IEEE Transactions on Antennas & Propagation, 2016, Manuscript ID is AP1512-1931.R2

Empirical Path Loss Models for Wireless Sensor Network Deployments in Short and Tall Natural Grass Environments

Tajudeen O. Olasupo, *Member, IEEE;* Carlos E. Otero, *Senior Member*, *IEEE*; Kehinde O. Olasupo, *Member, IEEE;* Ivica Kostanic, *Member, IEEE*

***Abstract*— Extensive research has not been done on propagation modeling for natural short- and tall-grass environments for the purpose of wireless sensor deployment. This study is essential for efficiently deploying wireless sensors in different applications such as tracking the grazing habits of cows on the grass or monitoring sporting activities. This study proposes empirical path loss models for wireless sensor deployments in grass environments. The proposed models are compared with theoretical models to demonstrate their inaccuracy in predicting path loss between sensor nodes deployed in natural grass environments. Results show that theoretical models deviate from the proposed models by 12 to 42%. Also, results of the proposed models are compared with experimental results obtained from similar natural grassy terrains at different locations resulting in similar outcomes. Finally, the results of the proposed models are compared with previous studies and other terrain models such as those in dense tree environments. These comparisons show that there is significant difference in path loss and empirical models' parameters. The proposed models, as well as the measured data, can be used for efficient planning and future deployments of wireless sensor networks in similar grass terrains.**

***Index Terms*— path loss model, RF propagation, short and tall natural grass, terrain, terrain factor, wireless sensor network, XBee radio.**

I. INTRODUCTION

RADIO wave propagation in grassy environments has not been studied extensively as compared to studies in forest environments [1], [2], [3], [4], [5], [6]. In some cases, studies of radio propagation have been intended to support animal grazing in large-scale farming [1]. Other studies are focused on anticipated applications of wireless sensor networks (WSNs) in rural areas [2]. Some researchers limit their interest to specific phenomena such as the impact of surface components on signal propagation in different environments [3]. A sample of the studies use both free space path loss (FSPL) and two-ray models which are inaccurate for WSN deployments [7], [8]. Previous studies use signal generators as sensor nodes instead of practical sensor nodes which in turn lead to inaccurate models. Therefore, the lack of availability of accurate models lead to poor decision-making during deployment of WSN especially in large-scale deployments. The scarcity of these propagation models also lead to poor energy efficiency of nodes and inaccuracy in localization and target-tracking applications [9] [10]. Research work in [11] demonstrates that terrain variations impact radio signal propagation in different environments. Therefore, there is a need for path loss models that accurately characterize the effect of terrain variations in grassy environments.

This study is conducted with the purpose of proposing accurate path loss models to solve some of the aforementioned problems. The proposed models can be used in applications that track the grazing habits of cows on the grass with the aid of wireless sensor networks. In addition, the proposed models will support future applications that enable the Internet of Things [12], [13], [14], [15], [16], such as monitoring the growth of grasses on major roads, house lawns, outdoor sport centers, and public places that are not easily accessible. Similarly, home-owners can use IoT devices to monitor and control irrigation systems, enabling self-management during long periods where home-owners are away. In these and many other cases, accurate propagation models are essential for efficiently implementing such systems. As the popularity and sophistication of WSN systems and applications continue to increase, so will the need for accurate propagation models.

This research develops accurate empirical propagation models for WSN deployment in grassy environments through experimental analysis and observations. The empirical models are compared with theoretical models. Also, the predictions of the empirical models are compared with measured values in similar environments at different locations. Furthermore, the results are compared with previous related work such as in vegetation and other outdoor radio wave propagation models. The results show commonalities and accuracy. The path loss models' parameters are compared with related previous studies and the results show that there is a significant difference.

The remainder of this paper is organized as follows. Section II presents a summary of the related work. Section III describes the experimental set-up and measurement campaign. The full analysis and result details are provided in section IV while section V

This manuscript is submitted for review in December 19, 2015; revised June 1, 2016.

The authors are with Department of Electrical and Computer Engineering, Florida Institute of Technology, Melbourne, Florida, USA. (e-mail: {tolasupo2011, kolasupo2011} @my.fit.edu, {cotero, kostanic} @fit.edu).

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2016.2583507, IEEE Transactions on Antennas and Propagation

summarizes the conclusion and provides avenues for future research.

II. Related work and background

A. Related work

In [1], the authors propose a study of radio signal propagation in grazing grounds intended to feed large herds of cows. Experiments are performed in open short-grass fields where the grass average height is about 25 cm and in scrublands where the scrubs height vary from 1.5 m to 1.8 m. The study incorporates ZigBee protocol devices in 2.4 – 2.5 GHz band with antenna height of 1.5 m. Also, the authors indicate that transmitters and receivers may be separated at most by a distance of 27 m in scrubland and 135 m in grassland to achieve a packet error rate of less than 2%. The authors state that a minimum of 0.7 node/hectare^2 in grassland and 14.4 nodes/hectare^2 in scrubland must be deployed to cover an entire herd in a grazing pasture. Likewise, the study in [2] focuses on open short-grass fields with emphasis on deploying WSNs in rural areas in general. The authors document measurements on scrublands and vegetation where the scrubs height varies from 1.5 m to 1.8 m. The vegetation includes forest, pine tree, eucalyptus tree, and a deciduous oak tree forest and meadows—these are classified as grasslands and scrublands. In their study, the authors use three discrete frequencies, namely: 2.4, 3.5, and 4.8 GHz. Unlike the research in [2], the research presented in this paper focuses on grassy environments. The authors in [2] also take into account various factors depending on their objectives, for example, they consider distances between transmitter and receiver from 1 m to 32 m in experiments performed in scrublands similar to [1]. Data are also collected over distances from 1 m to 150 m in grasslands. The authors confirm that attenuation is less severe in grasslands than scrublands. They also discover that vegetation growth—which is more pronounced in scrublands—tends to affect signal propagation. The growth affects signal propagation in different ways based on irregularities of terrains and antenna height, as well as the distance between transmitter and receiver. In addition, the authors confirm that distances between nodes are larger in 3.5 GHz over grassland due to the clearance on line-of-sight (LOS) between transmitting and receiving nodes. The authors observe that attenuation decreases when antenna height increases but increases when frequency increases. Finally, the authors develop a propagation model for a peer-to-peer WSN intended for deployment in rural areas. In contrast, the authors in [3] focus on terrains with 1 m tall-grass and hilly areas with grass interspersed with some trees. Devices that operate in 300 MHz and 2.4 GHz are used separately in their study. The authors perform experiments with distances that barely exceed 50 m. The hilly areas presented a slope gradient between 6 and 25 degrees. The authors are interested in small- and large-scale path loss effects occurring at the surface-level and in irregular terrains. They believe that surface components have significant impact on networks where nodes are placed close to the ground. They discover that large-scale path loss is log-normally distributed in irregular terrains. In addition, the authors point out that this large-scale path loss is similar to the received signal strength median within a small area in flat terrain. In [4], the authors discuss the characterization of wireless communication in hard court arenas used in sports, grass fields, and on roads. They take into consideration the effects of antenna height and orientation in the study.

