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RF PROPAGATION INVESTIGATIONS AT 915/2400 MHz IN INDOOR CORRIDOR ENVIRONMENTS FOR WIRELESS SENSOR COMMUNICATIONS

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Abstract—Propagation of Radio Frequency (RF) waves in indoor corridors is very complex and diverse as the propagation effects in the indoor scenarios are those that change over fractions of wavelength. Therefore, understanding of RF propagation characteristics is vital for the design of air interface and estimation of propagation losses is very much needed especially for wireless networks such as randomly deplorable Wireless Sensor Communications. In this research work, short-range, near floor/ground RF propagation path loss measurements at low antenna heights of 2 cm and 50 cm from the floor were made in typical narrow and wide straight indoor corridors at 915/2400 MHz in a modern multi-storied building utilizing RF equipment. Comparisons between measured and simulated path loss values were made utilizing Matlab simulations of Ray-tracing technique, free space and ITU-R models. Mean path loss exponent values were deduced from the measured data. The research work reported in this paper is predominately geared towards characterizing radio link for Wireless Sensor Communications/Networks in typical indoor corridor environments.

1. INTRODUCTION

In recent years, the world has witnessed the emergence of Wireless Sensor Networks (WSNs) in various fields ranging from health care, military surveillance to indoor navigation and home automation [1–3]. WSNs have emerged as a significant technology and have the potential to revolutionize the harnessing of data from the physical

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world, enabling applications that previously were not practical and are attracting increased interest for applications in a variety of fields. Measuring, monitoring and controlling nearly any process has become feasible with the current generation of wireless sensors. The work reported in this paper is part of a larger effort to model the WSN radio link in a range of settings within the Indian sub-continent. Some amount of work has been performed to characterize the WSN radio link in other countries [4–8], no results have been reported for WSN scenarios in India. The differences in building materials and construction practices in India when compared to the other countries in which WSN radio-link studies have been performed suggest that indoor propagation might also be different [9].

Radio propagation measurements have been performed and models developed for cellular frequencies (824–894 MHz) [10–13] and propagation path loss measurements have been performed in the VHF/UHF bands [14–18]. However, those measurements are not directly applicable to WSNs scenario because the sensor node antennas are likely to lie on or near the ground/floor (0 to 30 cm height) as opposed to a person holding a mobile phone ($\sim$ 1.5 m off the ground) and the environments in which wireless sensor nodes deployed are typically different from the cellular network scenarios. Around 11 dB decrease in signal strength was observed when a cellular phone user lowers from a standing position to a lying position by Welch et al. [4]. Abiola and Jeff [19] presented near-ground propagation models at 915 MHz based on field measurement data for open fields, woods and wooded hill environments. The effects of these environments on coverage area are explored for various power transmission levels. Channel propagation measurements at 800–1000 MHz were performed with ground-lying antennas by Sohrabi et al. [5]. The range of path loss exponent and shadowing variance for indoor and outdoor environments were determined. Foran et al. [6] analyzed the effects associated with placing a man-portable radio transceiver very near the ground (3–28 cm) using a 2-Ray model. A significant decrease in signal strength of 16.8 dB was observed at 915 MHz when a soldier drops from the crouched position to the prone position. Also, an additional set of channel measurements was performed to study the effect of rain on near-ground propagation at 1900 MHz in a forest environment. Wyne et al. [20] proposed a statistical model for indoor office wireless sensor channels and presented in-depth analysis of the propagation channels of typical sensor node locations in office environments utilizing ricean factor. Willis and Kikkert [21] described the development of a suitable long-range ad-hoc propagation model to predict the signal-to-noise ratio (SNR) for radio links over irregular terrain. Narrowband

and wideband channel measurement results at 300 and 1900 MHz were presented for near-ground propagation, characterizing the effect of antenna heights, radiation patterns and foliage environments by Joshi et al. [7]. Molina et al. [8] performed channel measurement campaigns in open quasi-ideal area, a university yard and a park at 868 MHz for WSNs. Yarkoni and Blaunstein did a semi empirical approach and the analytical model on how to predict the total path loss in various indoor communication links. Also done path loss experiments in indoor corridor environments utilizing laptop LAN cards [9]. Taha-Ahmed et al. [22] performed short-range propagation loss measurements in indoor corridors at 5.6 GHz band. It has been noted that the multipath induced fading tends to have Normal Distribution at low distance between the transmitting and the reception antennas. Also the human being obstruction causes an extra propagation loss of 2 to 10 dB.

Given the sensitive dependence of WSN performance on the radio link, any differences that exist should be understood before deploying WSNs. Robust communications is essential in the overall performance of sensor networks, as sensor measurements and control commands are transmitted over wireless links connecting the nodes. The major factors to be considered in the WSNs are the propagation losses and antenna placement. Wireless sensor transceiver systems typically have their antenna elements (transmitter and receiver) located at or near ground/floor. In most of the scenarios antenna in a WSN node is placed very close to the ground. Antenna impedance and field pattern fluctuate with varying height above the ground plane [23, 24] regardless of the antenna orientation especially with omni-directional antennas [23]. Furthermore non-uniform ground dielectric properties can also affect the path loss and finite conductivity of the ground cannot be ignored in the near-ground radiation problem [24, 25]. Precise estimation of propagation losses offers proper selection of transmitter locations and hence the radio link characteristics near the ground should be properly understood especially for WSNs. Further, equipped with the strides in indoor localization technologies, the focus is now on applications that will change our day to day life such as indoor navigation with the aid of maps, object tracking, surveillance and location information. To understand the possible unique nature of WSN radio-link propagation in indoor corridors, near floor RF propagation measurements and simulations were made at 915/2400 MHz utilizing RF equipment and Matlab simulations. The next section provides experimental details followed by comparison of measured/modeled observations with conclusions.

