A Model for Predicting Wireless Signal Transmission Performance of ZigBee-Based Sensor Networks in Residential Houses

Hui Li **Lingying Zhao, PhD** *Member ASHRAE* **Peter Ling, PhD** **Jia Liu, PhD**

ABSTRACT

The goal of this study was to establish a path loss model for predicting wireless signal transmission in residential house to guide configuration of reliable wireless network application in multi-zone HVAC system control. Our study focused on ZigBee, a wireless networking protocol tailored for low cost and power consumption sensor networks. Factors affecting wireless data transmission in a residential indoor environment include space separations (e.g., walls, floors, and furniture) and interference from other wireless devices. Effects of these factors on the path loss of wireless channels were quantified through an empirical signal attenuation model based on received signal strength indicator (RSSI) value. The model was validated by comparing the predicted pass loss to the measured loss. The results showed that the mean and the standard deviation of the prediction errors were 7.7±7.1 dB, which is comparable to previous literature research results. Our performance analysis showed that the over-prediction of our path loss model is bounded by 11.8%. The path loss model can be used as a means to determine the sensor locations for reliable networks and to improve the design of wireless transceivers.

INTRODUCTION

In the U.S., ASHRAE is taking a lead in designing and operating net-zero energy buildings. HVAC (heating, ventilation, and air conditioning) systems are widely used to ensure indoor occupants' comfort and health (Nassif and Moujaes, 2008) with significant amount of energy consumption in buildings. On average, HVAC systems consume 28% of total energy in commercial buildings and 43% in residential homes (Wang et al., 2006). Precision control of HVAC systems will significantly contribute to net-zero energy buildings.

Typical residential HVAC systems are single zone HVAC systems (i.e., using one thermostat for an entire house), which are not only energy inefficient, but also ineffective to meet various comfort requirements. (Wang et al., 2003). A significant amount of energy is wasted in heating and cooling unoccupied spaces. Multi-zone HVAC control systems can meet thermal comfort requirements much better and are more energy efficient (Mcdowall, 2007), but they are much more complex due to the large number of sensors and wires. It is costly to run wires in newly built houses for multi-zone HVAC control and even more expensive to retrofit HVAC control systems from one-zone to multi-zone systems in existing houses. Wireless technologies are promising in developing a more affordable multi-zone HVAC control system. Studies have shown 20-80% installation cost reduction potential where wireless technologies are used to replace wired industrial installations that cost $130-160 per meter (Wang et al., 2006).

Wireless sensor networks for HVAC control have received increasing attention from research communities and the industry in recent years. A prominent challenge in application of wireless sensor network is communication reliability (Redfern, et al. 2007). For example, a wireless sensing system for residential buildings was built and tested in several houses by the Center for the Built Environment at the University of California, Berkeley (Arens et al., 2006). Their study demonstrated challenges in achieving reliable communication among the wireless sensors. The locations and communication distances of the base station and sensor nodes were determined by a trial and error approach to assure that the communication range was not exceeded. Furthermore, the test results revealed that other home wireless devices could interfere with the system.

Hui Li is a former graduate research associate with the Ohio State University. He is currently an electrical design engineer with Sky Climber LLC, Delaware, OH. **Lingying Zhao** and **Peter Ling** are associate professors and **Jia Liu** is a postdoctoral researcher in the Department of Food, Agriculture, and Biological Engineering, Ohio State University, Columbus, OH.

The emergence of ZigBee (IEEE 802.15.4), a low-cost and mesh-route capable wireless networking protocol that was not used in the research above, can reduce the cost of wireless systems while improving the reliability of the communication (Osipov, 2008). Molina-Garcia et al. (2007) demonstrated a wireless heating and cooling load monitor and control system using ZigBee. The system performance was found satisfactory, although the communication performance was somewhat affected by noisy wireless channels. Raimo (2006) conducted three case studies on wireless mesh network for building HVAC control systems and indicated that more work was needed to reveal the performance of wireless signal transmission inside buildings. It is clear that ZigBee is a promising protocol for building control. However, it was also reported that 10% of the data was lost in ZigBee-based wireless sensor network in building environments (Arens et al., 2006). Therefore, better understanding of the ZigBee signal path loss in residential house environments through modeling is necessary.

