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RF PROPAGATION EXPERIMENTS IN AGRICULTURAL FIELDS AND GARDENS FOR WIRELESS SENSOR COMMUNICATIONS

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Abstract—This work presents results for the path loss due to foliage at 2.4 GHz using RF equipment and XBee-Pro ZB S2B transceiver modules in Agricultural fields (Corn, Paddy and Groundnut) and Gardens (Coconut garden with green grass, open lawn with dry green grass and wet green grass) targeting short-range, near ground RF propagation measurements for planning and deployment of Wireless Sensor Communications for precise agriculture and plantation management applications. Path Loss (PL), Path Loss Exponent (PLE) and corresponding Root Mean Square Error (RMSE) values were deduced from the measured RSS from various positions in these environments. Empirical foliage loss prediction models such as COST 235, Early ITU Vegetation and Weissberger models were compared with the experimental results.

1. INTRODUCTION

Wireless Sensor Networks (WSNs) are emerging as a significant technology and are a new paradigm of communication networks. WSNs have applications in variety of fields [1–3] of indoor/outdoor applications such as animal habitats, industrial sensing, health monitoring, consumer and military uses. In the past few years, the WSN has emerged into the research field of agriculture and garden monitoring. It provides a feasible way for low-cost, high-efficiency, and high-productivity agriculture farming [4, 5]. Some agriculture related parameters, such as soil temperature, soil moisture, CO_2, PH value and soil nutrients, could be monitored and then controlled by

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wireless sensor networks [6]. When WSNs are implemented within an agricultural field, the networked sensors can collaborate and aggregate the huge amount of sensed data to provide continuous and spatially dense observations of agricultural and environmental systems [7]. Hence, a sensor network can greatly improve the productivity by increasing situational awareness of the state of the cropland. The sensors are mainly used to monitor the underground conditions of a cropland. Usually the sensing parts of nodes have to be underground, and the buried sensor is connected with the surface antenna via wire [8]. Sometimes it is required that the sensor transceiver is placed near the ground surface. On the other hand, the mature plants in agricultural fields are usually tall and dense. For example, the mature plants are over 2 m for corn, 1 m for paddy, 10 m for coconut and 23 cm for groundnut respectively. When the sensor transceivers near the land surface are surrounded with high-density tall plants in an agricultural field and gardens, the signal transmitted will experience high-level of attenuation due to severe large-scale path loss. In addition, WSN must be able to operate in a range of environments for agricultural applications, from bare fields to orchards, from soybean fields to cornfields, from flat to complex topology, and over a range of weather conditions, all of which affect radio performance. However, there are limited data on radio performance as affected by agricultural setting, and no standard tests are available for qualifying WSN performance in agricultural applications [9].

Schwering et al. performed propagation experiments in vegetation environments under both summer and winter conditions, i.e., with tree in leaf and without leaves. The experimental results show that the range dependence is characterized by a high attenuation rate at short vegetation depths and a reduced attenuation rate at large depth [10]. Al-Nuaimi and Stephens proposed one of the models which express the attenuation as a function of frequency and depth of vegetation gives close predictions for the two broad generic cases of trees "in-leaf" and "out-of-leaf" and can be recommended for use in the range 10–40 GHz [11]. Seville presented a new semi-empirical model based on measurements of vegetation attenuation presented previously, and had some account of the measurement geometry. This model is compared with measured data and shown to give considerably better agreement than that given by previous models [12]. Savage et al. conducted measurements to investigate signal propagation through vegetation. The results show that the leaf state, measurement geometry and vegetation density are more important factors influencing signal attenuation than tree species or leaf shape [13]. Wang and Sarabandi presented the behavior of wave propagation through coniferous forest stands at millimeter-wave frequencies both theoretically and experimentally. A coherent wave propagation model is used to simulate the propagation through foliage [14].