2. EXPERIMENTAL DETAILS

2.1. Measurement Details

Measurements were made in Narrow Straight Corridor (NSC) and Wide Straight Corridor (WSC) in a modern multi-storied building, which is made-up of concrete and steel. The corridors are situated in Tech Park building at SRM University, Chennai, India (GPS Coordinates: 12°49′29.35″N and 80°02′43.40″E). The transmitter-receiver separation distance was 10 m in NSC and 8 m in WSC. The receiver was kept stationary and the transmitter is placed at each distance, i.e., (1 m, 2 m, 3 m, 4 m, ..., 10 m) to get the received power values. Repeated measurements were performed at each distance on the same day in an interval of 15–20 minutes to obtain the necessary received power values and an average of received power was taken to compute the path loss. Figure 1 illustrates the measurement set-up

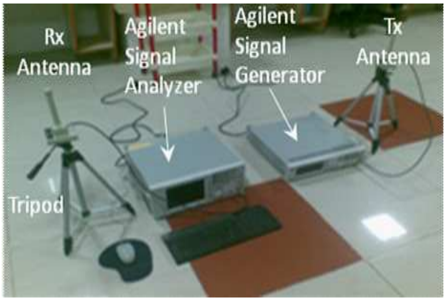

Figure 1. Measurement set-up.

Table 1. Summary of parameters and equipments used in measurement.

Parameters/Equipment	Values/Description
Transmitter	Agilent Signal Generator (N5182A)
Receiver	Agilent Signal Analyzer (N9010A)
Frequency	915/2400 MHz
Antenna Gain	915 MHz with 0 dBi 2400 MHz with 0 dBi/4 dBi
Modulation	BPSK
Filter	Gaussian, Filter-roll-off factor = 0.5
Transmitted Power Level	10 dBm (power at antenna input)

used in our experiments.

Table 1 provides equipment and parameters used in our experiments. The measurement signal from the Signal Generator at 915 and 2400 MHz is a BPSK modulated signal and the received signal is demodulated using Agilent's 89600 Vector Signal Analyzer software tool through Signal Analyzer equipment via omnidirectional antennas as shown in the Figures 1, 2 and 3. In Agilent 89600 Vector Signal Analyzer software, by placing the marker at peak position in Spectrum channel, we can get the received power values in dBm. Then using Equation (1), measured path loss (L_p) can be computed.

$$P_r = P_t + G_t + G_r - L_s - L_p \tag{1}$$

where P_r = Average received power (dBm), P_t = Transmitted power (dBm), G_t = Transmitter gain (dBi), G_r = Receiver gain (dBi), L_s = System loss factor, L_p = Measured path loss (dB). Considering Equation (1), for example if, $P_r = -45$ dBm, $P_t = 10$ dBm, $G_t = 0$ dBi, $G_r = 0$ dBi and $L_s = 0$, then the measured path loss (L_p) will be 55 dB.

2.2. Environment Description

Narrow Straight Corridor: RF propagation measurements are made in a Narrow Straight Corridor (NSC) of 14.0 m length, 1.83 m wide and 2.52 m height. The left and right walls of the NSC are made of concrete (relative permittivity [11, 25–28] $\varepsilon_r = 7.0$) with glass windows ($\varepsilon_r = 4.0$). Concrete ceiling is covered with gypsum board ($\varepsilon_r = 3.0$). **Case A:** The floor of the corridor is covered with porcelain tiles ($\varepsilon_r = 6.0$). **Case B:** Plywood ($\varepsilon_r = 2.0$) were placed on the floor covering the measurement space. The lights and the AC were switched ON during the measurement in both cases. Figure 2 depicts measurement environment in Narrow Straight Corridor.

Wide Straight Corridor: Measurements are made in a Wide Straight Corridor (WSC) of 10.0 m length, 2.82 m wide and 3.1 m

Figure 2. Narrow straight corridor.

Figure 3. Wide straight corridor.

height. The left and right walls of the WSC are made of concrete ($\varepsilon_r = 7.0$) with iron grilled glass windows. The ceiling is also made of concrete. **Case A:** The floor is filled with Green Granite ($\varepsilon_r = 7.75$). **Case B:** Plywood ($\varepsilon_r = 2.0$) were placed on the floor covering the measurement space. Figure 3 depicts measurement environment in Wide Straight Corridor.

3. SIMULATIONS AND THEORETICAL BACKGROUND DETAILS

Matlab simulations were executed utilizing a deterministic approach of a simple 2-D Ray-tracing technique based on classical geometrical optics and image method [11, 13] to account for the direct ray and reflected rays from wall, floor and ceiling, respectively.