The study in [5] focuses on an agricultural field. Devices that use ZigBee protocol in 2.4-2.5 GHz band are used in the study. The authors select antenna heights of less than 1 m as well as heights from 1.2 m to 2.3 m during experimental measurements. The authors are interested in determining the impact of antenna height and orientation on received signal strength (RSS) during deployment. They consider two directions in which the transmitting antenna is pointing. The authors state that variations in signal strength are significant due to ground reflection effects in distances beyond 50 m. It is stated that signal decay exhibits smoother variations in smaller distances around 0.5 m along the decay curve of the log-distance model. They discover that the log-distance model provides a better fit to signal loss in open grass fields than the free-space loss model.

In [17], the authors conduct experiments for radio propagation in crop fields and farm lands. They consider antenna factors and use log-distance to model the environment. The authors use antenna heights between 0.25 m to 1.5 m and distances between 1 m to 140 m. The experiments are carried out for different growing stages of crop fields. The frequency of operation for radio frequency link used is 2.4 GHz. Antenna height is proven to be an important factor for node deployment.

Authors in [18] conduct channel measurements for near-ground wireless sensors. Antenna heights between 0.75 to 1.55 m with a gain of 2.15 dBi are used. The distances of communication devices used range from 50 m to 500 m. They use wireless sensors at frequencies of 300 and 1900 MHz. The measurements are performed in a forest (with sparse trees, flat terrain, soil, limestones and sand stones) and take into account the influence of rain and foliage. The authors discover that there is no measurable effect of rain on the signal with frequencies between 300 and 1900 MHz. The common known path loss models are tested on their measurements similar to the study in [19]. Results from the study show that the effect of foliage on the signal in the forest is severe. The authors discuss the propagation analysis and propose a prediction model for ZigBee wireless sensor network in vineyard and agriculture environments. Another objective of their study is to characterize the coverage area of XBee Pro ZB S2B device used in the study. This device has output power of +18 dBm, receiver sensitivity -102 dBm, and operating frequency of 2.4 GHz. The authors conduct the measurement for $\pi/12$, $\pi/6$, $\pi/4$, and $\pi/2$ directions at distance of between 25 m to 50 m node placements.

The authors in [20] conduct a study of propagation modeling for areas consisting of trees with buildings combined. They incorporate the model into the Lee model. The authors rely on this model to design wireless sensor networks that monitor the consumption of electricity by users. They use a signal generator at 2.45 GHz, power of 10 dBm, and 8 dBi gain antenna for received signal measurements. The antenna heights are between 2.2 to 5 m and node distances are between 1 and 100 m.

The authors in [21] propose a test-bed for random deployment of wireless sensor nodes in “wild environments.” They define wild environments as those containing wild grass with weeds, small mud,

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2016.2583507, IEEE Transactions on Antennas and Propagation

flat cement, and no buildings. The authors use antenna heights of 25, 45, and 100 cm. A signal generator at 433 MHz at power of 10 dBm is used for signal generation and measurements in the described environment. They use segmented (linear) regression analysis to fit their model. Similarly, in [22], the authors carry out radio frequency (RF) propagation behavior measurements in agriculture fields and gardens. The agriculture terrain contains corn and ground nut, while the garden contains coconut garden with green, dry, and wet grass environments. The authors observe the experiment for different growing stages of the plants and similar to previous work, they use a signal generator at 2.4 GHz for the experiment.

In a related case, the authors in [23] present an empirical path loss model for wireless sensor network for sandy environment. They compare the model with that from sparse tree and long grass terrains. However, the authors present a linear model for sparse tree and long grass without extensive analysis. They propose that traditional free-space and two-ray path loss models are not appropriate for near-ground sensor network deployment. The authors use an RF generator at 1.925 GHz and antenna height of 20 cm. The transmitters and receivers are separated at distance of 5 m. The authors collect measurements between 5 to 40 m at 22.5 degrees radial angles to each point of measurement and compare their results with other type of propagation models. The authors in [24] also use the same type of equipment and approach to propose an empirical path loss model for an artificial turf grass environment. Likewise, authors in [25] use an Agilent signal generator and analyzer at frequencies of 868/915/2400 MHz with receive power of 17 dBm for measurement. They perform experiments in vegetation with bushes, small plants, and grove of trees.

A thorough review of the literature reveals a gap in results that analyze empirical propagation models for short- and tall-grass environments using practical wireless sensors. The study presented here contains detailed analysis of empirical models for sensors operating under real deployment conditions. In this study, natural short- and tall-grassy terrains are characterized by a non-obstructed line-of-sight between transmitter (Tx) and receiver (Rx) nodes except for the grasses that are on the path of propagation between them.

B. Background

Generally, the first order log-distance model is given as:

$$P_l(d)_{(dB)} = P_l(d_o)_{(dB)} + 10\gamma \log_{10}\left(\frac{d}{d_o}\right) \quad (1)$$

where $P_l(d)_{(dB)}$ is the first order log-distance polynomial model. If multipath effect due to obstacles and other effects are considered, (1) becomes [26, 27]:

$$P_l(d)_{(dB)} = P_l(d_o)_{(dB)} + 10\gamma \log_{10}\left(\frac{d}{d_o}\right) + X_\sigma \quad (2)$$

where d_o is far-field distance or reference distance, typically chosen as 1m, d is the distance between transmitter and receiver (in meters), $P_l(d_o)_{(dB)}$ is the median path loss at reference distance, that is, the intercept, slope $= 10\gamma$, where γ is the path loss exponent and X_σ is lognormal shadowing. Lognormal shadowing is the Gaussian random variable with zero mean and variance σ^2. The standard deviation ($\sigma_{(dB)}$) of X_σ may be determined from experimental data. An approximate method of finding $\sigma_{(dB)}$ is obtained by using (3),

$$\sigma_{(dB)} = \sqrt{\sum_{j=1}^{N} \frac{\left(P_{lm_j} - P_{lp}\right)^2}{N-1}} \quad (3)$$

where P_{lm_j} is the measured path loss values, P_{lp} is the predicted path loss mean, and N is the number of samples.

Additionally, statistical parameter - R^2 is used to test the significance of the proposed models. R^2 is a measure of the amount of reduction in variability of the response variable obtained by using the regressor variables in the model. The expression for R^2 is given in (4).

$$R^2 = \frac{SS_{Model}}{SS_{Total}} \quad (4)$$

where SS_{Model} is the sum of square of the model and SS_{Total} is the sum of square of the total.