In view of these circumstances, in order to characterize near ground radio link channels for WSNs in agricultural fields and gardens, Radio Frequency (RF) propagation experiments were done at ISM band 2.4 GHz utilizing RF equipments with BPSK modulated transmitted signals on omni-directional antennas and XBee-Pro ZB S2B transceiver modules with integrated whip antenna. Received Signal Strength (RSS) was observed at agricultural fields, gardens and converted into path loss values and compared with Early ITU Vegetation [15], Weissberger et al.'s and Seybold's results in [16, 17] and COST 235 [18] foliage loss prediction models using Matlab simulations. Further, an attempt is made to deduce the Path Loss Exponent (PLE) [19] from our measured RSS values.

2. BACKGROUND AND EXPERIMENTAL DETAILS

2.1. Measurement Details

Case A: RF propagation measurements were made at 2.4 GHz utilizing RF equipment, Vector Signal Generator (Agilent N5182A) as transmitter (Tx) and Vector Signal Analyzer (Agilent N9010A) as receiver (Rx) with vertically polarized omni-directional antennas (both Tx and Rx) of gain 0 dBi at transmitted power of 10 dBm (0.01 watt) and placed at a height of 1.0 m (corn), 15.0 cm (paddy), 15.0 cm (groundnut), 1.0 m (coconut) and 2.0 cm (open lawn) from the ground.

Case B: Similar to Case A, measurements were made at 2.4 GHz using Digi's XBee-Pro ZB S2B transceiver modules at transmitted power of 17 dBm (0.05 watt) with integrated whip antennas (Tx, Rx) of gain 1.5 dBi and placed at a height of 1.0 m (corn), 15.0 cm (paddy) and 15.0 cm (groundnut), 1.0 m (coconut) and 2.0 cm (open lawn) from the ground.

2.2. Environment Description

In order to obtain RSS values, experiments were done in agricultural fields, such as corn, paddy and groundnut fields, as well as in gardens, such as coconut garden with green grass, open lawn with dry green grass and wet green grass. In agricultural fields, we performed measurements during crop growth stage and maturity stage to investigate the difference in vegetation loss values obtained from our RF equipments and XBee-Pro ZB S2B transceiver modules. Fig. 1 illustrates the measurement setup used in our experiments.

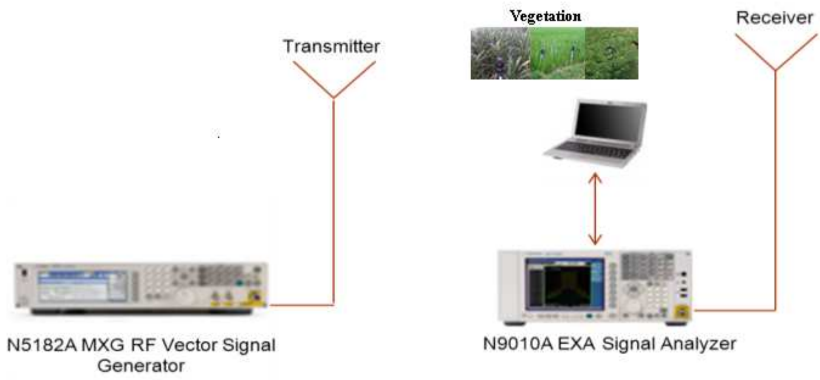

Figure 1. Measurement setup.

Corn Fields: The measurements were carried out in agricultural fields of Sivanthanpatti village, Thanjavur district, Tamilnadu, South India. The height of the corn plant is 1.5 m; the plant stem diameter is 1.8 cm. In maturity stage the height is 2.5 m. Corns are regularly planted in rows. The row width is about 60 cm, and within one row, the corn plants are usually planted 15 cm to 20 cm apart. [GPS Co-ordinates: 10°34'05.25"N, 79°01'12.28"E]. Fig. 2(a) depicts the Tx and Rx positions in corn fields.

Paddy Fields: The paddy fields are located very near to the corn fields in the same village. The height of the paddy crop is 20 cm; the crop stem diameter is 0.2 cm. During maturity stage the height is 1 m. [GPS Co-ordinates: 10°34'02.57"N, 79°01'14.92"E]. Fig. 2(b) depicts the Tx and Rx positions in paddy fields.