The Ray-tracing and ITU-R model considered here are for indoor environments. The Ray-tracing method is among the available methods for the relatively accurate estimation of field strengths to deal with the type of complex layouts in indoor environments. The 2-Ray model [11] can be a helpful tool in predicting the received power (R_R). It can further serve in the development of multi rays (Ray-tracing) model. It considers the direct ray and the ground reflected ray where the received power is given by Equation (2).

$$R_R = T_R \left(\frac{\lambda}{4\pi}\right)^2 a_t a_r \left| \frac{e^{-jkd_1}}{d_1} + R(\theta)\frac{e^{-jkd_2}}{d_2} \right|^2 \tag{2}$$

where λ is the wavelength, k the wave number, d_1 the length of the direct path, d_2 the length of the ground reflected path, a_t and a_r the directional functions of transmitter and receiver, $R(\theta)$ the reflection coefficient of the reflected ray on the reflecting surface, and T_R the transmitted power. The modeled received power using Matlab simulations is converted into path loss [11, 13] using the Equation (3).

$$\mathrm{PL}\,(\mathrm{dB}) = 10 \log_{10} \frac{T_R}{R_R(d)} \tag{3}$$

where PL (dB) is the path loss in dB, T_R transmitted power, and $R_R(d)$ the received power at distance d [11]. Further, for comparison/evaluation purpose, Matlab simulation of ITU-R site-general model [29] was performed as well. The site-general model of ITU-R requires little path or site information. The indoor radio path loss is characterized by both an average path loss and its associated shadow fading statistics. The distance power loss coefficients include an implicit allowance for transmission through walls and through obstacles, and for other loss mechanisms likely to be encountered within a single floor of a building and the model propagation loss is represented as Equation (4).

$$\mathrm{PL_{total}}\,(\mathrm{dB}) = 20\log_{10}(f) + N\log_{10}(d) + L_f(n) - 28 \qquad (4)$$

where N is the distance power loss coefficient, f the frequency (MHz), d the separation distance between transmitter and receiver (m), L_f the floor penetration loss factor (dB), and n the number of floors between transmitter and receiver ($n \geq 1$).

To perform simulations, $N = 33$, $L_f = 0$, $n = 1$, $T_R = 10\,\mathrm{dBm}$, $d = 1\,\mathrm{m}$ to $10\,\mathrm{m}$ for NSC and $1\,\mathrm{m}$ to $8\,\mathrm{m}$ for WSC, $\lambda = 0.33$ for 915 MHz and $\lambda = 0.125$ for 2400 MHz, $k = 2\pi/\lambda = 19.03$ for 915 MHz and $k = 2\pi/\lambda = 50.24$ for 2400 MHz have been considered. In addition, the height and width of the corridor, height of transmitter and receiver antenna, relative permittivity of ground, wall and ceiling have also been taken into account.

4. OBSERVATIONS/RESULTS

The following figures and tables provide measured and simulated/modeled Path Loss (PL) values obtained in our near ground/floor RF propagation measurements/simulations in indoor corridors at 915/2400 MHz.

4.1. Narrow Straight Corridor Measurement Results

Figures 4, 5, 6 and 7 show 915 MHz simulation and measurement results in NSC for all cases. From the figures it is observed that

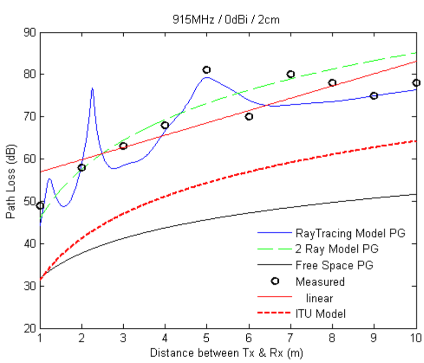

Figure 4. Measured and simulated path loss for Case A at 2 cm height.

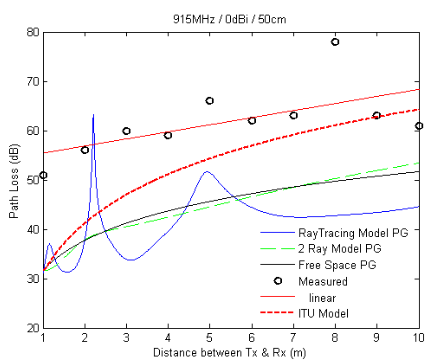

Figure 5. Measured and simulated path loss for Case A at 50 cm height.

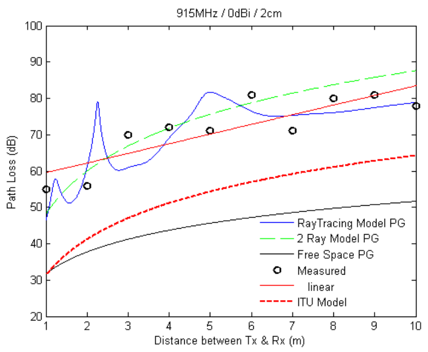

Figure 6. Measured and simulated path loss for Case B at 2 cm height.

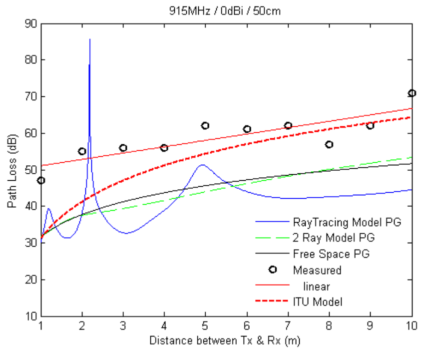

Figure 7. Measured and simulated path loss for Case B at 50 cm height.

the Ray-tracing and 2-Ray simulation are in close agreement to the measured PL values at 2 cm antenna height. However at 50 cm antenna height there is a large variation between the measured and Ray-tracing simulations PL values. The ITU-R model varies largely with the measured PL values in all cases. Also it is noticed that ITU-R model predicts less PL than the measured PL values in all cases. This could be due to close proximity of the antenna to the ground in our measurement setup which could result in RSS degradation. It is observed that the measured values differ from free space PL values by 20 dB to 30 dB on average. Further it is noticed that there is RSS degradation at around 5 to 6 m. This could be due to propagation through the very fine glass door and diffraction from the edge of the glass window at 5 m.