P-value, F-value, and α-level are other useful statistical parameters to determine the significance of a model [28]. These statistical parameters are used in this research to determine and validate the significance and accuracy of the proposed models.

III. Experimental Setup and Measurement Campaign

A. Equipment and device setup

This research focuses solely on radio signal propagation modeling for WSN deployment in natural short- and tall-grass environments as shown in Figs. 1 and 2. Short grass is defined as grass having height smaller than 3 cm. Tall grass is defined as grass exceeding 1 m in length. Unlike previous studies, this study does not use signal generators. Instead, it relies on actual sensor nodes that are deployed on the ground. The nodes are placed at 17 cm height from the ground in the short grass environments and at 3 cm and 0.5 m heights in tall grass. Some measurements are obtained when the distance between transmitting and receiving nodes is 1 m. Other measurements are for 5 m distance and for each study 128 radial measurements are obtained.

In the experimental set-up, the XBee Pro ZB S2B device [29] is used as the sensor node similar to [19]. The node has a linear antenna that is 2.6 cm high and with gain of 1.5 dB. The antenna is omnidirectional. The antenna element of this radio radiates perpendicularly to the pointing direction and propagation of radio waves from this node is linearly polarized. The nodes are portable devices with a dimension of approximately 3 cm x 2 cm x 3 cm (including the antenna). These practical, low data rate, and low power devices are used for all measurements in this study, since signal generators do not provide true representation of nodes in the field. The study in [30] shows that individual nodes in the same environment can change the model parameters. The ZigBee protocol is used in the transceiver of the node, which uses direct sequence

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2016.2583507, IEEE Transactions on Antennas and Propagation

spread spectrum (DSSS) as modulation technique to help shield against noise and interference [26] [29]. Two devices are used for measurements; one device is configured to be the coordinator or the sink node while the other is configured as router. The router sends packets to the sink node every second. The nodes' parameters are shown in Table I.

Both devices are connected to the laptop to serve as power source and as means for collecting the measurements. The radiated electric field from the node antenna is linearly polarized and measurements are obtained for when the node's field is oriented vertically and horizontally. The data collected includes the power measurement of packets that arrive at the sink. The devices operate at frequency of 2.4 GHz with 250 kbps data rate. Error rate of 3% is maintained in all of the measurements. During the experiment, it is observed that in some cases, the packet loss rate increases as distance goes beyond 40 m for this type of device. Both nodes have a transmit power of 63 mW and a receiver sensitivity of -102 dBm. Nodes are placed at distances spanning from 5 to 30 m in manner shown in Fig.3.

The process is repeated for the case when the nodes are placed on the grass at 1 m interval up to 12 m. In the grass, the packet loss rate is high at distances of more than 18 m. To ensure that accurate measurements are obtained, measurements are limited to 12 m. Fig. 2 shows the node orientation and Fig. 3 shows a pictorial diagram for nodes placed at different heights during measurements. Fig. 4 shows the path loss measurements plotted against distance for the case when the nodes are in short grass terrain at distance of 5 m.

TABLE I
DEVICE PARAMETERS

Node type	**Tx power**	**Rx sensitivity**	**LOS range**	**Protocol**	**Data rate**	**Modulation**	**Network**	**Node Size**	**Antenna**
XBee Pro ZB S2B	18 dBm	- 102 dBm	3000 m	ZigBee/IEEE 802.15.4	250 kbps	DSSS & OQPSK	point to point and mesh	3.2 cm x 2.4 cm x 0.68 cm	2.6 cm high, 1.5 dB gain

Fig. 1. Tall natural grass terrain.

Fig. 2. Nodes orientation for vertical polarization on the ground in short grass terrain.

IV. Analysis and Results

A. *Measured values*

The study in [4] proposes first order log-distance model for grass related environment and second order log-distance model for hard sport court environment. Other studies use free space path loss and two-ray models. It is observed from theory and experimentation that the two-ray model does not fit the measurement approach for wireless sensor deployment.

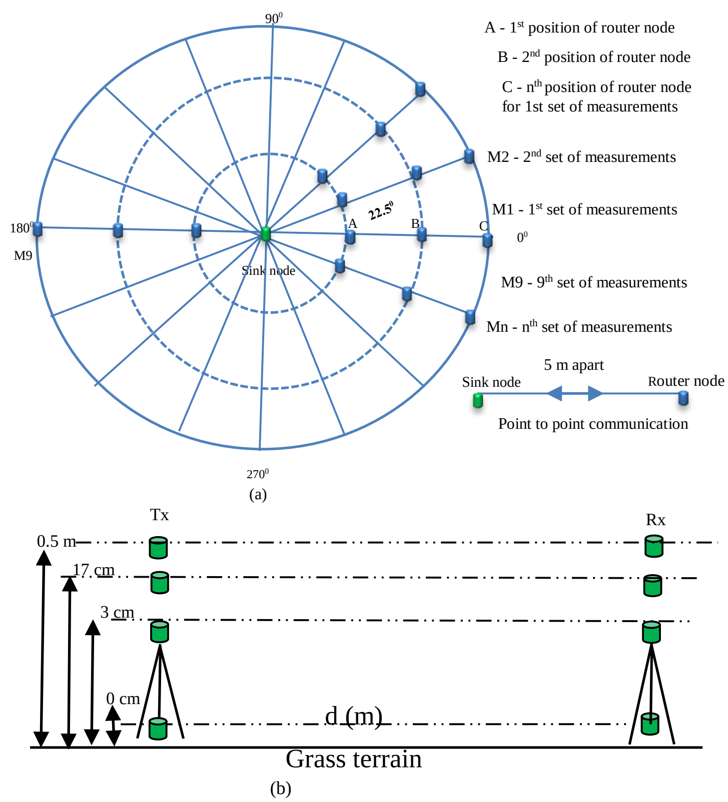

Fig. 3. (a) Conceptual overview of arrangement of nodes for measurement. (b) Transmitter (Tx) and receiver (Rx) set up.

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2016.2583507, IEEE Transactions on Antennas and Propagation

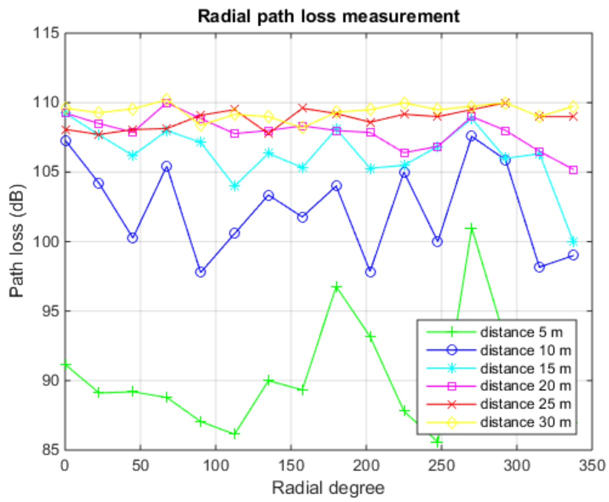

Fig. 4. Path loss (dB) measurements, for node on zero height (on the ground) in short grass terrain at every 5m: path loss vs radial degree measurement.