Groundnut Fields: Adjacent to the paddy field is groundnut field. The average height of the plants is 18 cm; the average diameter of crop stems is about 0.5 cm. At maturity stage, the crop approximately is 23 cm. [GPS Co-ordinates: 10°33'54.74"N, 79°01'21.02"E]. Fig. 2(c) depicts the Tx and Rx positions in groundnut fields.

Coconut garden with green grass: The measurements were conducted in SRM University campus, Kattankulathur, Kanchipuram district, Tamilnadu, South India. The height of the coconut tree is 10 m; the tree stem diameter is 1 m. Coconut trees are regularly planted in rows. The row width is about 80 cm, and within one row, the coconut trees are usually planted 30 cm to 40 cm apart. [GPS Co-ordinates: 12°49'25"N, 80°2'39"E]. Fig. 3(a) depicts the Tx and Rx positions in coconut gardens.

Open Lawn with dry and wet green grass: The open lawn with dry and wet green grass is located very near to the coconut garden in

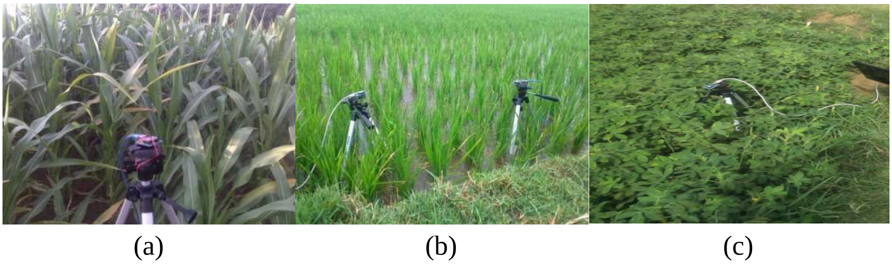

Figure 2. Measurement locations: (a) Corn field, (b) paddy field, (c) groundnut field.

Figure 3. Measurement locations: (a) Coconut garden with green grass, (b) open lawn with green grass.

the SRM University campus. The height of the grass is 10 cm; the crop stem diameter is 0.2 cm. [GPS Co-ordinates: 12°49'25"N, 80°2'41"E]. Fig. 3(b) depicts the Tx and Rx positions in open lawns.

2.3. Empirical Foliage Loss Models

Free Space Loss (FSL) model [20] is represented for radio wave propagation as

$$\mathrm{FSL} = 20\log_{10}(f) + 20\log_{10}(d) - 27.56 \tag{1}$$

where f is the frequency in MHz and d the distance in meters. And, in all wireless environments, the RSS power may be expressed [19] as

$$R_p = T_p + G_t + G_r - PL \tag{2}$$

where R_p is the received power in dBm, T_p the transmitted power in dBm, and G_t and G_r are transmitter and receiver antenna gains respectively in dBi. PL is the path loss in dB. Early ITU Vegetation model [10] was developed from measurements carried out mainly at ultra-high frequency, and was proposed for cases where either transmit or the receive antenna is near to a small groove of trees so that the majority of the signal propagates through the trees.

$$\mathrm{ITU}_L(\mathrm{dB}) = 0.2 * f^{0.3} * d^{0.6}, \quad d < 400\,\mathrm{m} \tag{3}$$

where f is the frequency in MHz and d the depth of the foliage in meters.

Weissberger's modified exponential decay model [11, 12] is applicable where the ray path is blocked by dense, dry, in-leaf trees found in temperature climates. It is applicable in situations where propagation is likely to occur through a grove of trees rather than by diffraction over the treetop.

$$\begin{aligned} W_L(\mathrm{dB}) \;=\; & 1.33 * f^{0.284} * d^{0.588}, \quad 14 < d \leq 400\,\mathrm{m} \\ & 0.45 * f^{0.284} * d, \qquad 0 \leq d < 14\,\mathrm{m} \end{aligned} \tag{4}$$

where f is the frequency in GHz, and d is the depth of the foliage in meters.

COST 235 model [13] proposed based on measurements through a small groove of trees is

$$\mathrm{COST}_L(\mathrm{dB}) = 15.6 * f^{-0.009} * d^{0.26}(\text{in-leaf}) \tag{5}$$

where f is the frequency in MHz and d the depth of the foliage in meters.