Table 2 shows the maximum, minimum and mean PL values for all cases at 915 MHz. It is observed from measurements that there is better RSS in Case B than in Case A. This could be due to the low relative permittivity of plywood as compared to porcelain tiles. Also it is noticed that this is more so in the case of 50 cm antenna height than that of 2 cm antenna height. Further, it is observed that the RSS is better at 50 cm antenna height than at 2 cm antenna height in all cases, because of degradation of RSS as antenna height approaches the ground [24]. In Case A it is observed that there is attenuation of almost 7 dB when the antenna height is decreased from 50 cm to 2 cm from the ground. Also in Case B it is observed that there is attenuation of almost 12 dB when the antenna height is decreased from 50 cm to 2 cm from the ground.

Figures 8, 9, 10, 11, 12 and 13 show 2400 MHz simulation and

Table 2. Summary of PL values in a narrow straight corridor at 915 MHz.

All Values in dB	Maximum	Minimum	Mean
Free Space Loss	51.67	31.67	41.67
ITU-R Model	64.23	31.23	47.73
Case A/Ant. Ht. 2 cm			
Ray-tracing Model	79.26	44.15	63.68
2-Ray Model	85.1	45.88	65.36
Measured Omni-Dir. Antenna	82.97	57.46	70.22
Case A/Ant. Ht. 50 cm			
Ray-tracing Model	63.43	31.2	39.61
2-Ray Model	53.43	31.62	41.19
Measured Omni-Dir. Antenna	70.27	55.82	63.04
Case B/Ant. Ht. 2 cm			
Ray-tracing Model	81.75	46.44	66.13
2-Ray Model	87.61	48.19	67.8
Measured Omni-Dir. Antenna	84.16	61.43	72.79
Case B/Ant. Ht. 50 cm			
Ray-tracing Model	96.18	30.15	39.43
2-Ray Model	53.38	31.7	40.98
Measured Omni-Dir. Antenna	68.35	51.02	59.68

measurement results in NSC for all cases. From the figures it is observed that the Ray-tracing and 2-Ray simulations are in close agreement to the measured PL values at 2 cm antenna height. The ITU-R model varies largely with the measured PL values in all cases. Also it is noticed that ITU-R model predicts less PL than the measured PL values in all cases. It is observed that the measured values differ from free space PL values by 16 dB to 30 dB on average. It is noticed that the RSS degradation occurs around 5 m to 6 m due to the presence of glass door which could be because of the difference in relative permittivity of glass and concrete. However it is not as prominent as in the case of 915 MHz.

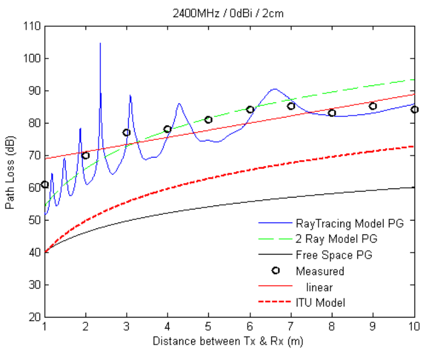

Figure 8. Measured and simulated path loss for Case A at 2 cm height.

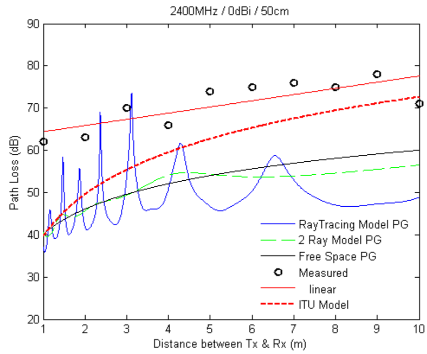

Figure 9. Measured and simulated path loss for Case A at 50 cm height.

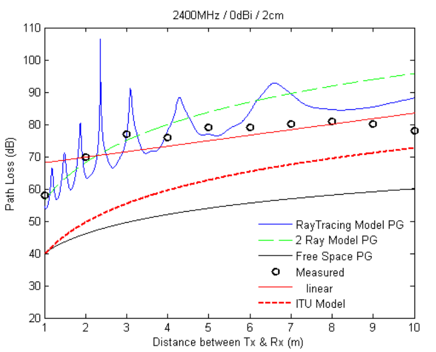

Figure 10. Measured and simulated path loss for Case B at 2 cm height.

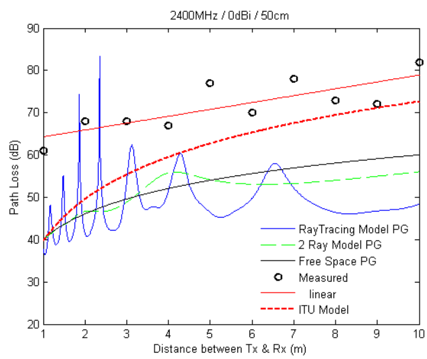

Figure 11. Measured and simulated path loss for Case B at 50 cm height.

Table 3 shows the maximum, minimum and mean PL values for all cases at 2400 MHz. It is observed from measurements that there is better RSS in Case B than in Case A. This could be due to the low relative permittivity of plywood as compared to porcelain tiles. Also, the same is observed to be more prominent with 50 cm antenna height than with 2 cm antenna height in all cases. Further in Case A it is observed that there is attenuation of almost 9 dB when the antenna height is decreased from 50 cm to 2 cm from the ground. However in Case B it is observed that there is attenuation of almost 5 dB when the antenna height is decreased from 50 cm to 2 cm from the ground.