According to authors in [26], [31], the two-ray model is reasonably accurate for predicting large scale path loss over distances of several kilometers for mobiles radio systems that use tall towers—those whose height exceeds 50 m. The model assumes that the distance between the transmitter and receiver is far greater than the heights of the transmitter and receiver. It also assumes that the earth is flat and a perfectly conducting plane. In this study, the grass terrain is not flat and the nodes are not placed on 50 m height. For all cases of measurements, both transmitting and recieveing nodes are placed on the same height. The maximum height used is 0.5 and the maximum distance between both transmitting and receiving nodes considered is 30 m. This approach is suitable for WSN deployment. However, due to the assumptions of the two-ray model, it is not suitable for WSN deployment [32]. The results in Fig. 10 and 11 show that there is a deviation in the two-ray model as compared to the measured values. During measurement in dense tall-grass environment, the devices drop connectivity when the node is on the ground and at distances beyond 12 m. The measurements are limited to 9 m in this case. An average path loss of the measurement is computed for all cases. Tables II and III show the average path loss measurements for nodes deployed at 1 m and 5 m interval respectively. The path loss value for a stationary transmitter with respect to a receiver at different distances varies in diverse directions. The expected value or true value at a particular distance will be the average of values in all directions. From Fig. 3, the average path loss at distance *A* from sink node will be the sum of *M1A*, *M2A*, up to *MnA* divided by 16. This average is used for analysis in this study.

B. Analysis to determine the best fit line or model

The measured path loss values presented in Tables II and III are used to obtain the proposed models. The proposed models are established at 95% confidence levels.

Case 1:

The analysis in this case pertains to nodes that are placed on the ground in short grass terrain. The plot for first order log-distance model is shown in Fig. 5. The residual plot in this case helps to see that the data follow normality and data variability. This suggests that the data could produce a good model. The first order log-distance polynomial model is presented in (5) which is obtained from the same plot. As seen in the figure, R^2 is 98.2% which helps explain the strength of relationship between distance and path loss. The path loss at 1 m is 70 dB and the path loss exponent is 3.4. The exponent characterizes the terrain type.

$$PL(dB) = 70.62 + 34.01 \log_{10} d \qquad (5)$$

Considering the statistical values for case 1, the F-value is high at 549 and the P-value is 0.000. These values are obtained from the plot analysis.

TABLE II
AVERAGE PATH LOSS (dB) AT 1m INTERVAL

Vertical Polarization		**Distance (m)**											
Terrain	**Node placement Height (cm)**	1	2	3	4	5	6	7	8	9	10	11	12
Short grass	*On the grass*	70.1	82.6	84.1	91.9	93.7	97.9	102.4	100.4	103.6	103.4	105.9	106.7
Tall grass	*3 cm*	57.0	60.7	68.4	68.3	70.6	77.7	81.3	82.4	87.3	-	-	-

TABLE III
AVERAGE PATH LOSS (dB) AT 5m INTERVAL

Scenarios			**Distance (m)**					
Polarization	**Terrain**	**Node placement Height (cm)**	5	10	15	20	25	30
Vertical	*Short grass*	*17*	66.4	77.2	83.1	87.2	94.5	96.7
		On the grass	90.5	102.4	106.3	107.6	108.9	109.4
Vertical	*Tall grass*	*50*	61.3	71.5	80.7	83.7	85.8	88.2

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2016.2583507, IEEE Transactions on Antennas and Propagation

Horizontal	*Tall tree*	*50*	67.0	82.4	80.4	81.2	87.8	91.0
Vertical	*Dense tree*	*50*	56.0	66.0	82.4	81.2	70.0	85.8

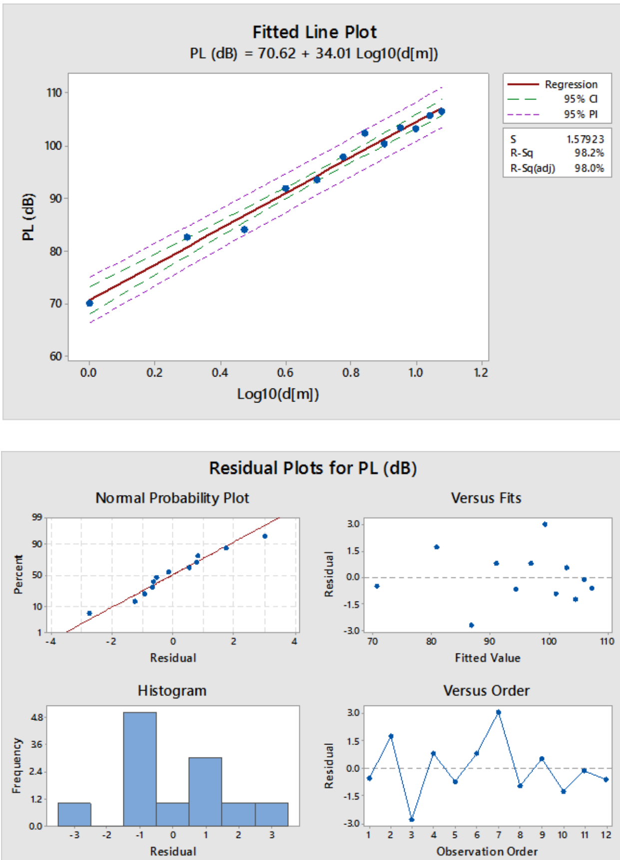

Fig. 5. Top: plot for PL (dB) versus Log (d) – first order log–distance model and bottom: Residual plot for Path loss for when the node on zero height (on the ground) in short grass terrain for first order log – distance model.

The P-value is less than the normally used value of 0.005 in statistical analysis. F and P values are significant in first order log-distance model. This supports the adequacy of the first order log-distance polynomial model. This model explains the variations of terrain and distance effects on the path loss for the radio frequency (RF) propagation in short grass at zero height. To further validate the proposed model, an additional round of measurements in a similar scenario is conducted. The new values are compared with the proposed model which show similarity as shown in Fig. 10.