To assess the wider application of models, Root Mean Square Error (RMSE) [20] between the models and the observed data were calculated. The RMSE is a frequently used measure of the difference between values predicted by a model and the values actually observed from the environment. RMSE is a good measure of accuracy of the models. Generally, RMSE is given by Equation (6), where X_{obs} is observed values, $X_{\mathrm{mod}\,el}$ the modeled values, and n the number of samples.

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}\left(X_{obs,i} - X_{\mathrm{mod}\,el,i}\right)^2}{n}} \tag{6}$$

3. OBSERVATIONS/RESULTS

In order to study the short-range near ground radio wave behavior in agricultural fields and gardens, some RF propagation measurements were conducted to gain practical insight on the short-range near ground wireless communications.

The measured and predicted path losses in agricultural fields using RF equipments and XBee-Pro modules are shown in Fig. 4 and Fig. 5 along with the various vegetation loss models at 2.4 GHz. Table 1 and Table 2 show the path loss values in agricultural fields during growth stage and maturity stage achieved using RF equipments and XBee-Pro modules respectively. From Table 1 and Table 2, it is evident that path loss values are higher in maturity stage than growth stage. This is due to type of vegetation and its density, high crop plant, wide stem diameter and long leaves which tend to increase the path loss in agricultural fields [21]. When considering the case of corn field, 0.6 of the first Fresnel zone radius along the path is less than the antenna height, and hence the vegetation attenuation is mainly caused by free space loss and canopy reflection. In the case of paddy

Table 1. Path loss values in agricultural fields using RF equipments.

Vegetation Depth (m)	Corn Field (dB)		Paddy Field (dB)		Groundnut Field (dB)	
	Growth Stage	Maturity Stage	Growth Stage	Maturity Stage	Growth Stage	Maturity Stage
5	82.5	91.5	82.5	91.0	84.5	93.0
10	88.0	96.0	87.5	95.5	89.5	98.0
15	92.0	100.5	91.5	99.0	94.5	103.5
20	96.5	105.0	95.0	103.0	97.5	107.0

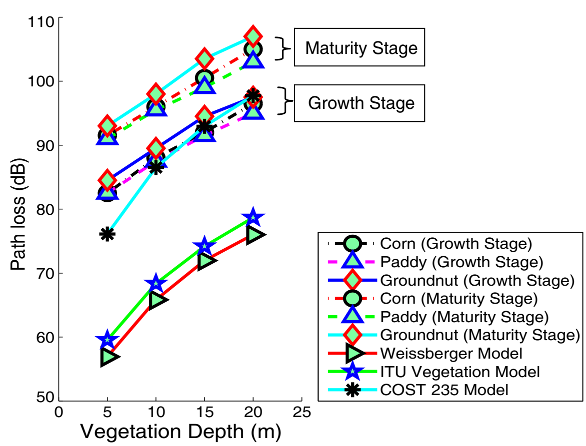

Figure 4. Measured and predicted path loss in agricultural fields using RF equipments.

Table 2. Path loss values in agricultural fields using XBee-Pro modules.

Vegetation Depth (m)	Corn Field (dB)		Paddy Field (dB)		Groundnut Field (dB)	
	Growth Stage	Maturity Stage	Growth Stage	Maturity Stage	Growth Stage	Maturity Stage
5	80	90	79	89	81	92
10	86	94	84	93	85	96
15	90	99	88	98	92	102
20	93	103	91	102	95	105

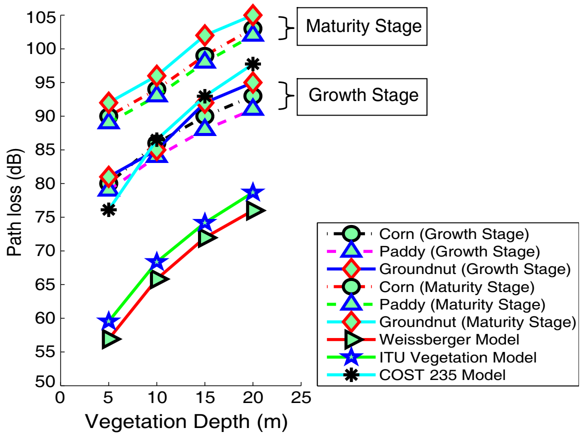

Figure 5. Measured and predicted path loss in agricultural fields using XBee-Pro modules.

field and groundnut field, the ground reflection plays a major role and significantly influences path loss.