Table 3. Summary of PL values in a narrow straight corridor at 2400 MHz.

All Values in dB	Maximum	Minimum	Mean
Free Space Loss	60.05	40.05	50.05
ITU-R Model	69.6	39.6	54.6
Case A/Ant. Ht. 2 cm			
Ray-tracing Model	104.5	51.66	71.59
2-Ray Model	93.35	54.13	73.61
Measured Omni-Dir. Antenna (0 dBi)	93.85	68.58	81.22
Case A/Ant. Ht. 50 cm			
Ray-tracing Model	73.42	35.95	47.41
2-Ray Model	56.51	39.51	49.43
Measured Omni-Dir. Antenna (0 dBi)	79.96	64.50	72.23
Measured Omni-Dir. Antenna (4 dBi)	76.80	59.90	68.35
Case B/Ant. Ht. 2 cm			
Ray-tracing Model	107.4	53.92	73.94
2-Ray Model	95.76	56.34	75.95
Measured Omni-Dir. Antenna	86.34	68.12	77.23
Case B/Ant. Ht. 50 cm			
Ray-tracing Model	80.68	36.42	47.33
2-Ray Model	56.04	40.21	49.41
Measured Omni-Dir. Antenna (0 dBi)	81.10	64.28	72.69
Measured Omni-Dir. Antenna (4 dBi)	76.33	56.85	66.59

Also, in Case A the use of 4 dBi antenna resulted in decrement of mean PL by around 4 dB while in Case B the decrement is observed to be around 6 dB.

Table 4 shows the standard deviation of errors in narrow straight corridor. The error is calculated by determining the difference between the observed PL mean value and the calculated PL mean value. It provides an insight to the suitability of the simulated and modeled methods with measured PL values in our study. It is noticed that in both cases, at 2 cm antenna height the Ray-tracing and 2-Ray models predict less error varying from 1.28 to 9.63 at 2400 MHz and from 4.86 to 6.66 at 915 MHz. The 2-Ray model at 2400 MHz in Case B at 2 cm antenna height predicts the least error of 1.28 whereas the ITU-R model predicts error of 22.63. This could be due to the placement of antenna very near the ground in our measurement, and ITU-R model does not consider antenna height. However, it should be noted that at 50 cm antenna height, ITU-R model predicts lesser error than Ray-tracing simulations.

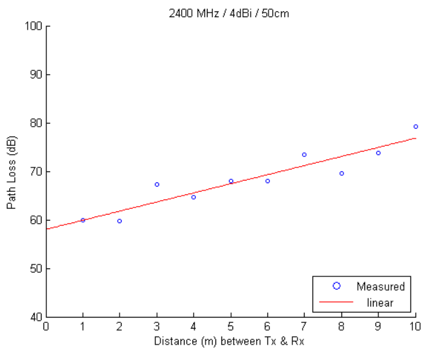

Figure 12. Measured path loss in Case A with 4 dBi at 50 cm height.

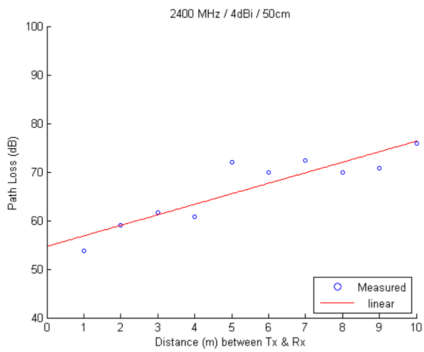

Figure 13. Measured path loss in Case B with 4 dBi at 50 cm height.

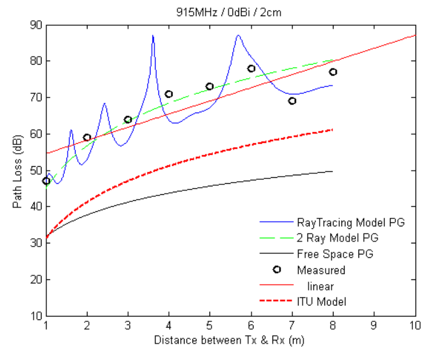

Figure 14. Measured and simulated path loss for Case A at 2 cm height.

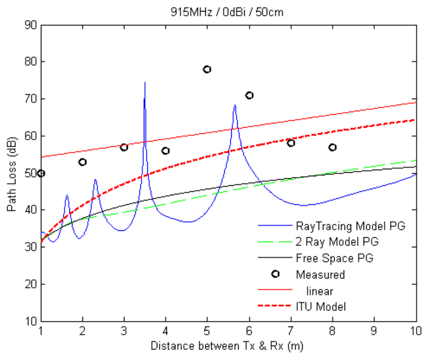

Figure 15. Measured and simulated path loss for Case A at 50 cm height.

Table 4. Standard deviation of model errors in narrow straight corridor at 915/2400 MHz.