Case 2:

The analysis in this case refers to nodes that are placed at 17 cm from the ground in short grass terrain. Fig. 6 shows the residual plot to see that the data follow normality and data variability. This suggests that the data can produce a good model. The first order log-distance polynomial is given in (6). R^2 is 98.6% and the path loss at 1 m is 38 dB. The path loss exponent is 3.9. The statistical parameters are significant. Hence, (6) is provided as the proposed model.

$$PL(dB) = 38.36 + 39.00\ \log_{10} d \tag{6}$$

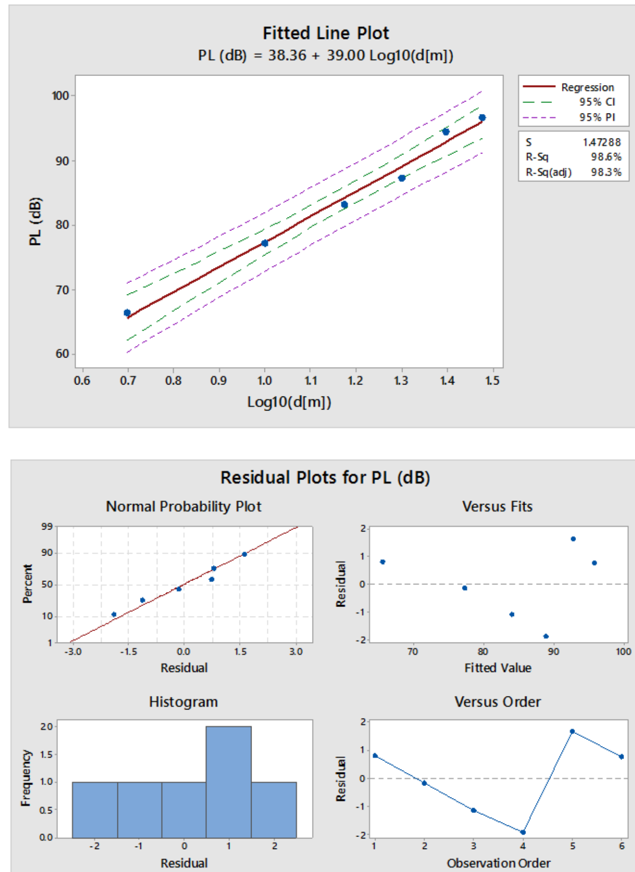

Fig. 6. Top: Fitted Line: PL (dB) versus Log(d) for when node is at 17 cm from the ground at short grass terrain and bottom: Residual Plots for PL (dB) for when node is at 17 cm from the ground in short grass terrain.

Case 3:

In this case nodes are placed at 3 cm from the ground in tall grass. Fig. 7 shows the residual plot as evidence that the data follow normality and data variability. This also implies that data can produce a good model. First order log-distance polynomial is proposed for this case as given in (7). R^2 is 91.2%. The path loss at 1 m is 53 dB and the path loss exponent is 3.1. The statistical parameters are significant. Hence, (16) is provided as the proposed model.

$$PL(dB) = 53.29 + 31.31\ \log_{10} d \tag{7}$$

This article has been accepted for publication in a future issue of this journal, but has not been fully edited. Content may change prior to final publication. Citation information: DOI 10.1109/TAP.2016.2583507, IEEE Transactions on Antennas and Propagation

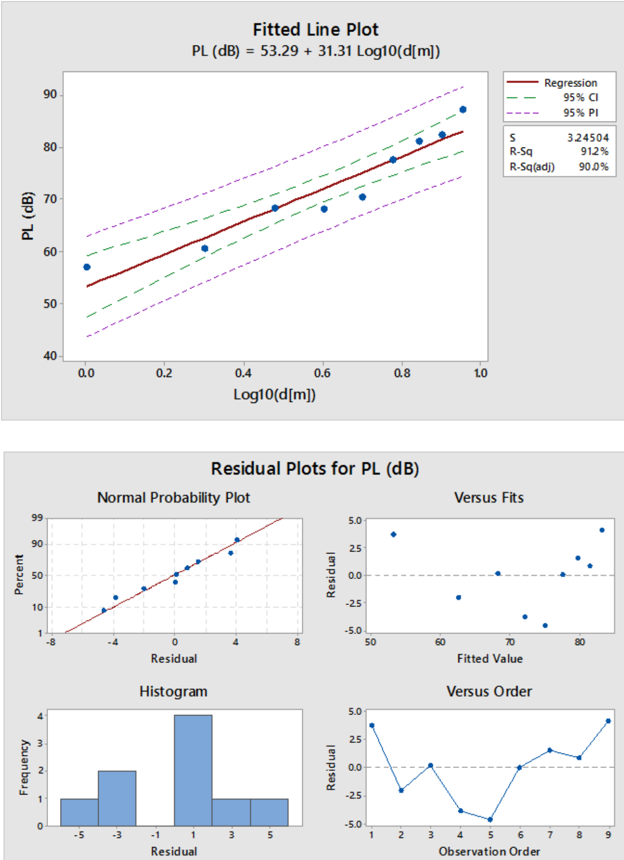

Fig. 7. Fitted Line: PL (dB) versus Log(d) for when node is at 3 cm from the ground at tall grass (1m high) terrain and Residual Plots for PL (dB) for when node is at 3cm from the ground in tall grass (1m high) terrain.

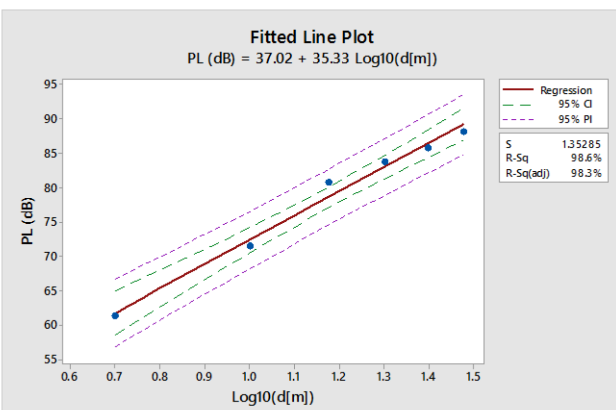

Fig. 8. Fitted Line: PL (dB) versus Log(d) for when node is at 0.5 m from the ground in tall grass (1m high) terrain

Case 4:

In this case the nodes are placed at 0. 5 m from the ground in the tall grass terrain. Using Fig. 8, the first order log-distance polynomial is given in (8). R^2 is 98.6%. The path loss at 1 m is 37 dB and the path loss exponent is 3.5. The statistical parameters are significant in first order log-distance polynomial model. Therefore, the best model in this case is first order log-distance model. The path loss values are consistent with reports in [33], [34]. The overall results of proposed models are given in Table VI.

$$PL(dB) = 37.02 + 35.33\ \log_{10} d \tag{8}$$

Case 5:

In this case the nodes are placed at 0.5 m from the ground in tall-grass terrain. The transmission and reception uses horizontal polarization. From Fig. 9, it is shown that path loss is higher when signal propagates in horizontal polarization than vertical polarization in tall grass. Propagation effects from the ground surface and grasses could also have impacted the high path loss.