Table 3 shows the path loss values obtained using RF equipments and XBee-Pro modules in garden environment. From Table 3 it is clear that path loss values increase with the increase in vegetation depth in all garden environments. The main reason for the increase in path loss due to foliage seen in the gardens could be due to dense bushes and shrubs that are obstructing the line-of-sight between transmitter and receiver. The most important effect in coconut garden seems to be the diffraction by tree trunks which augments the vegetation loss. In the case of open lawn with dry green grass, the antenna height (2 cm) is much less than the wavelength (12.5 cm), so the increase in path loss is due to a surface wave attenuated by the green grass. When

Table 3. Path loss values in gardens using RF equipments and XBee-Pro modules.

Vegetation Depth (m)	Coconut Garden with green grass (dB)		Open Lawn with dry green grass (dB)		Open Lawn with wet green grass (dB)	
	RF Equipments	XBee-Pro modules	RF Equipments	XBee-Pro modules	RF Equipments	XBee-Pro modules
5	81	78	83	79	82	80
10	86	83	88	82	87	83
15	92	88	93	87	92	87
20	96	93	98	92	97	91

Table 4. Path loss values predicted by empirical foliage loss models.

Vegetation Depth (m)	Weissberger Model (dB)	Early ITU Model (dB)	COST-235 Model (dB)
5	56.9	59.5	76.1
10	65.8	68.3	86.5
15	71.9	74.1	92.9
20	76.0	78.6	97.7

measuring in the open lawn with wet green grass, the foliage was wet due to slight drizzle, which certainly increased the measured path loss. Table 4 shows the path loss values predicted by empirical foliage loss models. The measured and predicted path loss in gardens using RF equipments and XBee-Pro modules has been shown in Fig. 6 and Fig. 7 along with the various vegetation loss models at 2.4 GHz.

Figures 8–10 show Root Mean Square Error (RMSE) values at crop growth stage, maturity stage and gardens, respectively. Both Early ITU Vegetation model and Weissberger model are under predicting when compared with the measured path loss. These models were mainly prepared from the data gathered from measurements in

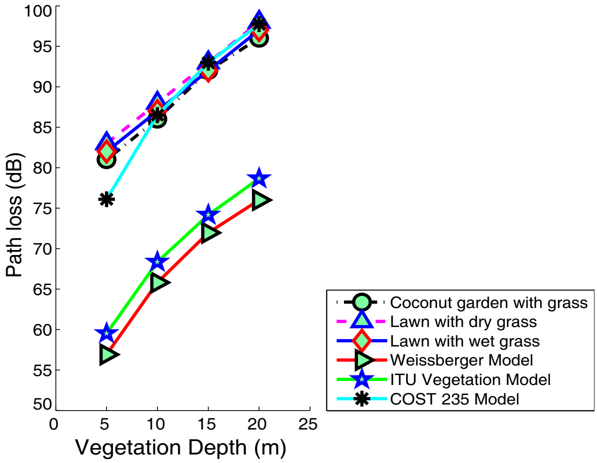

Figure 6. Measured and Predicted Path loss in Gardens using RF equipments.