Models	915 MHz	2400 MHz
Case A/Ant. Ht. 2 cm/0 dBi		
Free Space Loss	28.55	31.17
Ray-tracing Model	6.54	9.63
2-Ray Model	4.86	7.61
ITU-R Model	22.49	26.62
Case A/Ant. Ht. 50 cm/0 dBi		
Free Space Loss	21.37	22.18
Ray-tracing Model	23.43	24.83
2-Ray Model	21.85	22.8
ITU-R Model	15.31	17.63
Case B/Ant. Ht. 2 cm/0 dBi		
Free Space Loss	30.62	27.18
Ray-tracing Model	6.66	3.29
2-Ray Model	4.99	1.28
ITU-R Model	25.06	22.63
Case B/Ant. Ht. 50 cm/0 dBi		
Free Space Loss	18.01	22.64
Ray-tracing Model	20.25	25.36
2-Ray Model	18.7	23.28
ITU-R Model	11.95	18.09

4.2. Wide Straight Corridor Measurement Results

Figures 14, 15, 16 and 17 show simulation and measurement results at 915 MHz in WSC for all cases. From the figures it is observed that the Ray-tracing and 2-Ray simulations are in close agreement with the measured PL values at 2 cm antenna height. However, at 50 cm antenna height there is a large variation between the measured and Ray-tracing simulation PL values. The ITU-R model varies largely with the measured PL values in all cases. Also it is noticed that ITU-R model predicts less PL than the measured PL values in all cases. This could be due to close proximity of the antenna to the ground in our measurement setup which could result in RSS degradation. It is observed that the measured values differ from free space PL values

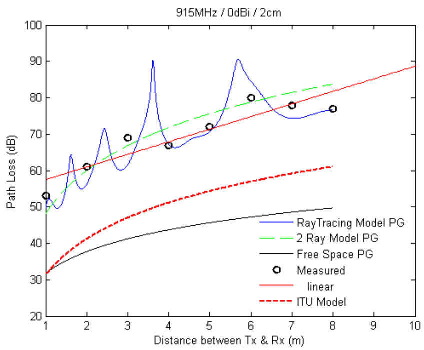

Figure 16. Measured and simulated path loss for Case B at 2 cm height.

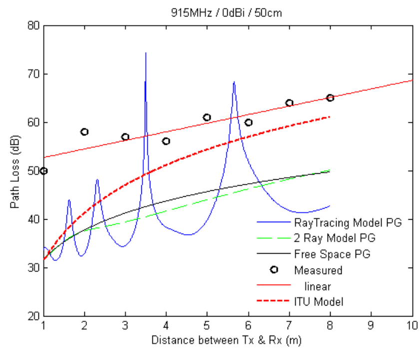

Figure 17. Measured and simulated path loss for Case B at 50 cm height.

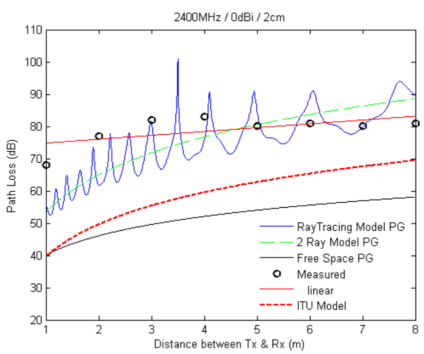

Figure 18. Measured and simulated path loss for Case A at 2 cm height.

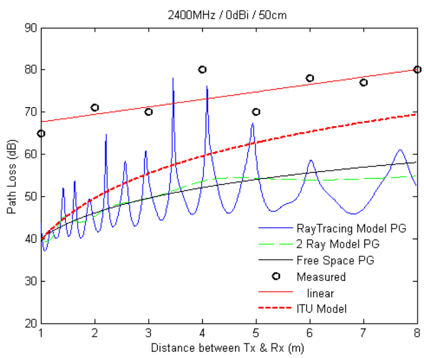

Figure 19. Measured and simulated path loss for Case A at 50 cm height.

by 19 dB to 31 dB on average. Further, it is noticed that there is RSS degradation at around 5 m to 7 m in the measurement. This is probably due to variance in the wall's architecture and transmission loss through iron grilled glass window at 6 m.

Table 5 shows the maximum, minimum and mean PL values for all cases at 915 MHz. It is observed from measurements that there is better RSS in Case B than Case A. This could be due to the low relative permittivity of plywood as compared to green granite. Also it is noticed that this is more so in the case of 50 cm antenna height than that of 2 cm antenna height. Further, it is observed that the RSS

Table 5. Summary of PL values in a wide straight corridor at 915 MHz.

All Values in dB	Maximum	Minimum	Mean
Free Space Loss	49.73	31.67	40.7
ITU-R Model	61.03	31.23	46.13
Case A/Ant. Ht. 2 cm			
Ray-tracing Model	88.54	47.21	62.87
2-Ray Model	81.25	45.88	63.45
Measured Omni-Dir. Antenna	81.49	55.78	68.64
Case A/Ant. Ht. 50 cm			
Ray-tracing Model	75.25	30.76	39.6
2-Ray Model	50.28	31.62	40.04
Measured Omni-Dir. Antenna	67.10	53.47	60.29
Case B/Ant. Ht. 2 cm			
Ray-tracing Model	91.06	49.58	65.31
2-Ray Model	83.75	48.19	65.88
Measured Omni-Dir. Antenna	82.30	58.48	70.39
Case B/Ant. Ht. 50 cm			
Ray-tracing Model	65.71	31.23	39.43
2-Ray Model	50.11	31.7	39.83
Measured Omni-Dir. Antenna	67.81	52.36	60.09

is better at 50 cm antenna height than at 2 cm antenna height in all cases. In Case A, it is observed that there is attenuation of almost 8 dB when the antenna height is decreased from 50 cm to 2 cm. Also in Case B, it is observed that there is attenuation of almost 10 dB when the antenna height is decreased from 50 cm to 2 cm from the ground.