C. Validation of Proposed Models

To further validate the proposed model, additional rounds of measurements are conducted using the same methodology in similar grassy environments but at different locations. These new measured values are plotted and compared with the proposed model as shown in Fig. 10. Results show good correlation between the predicted values and measured values. Ts - (Tracking Signal given in equation (10)) values for the comparison is 5.6. In addition, this study compares the proposed models with theoretical models that are obtained from [8], [34], [35], [36], [37], [38].

Statistical parameters for the comparison are shown in Tables IV and V. Expression for $MAPE$ (Mean Absolute Percentage Error) and Ts are given in (9) and (10) respectively. $MAPE$ expresses accuracy as a percentage of error [39]. Ts is used to check for bias in the models. A large Ts indicates bias in the models. Absolute deviation, $MAPE$, and Ts of theoretical models' results are high as compared to measured values. This suggests that theoretical models are inadequate for prediction of radio propagation behavior for ground sensor networks.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{EM - TM}{EM}\right| \times 100\% \tag{9}$$

$$Ts = \frac{\sum_{i=1}^{n} EM - TM}{\left(\sum_{i=1}^{n}|EM - TM|\right)/n} \tag{10}$$

In (9) and (10), EM is the empirical model values, TM is the theoretical model values, Ts is the tracking signal, $MAPE$ is the mean absolute percentage error, and n is number of sample. For accuracy of model, Ts should be between (-6, 6) and $MAPE$ should be less than 10 [39].

Also,

$$MSE = \sum_{j=1}^{n}\frac{(EM - TM)^2}{n-1}, \qquad RMSE = \sqrt{MSE} \tag{11}$$

where MSE is means squared error and $RMSE$ root mean squared error.

Based on the observation during experimental analysis, it is therefore recommended that when low-power (63mW), low-data rate (250kbps) devices are to be deployed barely on the ground in grass environment, distances between the nodes should be less than 15 m.

In addition, log-distance propagation model should be used in such design and the radiated field should be vertically polarized. However, for tall grass of about 1 m high and in tree terrain, the distance could be 40 m when node is at height of 0.5

m from the ground. This deployment situation will ensure packet loss of less than 3%.

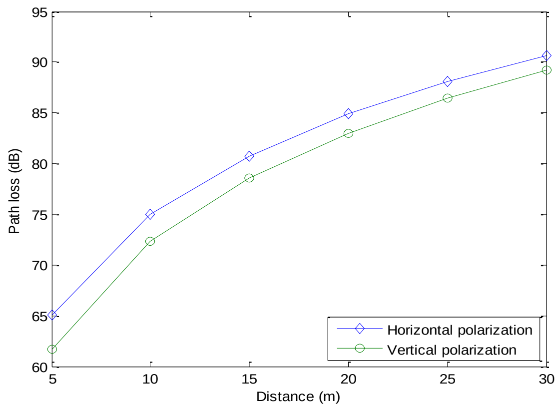

Fig. 9. Vertical and horizontal polarization in tall grass (node at 0.5m).

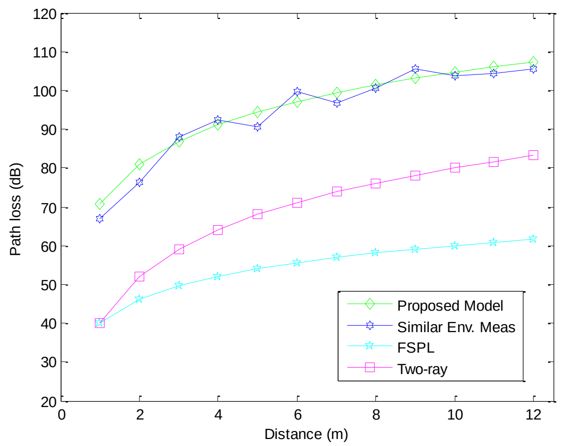

Fig. 10. Comparison between theoretical models, measured values in similar short grass environment (Similar Envi. Meas), and proposed model in short grass of 3cm high.

TABLE IV
STATISTICS FOR COMPARISON BETWEEN THEORETICAL MODELS AND PROPOSED MODEL IN SHORT GRASS ENVIRONMENT

Models	MAPE (%)	MSE	RMSE	Ts
FSPL	42	6730	82	19
two-Ray	25	2370	48.7	19
Measured	1.1	7	2.6	5.6

TABLE V
STATISTICS FOR COMPARISON BETWEEN THEORETICAL MODELS AND PROPOSED MODELS IN THE GRASS ENVIRONMENTS

Terrain	Models	Deviation	two-ray	FSPL
Short grass	$70.62 + 34.01 \log_{10} d$	*value inference*	46 % Under predict	51 % Under predict
Short grass	$38.36 + 39.00 \log_{10} d$	*value inference*	11% Close predict	15 % Close predict
Tall grass	$53.29 + 31.31 \log_{10} d$	*value inference*	21% Under predict	27 % Under predict
Tall grass	$37.02 + 35.33 \log_{10} d$	*value inference*	6 % Close predict	11% Close predict
Dense tree	$52.23 + 28.11 \log_{10} d$	*value inference*	17 % Under predict	22 % Under predict
Dense tree	$35.0 + 32.74 \log_{10} d$	*value inference*	2 % Same predict	7 % Close predict
Tall grass	$43.04 + 31.39 \log_{10} d$	*value inference*	10 % Close predict	14 % Close predict

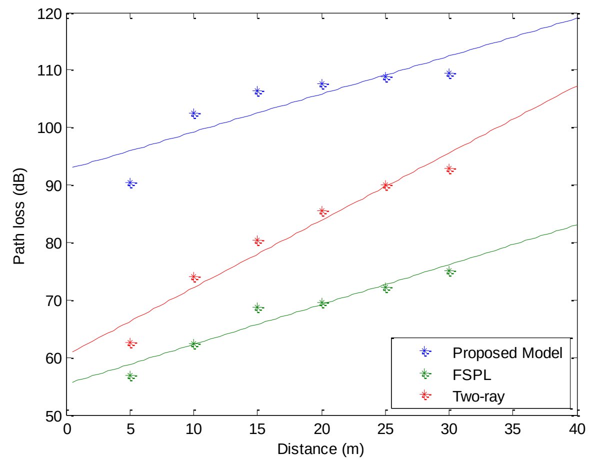

Fig. 11. Comparison between proposed model in short grass of 3cm high and theoretical models.

V. Conclusion

In this study, path loss models are proposed for natural short- and tall-grass terrain environments. These proposed models are derived from experimental analysis. The empirical models are compared with theoretical models and the evidence suggests a significant discrepancy between the measured data and the theoretical models as seen in Figs. 10 and 11.