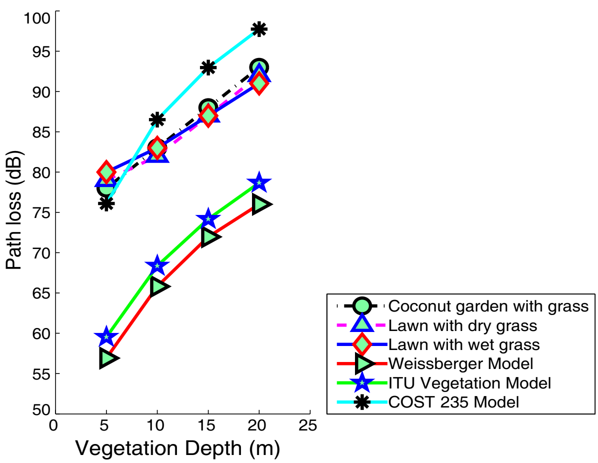

Figure 7. Measured and predicted path loss in gardens using XBee-Pro modules.

temperate climate. However, the type of vegetation found in tropical climate is different from that of temperate climate. Crops found in tropical climate have broad leaves with waxy leathery or hairy texture. It allows the rain water to run off easily and minimizes the loss of moisture through transpiration. Some leaves are narrow with downward pointing tips. It helps the crops to adapt to the high

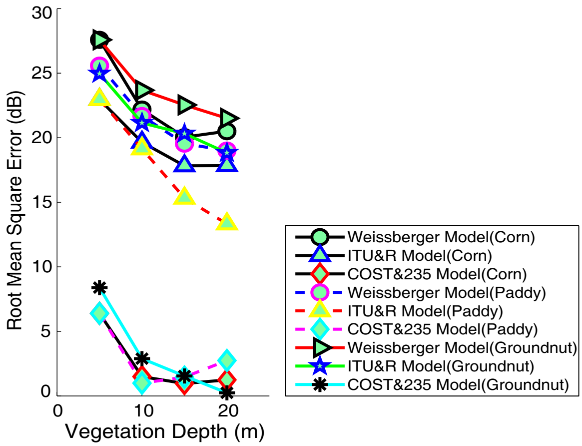

Figure 8. Root mean square error in agricultural fields during crop growth stage.

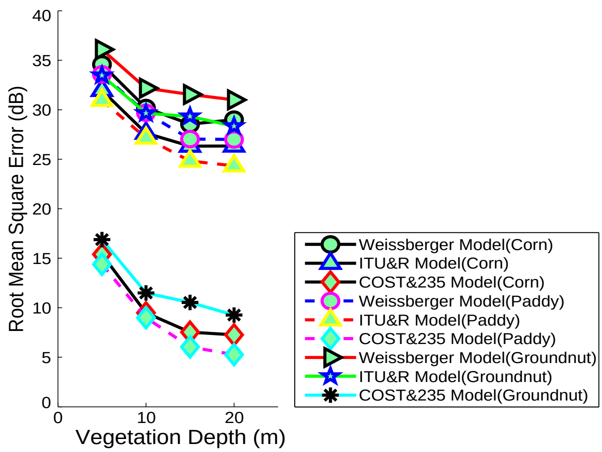

Figure 9. Root mean square error in agricultural fields during crop maturity stage.

amount of precipitation and allow rainwater to flow quickly off the leaves. Therefore, the vegetation in tropical climate has high moisture retaining capacity.

During the growth and maturity stages of crops, wireless sensor networks in agricultural fields and gardens will face different weather conditions. In addition, the humidity in agricultural fields and gardens is usually much higher than that in other places [22]. The humidity

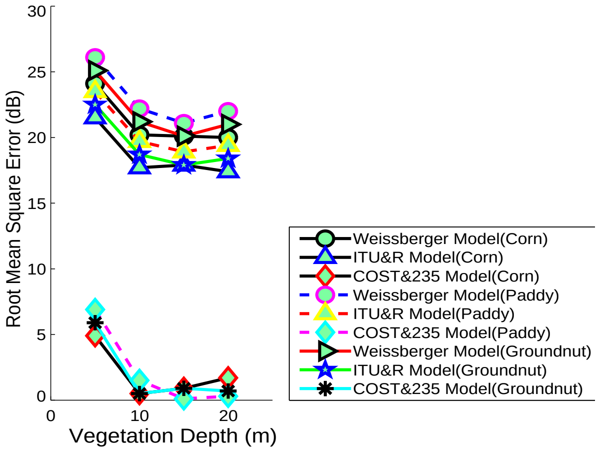

Figure 10. Root mean square error in gardens.