Path loss modeling is an important and widely-used method to predict and evaluate wireless signal attenuation and transmission performance (Lott and Forkel, 2001; Ghassemzadeh and Tarokh, 2003; Ghassemzadeh et al., 2002; Cheung et al., 1998; Panjwani et al., 1996; Andersen et al., 1995; Seidel and Rappaport, 1992). Seidel and Rappaport (1992) developed distance dependent path loss models for wireless communications at 914MHz in multifloored buildings. Path loss models for radio frequencies 900 MHz, 1300 MHz, 1500 MHz, 1900 MHz, and 4000 MHz were developed by Andersen et al. (1995). A multi-wall-and-floor path loss model for 5GHz was developed by considering the materials of walls and floors (Lott and Forkel, 2001). The above research works mainly focused on commercial buildings. Path loss models capturing LOS (line-of-sight) and NLOS (Non-line-of-sight) transmission at 5GHz within residential homes were developed by Ghassemzadeh and Tarokh (2003). However, path loss models for 2.4GHz (the frequency that ZigBee operates at) in residential home environments do not exist. Liechty et al. (2007) refined the empirical path loss model for 2.4GHz in outdoor environment based on Seidel-Rappaport path loss model. Lymberopoulos et al. (2006) characterized the radio signal strength variability in indoor environment (basketball court and test bed) using ZigBee wireless transceivers. The main finding was that antenna orientation could greatly affect the signal transmission. Another path loss model was developed to predict the signal transmission performance of ZigBee wireless sensor network in poultry layer facilities (Darr and Zhao, 2008). However, a good understanding on radio signal attenuation of 2.4 GHz wireless channels in residential home environments remains lacking.

The goal of this work was to quantify the wireless signal transmission performance of ZigBee wireless signals within a residential house environment for installation of reliable wireless sensor networks. Specific objectives include:

- to determine key factors affecting wireless signal transmission in indoor environments of residential houses,
- to develop a path loss model to predict 2.4 GHz wireless signal transmission in residential house environments, and
- to validate the path loss model using field measurement data.

PATH LOSS MODELS FOR WIRELESS CHANNELS: A PRIMER

Wireless signal transmission is based on radio wave propagation through the air. Generally speaking, the signal strength is attenuated by three basic physical phenomena: reflection, diffraction, and scattering, as illustrated in Figure 1 (Rappaport, 2002).

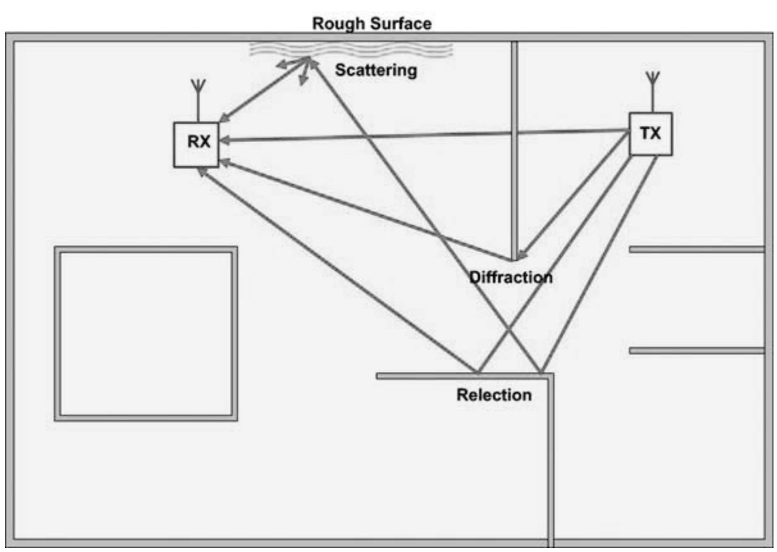


Figure 1 *Wireless signal attenuation due to reflection, diffraction, and scattering.*