Figures 18, 19, 20, 21, 22 and 23 show 2400 MHz simulation and measurement results in WSC for all cases. From the figures it is observed that the Ray-tracing and 2-Ray simulations are in close agreement to the measured PL values at 2 cm antenna height. The ITU-R model varies largely with the measured PL values in all cases. Also it is noticed that ITU-R model predicts less PL than the measured

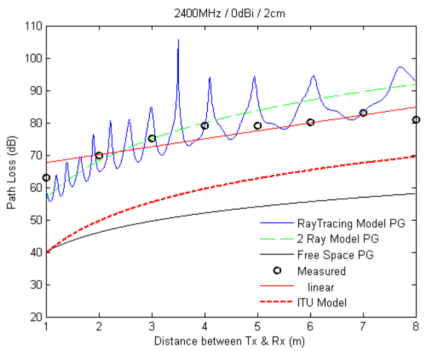

Figure 20. Measured and simulated path loss for Case B at 2 cm height.

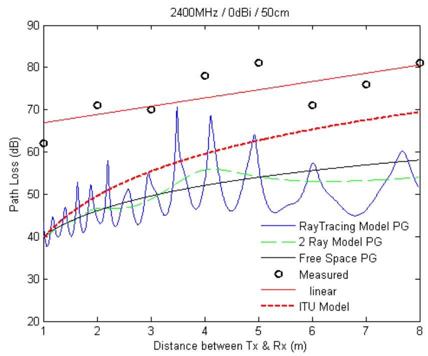

Figure 21. Measured and simulated path loss for Case B at 50 cm height.

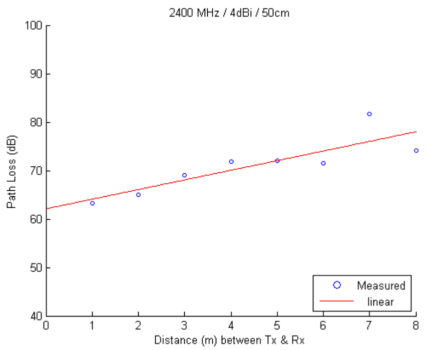

Figure 22. Measured path loss in Case A with 4 dBi at 50 cm height.

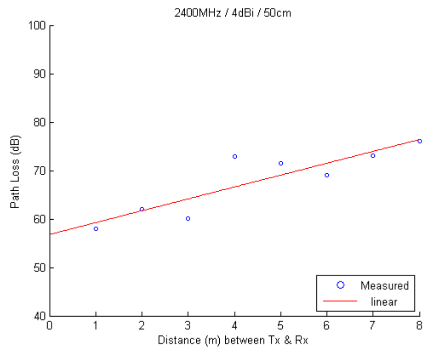

Figure 23. Measured path loss in Case B with 4 dBi at 50 cm height.

PL values in all cases. It is observed that the measured values differ from free space PL values by 17 dB to 31 dB on average. It is noticed that the RSS degradation occurs around 5 m to 7 m due to the presence of wooden door. However it is not as prominent as in the case of 915 MHz.

Table 6 shows the maximum, minimum and mean PL values for all cases at 2400 MHz. It is observed from measurements that there is better RSS in Case B than that in Case A. This could be due to the low relative permittivity of plywood as compared to green granite. Also, the same is observed to be more prominent with 50 cm antenna

Table 6. Summary of PL values in a wide straight corridor at 2400 MHz.

All Values in dB	Maximum	Minimum	Mean
Free Space Loss	58.11	40.05	49.08
ITU-R Model	66.7	39.6	53.15
Case A/Ant. Ht. 2 cm			
Ray-tracing Model	99	53.18	71.09
2-Ray Model	89.5	54.13	71.69
Measured Omni-Dir. Antenna (0 dBi)	87.65	74.24	80.94
Case A/Ant. Ht. 50 cm			
Ray-tracing Model	72.49	37.34	47.99
2-Ray Model	54.71	39.51	48.78
Measured Omni-Dir. Antenna (0 dBi)	82.58	67.72	75.15
Measured Omni-Dir. Antenna (4 dBi)	77.99	64.08	71.03
Case B/Ant. Ht. 2 cm			
Ray-tracing Model	100.5	55.45	73.44
2-Ray Model	91.9	56.34	74.03
Measured Omni-Dir. Antenna	89.22	67.81	78.52
Case B/Ant. Ht. 50 cm			
Ray-tracing Model	70.33	37.86	47.84
2-Ray Model	55.96	40.21	48.81
Measured Omni-Dir. Antenna (0 dBi)	83.82	67.55	75.68
Measured Omni-Dir. Antenna (4 dBi)	76.39	59.24	67.82

height than with 2 cm antenna height in all cases. Further in Case A it is observed that there is attenuation of almost 9 dB when the antenna height is decreased from 50 cm to 2 cm from the ground. However in Case B it is observed that there is attenuation of almost 5 dB when the antenna height is decreased from 50 cm to 2 cm from the ground. Also, in Case A using 4 dBi antenna decreased the mean PL by around 4 dB while in Case B the decrement is observed to be around 8 dB. Further it is observed that mean PL increased with increasing frequency in both NSC and WSC. Also, at 915 MHz mean PL decreased in WSC as

Table 7. Standard deviation of model errors in wide straight corridor at 915/2400 MHz.