in the vegetation is an important parameter that determines its dielectric properties and, as a consequence, influences radio wave propagation [21]. The relative humidity in tropical climate like Sivanthanpatti village and Kattankulathur, where we have done our experiments can reach as high as 74% (very humid) in a typical August/October day. The relative humidity of Sivanthanpatti village and Kattankulathur ranges from 67% to 74% over the course of the year [23]. The high level of humidity as that of Sivanthanpatti village and Kattankulathur significantly increases the attenuation due to vegetation [24]. Further, with the WSN application in mind we have used very low power of 10 dBm at low antenna height of 15 cm. These could be the reasons for under prediction and high RMSE values for Early ITU Vegetation model and Weissberger models.

Early ITU, Weissberger and COST 235 models depend only on frequency and distance. For each type of vegetation, RMSE was plotted to predict which model is most suitable for WSN planning and deployment in agricultural fields and gardens. It is observed that COST 235 model is showing smallest RMSE in agricultural fields and gardens. It is apparent that the prediction accuracy of COST 235 model is quite high as compared to other models. Though COST 235 model is based on measurements made at millimeter wave frequencies, the dense leaves and the highly humid environment is resulting in higher path loss making COST 235 model more suitable for modeling in the agricultural fields and gardens. The prediction accuracy of COST 235 model is higher in the crop growth stage as compared to the maturity stage in agricultural fields.

Further, we have deduced 'n', the Path Loss Exponent (PLE), values [14] utilizing (7). Table 5 and Table 6 show the observed PLE values from our experiments in agricultural fields and gardens respectively.

$$PL(d) = PL(d_0) + 10 * n * \log\left(\frac{d}{d_0}\right) + S \quad (7)$$

whereas $PL(d)$ is the measured average path loss in dB, $PL(d_0)$ the reference distance path loss in dB, n the path loss exponent, and S for shadow fading. Since our application is intended for short-ranges, the reference distance $d_0 = 1\,\text{m}$ has been taken. The reference distance path loss $PL(d_0)$ is taken to be the free space path loss at 1 m. Similarly, the shadow fading $S = 0\,\text{dB}$ has been taken.

Table 5. PLE values in agricultural fields.

Fields	**Growth Stage**	**Maturity Stage**
Corn Field	4.90	5.77
Paddy Field	4.85	5.47
Groundnut Field	5.08	5.97

Table 6. PLE values in gardens.

Fields	**PLE Values**
Coconut garden with green grass	4.70
Open lawn with dry green grass	4.90
Open lawn with wet green grass	4.80

In open lawn with green grass environment, we noticed that PLE values decrease with the increase in vegetation depth, which may be due to the surface wave attenuated by the green grass which tends to add towards the received signal, and hence the path loss exponent is lower for wet green grass when compared with dry green grass.

4. CONCLUSIONS

In this paper existing empirical foliage loss models have been compared with the measured path loss to find the suitability of the foliage loss models for WSN planning and deployment in agricultural fields and gardens. The Early ITU vegetation and Weissberger models show very poor prediction accuracy in all of these environments. This poor prediction is due to the high humidity in the tropical climate, low antenna height and the use of low transmitter power of 10 dBm which was set considering the various WSN applications.

Path loss is more in maturity stage because of the dense grown up leaves and stems obstructing the line-of-sight between the transmitter and receiver antenna. The free space loss, ground reflection, canopy reflection and diffraction by tree trunks have huge impact on augmenting the vegetation loss in agricultural fields and gardens. We also noticed that path loss exponent 'n' values vary from 4.85 to 5.08 during growth stage and 5.47 to 5.97 during maturity stage in agricultural fields. Similarly, the PLE values vary from 4.70 to 4.90 in gardens. Results show that the COST 235 model gives consistently low RMSE's when there is vegetation in the line-of-sight path. Overall, it is concluded that COST 235 model is suitable for WSN planning and deployment in agriculture fields and gardens. Our contributions in this work towards propagation losses in agriculture fields and gardens will be very valuable to wireless sensor network planners and for precision agriculture technologies which are expected to flourish over the next years.

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