The comparison between these models show a high Mean Absolute Percentage Error ($MAPE$). Theoretical models deviate from the proposed models and measured values by 12 to 42% as shown in Table V. The measured values in similar environments give $MAPE$ of 1.1% and Ts of 5.6 when compared with the proposed model in short grass environment. This suggests that theoretical models are not suitable for predicting propagation loss for WSN deployment in 0 to 1 m high dense grass environment. The $RMSE$ values- equation (11) - are very high for theoretical models. The path loss and empirical models' parameters are compared with related previous studies which also show significant difference. The results presented in this study are similar to previous related work such as in vegetation and other outdoor radio wave propagation models. The proposed models' results show commonalities and accuracy. This analysis can be seen in Figs. 10 and 11. The path loss exponents for these terrains are also displayed in Table VI. The provided models, as well as the measured data, could be used for easy planning and deployment of wireless sensor networks in similar grass terrain in the future.

Future work will consider the effects of more factors such as casing (for protecting the device), hardware type, time and computation efficiency, energy management, and repeated experiments in different terrains. Moreover, the effect of electrical properties of natural grass, other terrains, and ground on radio propagation will be investigated. Finally, to optimize deployments of WSN in grassy environments, the results presented in this work will be incorporated into the optimization model similar to the one presented in [40].

TABLE VI
SUMMARY OF PROPOSED MODELS

	Terrains	Cases	Models	Path loss exponents	Shadowing values – $\sigma_{(dB)}$
Vertical polarization	Short grass (3cm) high	Node at zero height	$70.62 + 34.01\ \log_{10} d$	3.4	10.8
		Node at 17 cm	$38.36 + 39.00\ \log_{10} d$	3.9	10.3
	Tall grass (1m) high	Node at 3 cm	$53.29 + 31.31\ \log_{10} d$	3.1	9.7
		Node at 0.5 m	$37.02 + 35.33\ \log_{10} d$	3.5	9.3
	Dense tree	Node at zero height	$52.23 + 28.11\ \log_{10} d$	2.8	8.4
		Node at 0.5 m	$35.0 + 32.74\ \log_{10} d$	3.2	10.5
Horizontal polarization	Tall grass (1m) high	Node at 0.5 m	$43.04 + 31.39\ \log_{10} d$	3.1	8.6

VI. References

[1] J. A. Gay-Fernandez, I. Cuinas, M. G. Sanchez and A. V. Alejos, "Radio-Electric Validation of an Electronic Cowbell Based on ZigBee Technology," *IEEE Antennas and Propagation Magazine*, vol. 53, no. 4, pp. 40-44, August 2011.

[2] J. A. Gay - Fernandez and I. Cuinas, "Peer to Peer Wireless Propagation Measurements and Pathloss Modeling in Vegetated Environments," *IEEE Transactios on Antenna and Propagation,* vol. 61, no. 6, pp. 3302 - 3311, 2013.

[3] P. K. Chong and D. Kim, "Surface - Level Pathloss Modeling for Sensor Networks in the Flat and Irreglar Terrain," *ACM Transaction on SensorNetworks*, vol. 9, no. 2, March 2013.

[4] D. L. Ndzi, M. A. M. Arif, A. Y. M. Shakkaf , M. N. Ahmad, A. Harun, L. M. Kamarudin, A. Zakaria, M. F. Ramli and M. S. Razalli, "Signal Propagation Analysis For Low Data Rate Wireless Sensor Network Application in Sports Grounds and on Roads," *Progress In Electromagnetics Research,* vol. 125, pp. 1-19, 2012.

[5] A. Harun, M. F. Ramli, D. L. Ndzi, L. M. Kamarudin, A. Y. M. Shakaff, M. N. Jaafar and A. Zakaria, "Antenna Positioning Impact on Wireless Sensor Networks Deployment in Agriculture," *Australian Journal of Basic and Applied Sciences,* vol. 7, no. 5, pp. 55 - 60, 2013.

[6] T. Tamir, "On radiowave propagation in forest environments," *IEEE Transactions on Antennas and Propagation,* Vols. AP-15, pp. 806-817, November 1967.

[7] J. D. Parsons, The Mobile Radio Propagation Channel, 2nd ed., Wiley, 2000.

[8] S. R. Saunders and A. A. Zavala, Antennas and Propagation for Wireless Communciations Systems, 2nd ed., Delhi: Pashupai Printing, 2008, pp. 51-351.

[9] I. F. Akyildiz, Wireless Sensor Network, Wliey, 2010.

[10] R. P. Sawant, Q. Liang, D. O. Popa and F. L. Lewis, "Experimental Path loss Models for Wireless Sensor Networks," in *Military Communications Conference*, Orlando, 2007.

[11] T. Olasupo, C. E. Otero, I. Kostanic and S. Shaikh, "Effects of Terrain Variations in Wireless Sensor Network Deployments," in *IEEE International RF amd Microwave Conference (to be published)*, Sarawak, 2015.

[12] C. Tsai, C. Lai, M. Chiang, M. Lawrence and T. Yang, "Data Mining for Internet of Things: A Survey," *IEEE Communications Surveys and Tutorials*, vol. 16, no. 1, 2014.

[13] S. Raza, L. Wallgrena and T. Voigt, "Real - Time Intruction Detection in the Internet of Things," *Ad Hoc Networks Journal*, vol. 11, pp. 2661 - 2674, 2013.

[14] K. Irgan, C. Unsalan and S. Baydere, "Low - Cost Prioritization of Image block in Wireless Sensor Networks for Border Surveillance," *Journal of Networks and Computer Applications*, vol. 11, pp. 54 - 64, 2014.

[15] H. Karl and A. Willig, Protocol and Architectures for Wireless Sensor Networks, John Willey & Son, Inc, 2012.

[16] C. E. Otero, A. Velazquez, I. Kostanic, C. Subramanian , J. P. Pinelli and L. Buist, "Real - Time Monitoring of Hurricane Winds using Wireless and Sensor Technology," *Journal of Computers*, vol. 4, no. 12, pp. 1275 - 1285, 2009.

[17] H. Liu, Z. Meng and Y. Shang, "Sensor Nodes Placement for Farmland Environmental Monitoring Applications," in *IEEE Wireless Communications, Networking and Mobile Computing*, 2009.

[18] G. G. Joshi, C. B. Dietrich, C. R. Anderson and W. G. Newhall, "Near-Ground Channel Measurements over Line-of-Sight and Forested paths," *IEE Proceedigns on Microwaves, Antennas and Propagation*, pp. 589-596, December 2005.

[19] F. P. Correia, F. B. Carvalho, B. G. Leal and W. T. Lopes, "Propagation Analysis in Precision Agriculture Environment using XBee Devices," in *Microwave & Optoelecronics Conference (IMOC) IEEE MTTS-S International*, Rio de Janeiro, 2013.

[20] M. Galvan - Tejada and Q. Duarte-Reynoso, "A Study Based on the Lee Propagation Model for a Wireless Sensor Network on a Non-Uniform Vegetation Environment," in *IEEE Conference*, 2012.

