601n^2 - 14.689n + 5.9536$
3000	72.36	$65.96 + 4.77n$	$6.4 - 4.77n$	$22.7529n^2 - 61.056n + 40.96$
5000	80.34	$65.96 + 6.98n$	$14.38 - 6.98n$	$48.7204n^2 - 200.7448n + 206.7844$
10000	113.26	$65.96 + 10.0n$	$47.3 + 10.0n$	$100.0n^2 - 946n + 2237.29$

Evaluating the value of the mean square error from the Table 6 gives:

$$\sum_{i=1}^k (Pl - \hat{Pl})^2 = 180.5334n^2 - 1222.4898n + 2490.988 \quad (4)$$

Differentiating equation (4) and equating it to zero gives the value of n below:

$$\frac{d}{dn} (180.5334n^2 - 1222.4898n + 2490.988) = 0 \quad (5)$$

$$n = 3.38$$

Having derived the parameter of the propagation loss exponent n , therefore the standard deviation σ (dB) of random shadowing effect is computed using the relationship below (6):

$$\sigma(dB) = \sqrt{\sum_{i=1}^K [P_L(d_i) - \overline{P_L}(d_i)]^2 / K} \quad (6)$$

Recalling that $n=3.38$ and $k = 5$ i.e the number of sites cell investigated, therefore substituting these values in equation (6) gives the computed to be $\sigma[dB] = 9.2$ dB

Substituting the above calculated propagation path loss exponent n and the standard deviation σ into the log-normal shadowing model in equation (2) gives the model that describes the design parameters the mobile link in that location.

$$PL(dB) = 65.96 + 10(3.38) \log(d) + 9.2$$

$$PL(dB) = 75.16 + 33.8 \log d \quad (7)$$

The equation (7) models the radio propagation channel/link for the mobile system in the location the research was carried out. This model can also be used in computer simulation to provide received power levels for random locations in mobile communication system design and analysis.

5. Recommendation

The telecommunication companies in Europe, Africa and other continent whether based on wireless or CDMA technologies operating at radio frequency bands in smart grid environments, should apply the knowledge presented in this paper in radio link budget design and analysis so as to further improve their

services, thereby serving high quality signals to their teeming subscribers in sub/urban areas.

Researchers who are motivated to perform propagation surveys for the purpose of radio system development and deployment should use this model to predict signal strength loss in environment with similar characteristics and use as validation propagation prediction tool.

For future works, smart grid requires a reliable wireless communication infrastructure that should operate in various deployment scenarios either fixed or mobile giving rise to different channel time selectivity characteristics. Expansion of the grid as more renewable energy sources are integrated is likely to lead to unique communication related issues as well. For instance, signal propagation characteristics in renewable energy sites such as wind power generation stations should be studied in depth for either establishing reliable wireless systems in these sites or understanding their impact on existing legacy wireless systems such as radar signals.

6. Conclusion

The objective of the paper was to develop a model that appropriates for certain geographical areas, that would assist system engineers determine signal strength in error and efficient path loss prediction tool that would enhances proper network design to improve the quality of cellular signal strength for transformation. Measurement of received signal level was conducted in the test-bed area of Niger-Delta in Nigeria with the use NOKIA handset equipped with net-monitor software Transmission Evaluation Monitoring System TEMS. The measured data were analyzed by the method of linear regression (LR) analysis. To formulate this model the mobile radio link parameters that Communication System engineers are generally concern with were determined. The mobile radio link parameters consist of the path loss exponent (n) = 3.38 and the standard deviation (σ)=9.2dB that characterized the propagation environment.

Conclusively, it is essential that for reliable mobile wireless system design the accurate qualitative understanding of the propagation using propagation loss model as a function of distance from where the signal level could be predicted.

Acknowledgement

We wish to acknowledge the cooperation of Glo networks for providing enabling environment for this study. The relevance of the contribution of references consulted is also acknowledged

References

- [1] Ghassemzadeh SS, Jana R, Rice CW, Turin W, Tarokh V. A statistical path loss model for in-home UWB channels. In: *Proc. of IEEE Conference on Ultra Wideband Systems and Technologies*, 2002:59-64.
- [2] Rice L, Longley AG, Norton KA, Basrsis AP. *Transmission Loss Predictions for Troposphere Communication Circuits*. NBS Tech Note 101, New York, 1967.
- [3] Rappaport, TS. *Wireless communications: Principles and practice*. Prentice hall communications engineering and emerging technologies series. Upper Saddle River, NJ: Prentice Hall PTR, 2002.
- [4] Rappaport TS. *Wireless Communications: Principles and Practice*, Prentice Hall PTR, Upper Saddle River, New Jersey, 1996.
- [5] Seidel S, *et al.* Path loss, Scattering and multipath delay statistics. *IEEE Transactions on Vehicular Technology*, 1991; (40)4:721-730
- [6] Pavlos F, Sofoklis K, George K. Enhanced handover performance in cellular systems based on position location of the mobile terminals. *Seminar paper, Telecommunications Laboratory*, National Technical University of Athens. 2007:2-3.
- [7] Moinuddin AA, Singh S. Accurate Path Loss Prediction in Wireless Environment, *The Institution of Engineers (India)*, July 2007; (88):9-13.