Models	915 MHz	2400 MHz
Case A/Ant. Ht. 2 cm/0 dBi		
Free Space Loss	27.94	31.86
Ray-tracing Model	5.77	9.85
2-Ray Model	5.19	9.25
ITU-R Model	22.51	27.79
Case A/Ant. Ht. 50 cm/0 dBi		
Free Space Loss	19.59	26.07
Ray-tracing Model	20.69	27.16
2-Ray Model	20.25	26.37
ITU-R Model	14.16	22.00
Case B/Ant. Ht. 2 cm/0 dBi		
Free Space Loss	29.69	29.44
Ray-tracing Model	5.08	5.08
2-Ray Model	4.51	4.49
ITU-R Model	24.26	25.37
Case B/Ant. Ht. 50 cm/0 dBi		
Free Space Loss	19.39	26.6
Ray-tracing Model	20.66	27.84
2-Ray Model	20.26	26.87
ITU-R Model	13.96	22.53

compared to NSC. However at 2400 MHz mean PL increased in WSC as compared to NSC.

Table 7 shows the standard deviation of errors in wide straight corridor. It is noticed that in both cases at 2 cm antenna height the Ray-tracing and 2-Ray models predict less error which varies from 4.51 to 5.77 at 915 MHz and from 4.89 to 9.55 at 2400 MHz. The 2-Ray model at 2400 MHz in Case B predicts the least error of 4.51. However, it should be noted that at 50 cm antenna height the ITU-R model predicts less error than the Ray-tracing and 2-Ray models.

Furthermore, we have derived PL exponents [11] values from our field strength experiments in indoor corridors utilizing linear regression analysis. The average path loss between the transmitter and receiver is expressed by a function of distance using a path loss exponent, 'n', as follows:

$$\mathrm{PL}(d) = \mathrm{PL}(d_0) + 10n\log(d/d_0) + S \qquad (5)$$

where 'n' is the path loss exponent which indicates the rate of increment of path loss with respect to distance, $\mathrm{PL}(d_0)$ the reference path loss at the reference distance d_0, $\mathrm{PL}(d)$ the measured path loss at the distance 'd', and 'S' for shadow fading. We have taken the reference distance d_0 to be 1 m. For free space propagation the PL exponent [11] is equal to 2. This PL exponents value changes with respect to the changes in multipath propagation and obstruction between transmitter and receiver. The PL and PL exponents information is vital for the coverage of transmitter and optimization in planning and deployment

Table 8. Path loss exponents.

915 MHz	2400 MHz
NSC	
Case A/Ant. Ht. 2 cm/0 dBi	
1.78	1.76
Case A/Ant. Ht. 50 cm/0 dBi	
1.01	1.08
Case A/Ant. Ht. 50 cm/4 dBi	
- - - - -	1.18
Case B/Ant. Ht. 2 cm/0 dBi	
1.59	1.27
Case B/Ant. Ht. 50 cm/0 dBi	
1.21	1.17
Case B/50 cm/4 dBi	
- - - - -	1.36
WSC	
Case A/Ant. Ht. 2 cm/0 dBi	
2.06	1.07
Case A/Ant. Ht. 50 cm/0 dBi	
1.09	1.19
Case A/Ant. Ht. 50 cm/4 dBi	
- - - - -	1.38
Case B/Ant. Ht. 2 cm/0 dBi	
1.91	1.71
Case B/Ant. Ht. 50 cm/0 dBi	
1.24	1.30
Case B/Ant. Ht. 50 cm/4 dBi	
- - - - -	1.37

issues of wireless networks.

Table 8 shows the PL exponents observed at 915/2400 MHz for the NSC and WSC. The PL exponents values are observed to be ranging from 1.01 to 2.06, and in accordance with similar results [11, 30–32] which could be attributed to the evidence of waveguide effects [30–33] due to architectural and structural dimensions, type of construction material and type of interiors of the indoor corridors.

5. CONCLUSIONS

To understand the possible unique nature of WSN radio-link propagation in indoor corridors, comparisons of RF propagation field strength measurements and Matlab simulations at 915/2400 MHz for short-range wireless sensor communication/networks in narrow and wide straight corridors with 2 cm and 50 cm antenna heights is presented in this research work. It is observed that the measured PL values using RF equipment and simulated Ray-tracing and 2-Ray models are in close agreement in all cases at 2 cm antenna height. In our indoor corridors, it is noticed that 2-Ray model predicts lower standard deviation of error values at 2 cm antenna height than other models. It is noted that the PL values given by ITU-R model varies largely with the measured values in all cases. It may be due to the antenna placement near the ground where the RF propagation is more prone to degradation and omni-directional transmission patterns. Also it is observed that the attenuation shows increasing trend with the increase in frequency. The PL exponents values observed in the present study ranges from 1.01 to 2.06. The measured PL exponents being less than free space PL exponents can be attributed to the waveguide effect and construction architectural issues that prevail in indoor corridors.

From our measurement campaign it is noticed that there is lower mean PL in Case B (plywood) than in Case A (porcelain tiles/green granite) and the rate of attenuation with increasing distance is also low. This could be due to the low relative permittivity of plywood than other materials. It can be concluded from the results that the building materials and furnishings can affect indoor propagation. Indoor localization technologies are moving forward with the aid of mapping and object tracking where the available RSS plays a vital role. Thus in this respect as observed from our measurements, the flooring/walls material in indoor environment should be made of low relative permittivity such as plywood which allows better RSS. The value of this present work is that it demonstrates the variation between several measurement approaches and highlights the differences between commonly used modeling techniques. Our efforts in this work towards understanding propagation losses in indoor environments will be very supportive to wireless network planners and for indoor location technologies which are expected to proliferate across very wide variety of consumer devices over the next years.

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