[21] Y. He, W. Zhang, N. Jiang and X. Luo, "The Research of Wireless Sensor Network Channel Propagation Model in the Wild Environment," in *IEEE International Conference on P2P, Parallel, Grid Cloud and Internet Computing*, 2014.

[22] D. Balachander, T. Rama Rao and G. Mahesh, "RF Propagation Investigation in Agricultural Fields and Gardens for Wireless Sensor Communications," in *IEEE Conference on Information and Commucnication Technologies*, 2013.

[23] A. Alsayyari, I. Kostanic and C. Otero, "An Emperical Pathloss Model for Wiresless Sensor Network Deployment in a Sand Terrain Environment," in *IEEE World Forum on Internet of Things (WF-IoT)*, 2014.

[24] A. AlSayyari, I. Kostanic and C. E. Otero, "An Empirical Path Loss Model Wireless Sensor Network Deployment in an Artificial Turf Evironment," in *Networking, Sensing and Control (ICNSC), IEEE 11th International Conference*, Maimi, FL, 2014.

[25] T. R. Rao, D. Balachander, A. Nanda Kiran and S. Oscar, "RF Propagation Measurements in Forest & Plantation Environments for Wireless Sensor Networks," in *International Conference on Recent Trends in Information TEchnology*, Chennai, 2012.

[26] T. S. Rappaport, Wireless Communications: Principle and Practice, 2nd ed., NJ: Prentice Hall, 2002.

[27] C. E. Otero, R. Haber, A. M. Peter, A. AlSayyari and I. Kostanic, "A Wireless Sensor Networks' Analytics System for Predicting Performance

in On-Demand Deployments," *IEEE SYSTEMS JOURNAL*, no. 99, pp. 1-10, 2014.

[28] D. Montegomery, Design and Analysis of Experiments, Wiley, John & Son, 2012.

[29] ZigBee, "ZigBee Technology," [Online]. Available: www.digi.com.

[30] J. Vallet, O. Kaltiokallio, J. Saarinen, M. Myrsky and M. Bocca, "On the Sensitivity of RSS Based Localization Using the Log-Normal Model: An Empirical Study," in *Positioning Navigation and Communication (WPNC), IEEE*, Dresden, 2013.

[31] M. J. Feuerstein, K. L. Blackard, T. S. Rappaport, S. Y. Seidel and H. H. Xia, "Path Loss, Delay Spread, and Outage Models as Functions of Antenna Height for Microcellular System Design.," *IEEE TRANSACTIONS ON VEHICULAR TECHNOLOGY,* vol. 43, no. 3, 1994.

[32] D. E. Kerr, Propagation of Short Radio Waves, McGraw-Hill, 1990.

[33] www.teagastic.ie. [Online].

[34] www.isi.edu. [Online].

[35] "http://en.wikipedia.org," [Online].

[36] A. Ghasemi, A. Abedi and F. Ghasemi, Propagation Engineering in Wireless Communications, Springer New York, 2012.

[37] J. S. Seybold, Introduction to RF Propagation, John Wiley and Sons Inc., 2005.

[38] M. M. Weiner, Monopole Antennas, Marcel Dekker Inc., 2003.

[39] B. Mahadevan, Operation Management: Theory and Practice, 1st ed., Prentice Hall, 2009, pp. 274-281.

[40] C. E. Otero, W. H. Shaw, I. Kostanic and L. D. Otero, "Multi-Response Optimization of Stochastic WSN Deployments using Response Surface Methodology and Desirability Functions," *IEEE Systems Journal*, vol. 4, no. 1, pp. 39-48, 2010.

Tajudeen O. Olasupo received his B.S. in electrical and electronics engineering from Federal University of Technology, Akure, Nigeria and M.S. in electrical engineering from Florida Institute of Technology (FIT), Melbourne, FL. He is a current PhD student in computer engineering at FIT. His primary research interests include wireless sensor networks, wireless communications, microwave radio propagation, remote monitoring & control, Big data, and embedded & network programming.
He is currently Teaching Assistant for computer communications, signals & systems and communication laboratory in the department of Electrical & Computer Engineering at the Florida Institute of Technology, Melbourne, Florida. He has over 8 years of industry experience in satellite, cellular & microwave communication systems.
Mr. Olasupo is a student member of the IEEE since 2012. Mr. Olasupo's awards and honors include Florida tech most outstanding graduate student, Florida tech graduate assistantship & scholarship, and outstanding corps member at the paramilitary service for federal republic of Nigeria.

Carlos E. Otero (SM'09) was born in Bayamon, Puerto Rico, in 1977. He received the B.S. degree in computer science, the M.S. degree in software engineering, the M.S. degree in systems engineering, and the Ph.D. degree in computer engineering from Florida Institute of Technology, Melbourne.
He is currently Associate Professor and Co-Director of the Wireless Center of Excellence at Florida Tech. Previously, he was Assistant Professor at University of South Florida and University of Virginia at Wise. He has published close to 70 papers in the areas of wireless sensor networks, internet-of-things, big data, and hardware/software systems. His research interests lie mainly in the performance analysis, evaluation, and optimization of computer systems, including wireless *ad hoc* and sensor networks.
Dr. Otero has over twelve years of industry experience in satellite communications systems, command and control systems, wireless security systems, and unmanned aerial vehicle systems. He is a senior member of the IEEE.

Kehinde O. Olasupo received her B.S. in electrical and electronics engineering from Federal University of Technology, Akure, Nigeria and M.S. in electrical engineering from Delft university of Technology, Netherlands. She is a current PhD student in electrical engineering at FIT. Her primary research interests include RF propagation, personal communication systems, QoS in wireless communication systems, radio planning and optimization, and sustainable energy (solar technology) for low power wireless communication device.
She is currently Teaching Assistant for electrical and electronics circuits in the department of Electrical & Computer Engineering at FIT. She has over 7 years of industry experience in cellular and network operation & maintenance.
Ms. Olasupo is a student member of the IEEE since 2014. Ms. Olasupo's awards and honors include Florida tech graduate assistantship & scholarship, Delft University of Technology faculty scholarship, Delft University of Technology convocation valedictory speech presenter, best female graduating student in the department of electrical & electronics engineering, overall best female graduating student in the school of engineering at Federal University of Technology, Akure, of Nigeria, and Federal Government of Nigeria scholarship award for outstanding academic performance.

Ivica Kostanic obtained BSEE, MSEE and PhD from Belgrade University, Florida Institute of Technology and University of Central Florida respectively. His principal research interests include various topics in radio communication, cellular systems and wireless sensor networks.
Currently, he is faculty member in the Electrical and Computer Engineering department at Florida Institute of Technology where he teaches courses related to wireless communication, personal communication and microwave circuit design. He is the technical director of Wireless Center of Excellence (WiCE) which is a group at Florida Tech dedicated to promoting research in wireless communication and computing technologies.
Dr. Kostanic is a member of the IEEE Communication Society.