Path loss, defined as the difference between the transmitted and the received power levels, is widely used to measure the signal attenuation. In open-space path loss estimation where a dominant line-of-sight (LOS) path exists, it can be theoretically shown that the path loss follows the Friis free space model as shown in Equation 1 (Rappaport, 2002). Here, free space means that there is no obstruction between the transmitting and receiving antennas.

$$P_r(d) = \frac{P_t G_r G_t \lambda^2}{(4\pi d)^2 L} \tag{1}$$

where

- $P_r(d)$ = power received (dBm) at a (transmitter-receiver) separation distance of d, m
- P_t = transmit power, dBm
- G_r = receiver antenna gain, unitless
- G_t = transmitter antenna gain, unitless
- λ = wavelength, m
- L = system loss factor, unitless
- d = transmission distance, m

In Equation 1, the system loss factor L is caused by the communication system hardware. L=1 means that there is no loss due to the communication hardware. Throughout this paper, we assume that L is equal to 1. This assumption is reasonable since the cable loss of the ZigBee module used in our test was only 0.2dB (Digi Datasheets).

The Friis free space equation can be equivalently expressed as the ratio between received and transmitted power levels as follows (Rappaport, 2002):

$$\begin{aligned} PL &= 10 \log_{10} \frac{P_t}{P_r} = -10 \log_{10} \left[\frac{G_t G_r \lambda^2}{(4\pi d)^2}\right] \\ &= -10 \log_{10}\left[\frac{G_t G_r \lambda^2}{(4\pi)^2}\right] + 20 \log_{10}(d) \end{aligned} \tag{2}$$

It can be seen from Equation 2 that the first term in the summation is based only on antenna gains and signal wavelength. This is a constant for a particular wireless link and independent of environmental factors. In contrast, the second term depends only on the transmission distance between a transmitter and a receiver.

Although the Friis model is valid under ideal free space, it usually does not hold in environments where obstructions exist. In such environments, however, accurately predicting path loss is difficult since it is impractical to measure every possible reflection, diffraction, and scattering between the transmitter and receiver. As a result, empirical models are not only desirable but also necessary for path loss estimation. A common strategy in developing empirical models is to retain the structure of the Friis model while introducing new parameters to refine its accuracy. In most path loss modeling, a parameter of n, which is called path loss exponent, is used to characterize how fast the signal attenuates with respect to the communication distance, as Equation 3 shows (Ghassemzadeh et al., 2002).

$$PL = PL(d_0) + 10n\log_{10}\frac{d}{d_0} + X_\sigma \tag{3}$$

The first term on the right-hand-side of Equation 3 is the path loss at a known close-in reference distance d_0, which is usually 1 m for indoor environment (Andersen et al., 1995). X_σ(in dB) is the uncertainty associated with the signal transmission. Typical values of n and X_σ for different communication frequencies in various environments can be found in Andersen et al. (1995). Comparing Equations 2 and 3, it is easy to see that n=2 corresponds to the Friis free space model. To consider obstructions between a transmitter and a receiver, Equation 4 below was proposed (Liechty et al., 2007), where OBS_i denotes obstruction type i and AF_i is the attenuation factor of obstruction type i.

$$PL = PL(d_0) + 10n\log_{10}\frac{d}{d_0} + \sum_t \mathrm{OBS}_i \times AF_i + X_\sigma \tag{4}$$

It was found by Andersen et al. (1995) that the path loss between floors is non-linear with respect to the separation distance. To model the signal attenuation through floors, a floor-attenuation-factor (FAF) was proposed by Panjwani et al. (1996). As a result, the overall indoor path loss model can be written as

$$PL = PL(d_0) + 10n\log_{10}\frac{d}{d_0} + \sum_i \mathrm{OBS}_i \times AF_i + FAF + X_\sigma \tag{5}$$

Using Equation 5, one can predict the path loss of wireless signal through residential house environment with reasonable accuracy by determining the values of n, AF_i, PL (d_0), and FAF. Therefore, our goal was to determine the proper values of all these factors empirically for ZigBee wireless networks in residential house environments.

METHODOLOGY

RSSI (received signal strength indication) is proposed for wireless signal attenuation quantification of our empirical model development effort. The RSSI statistics in most wireless transceivers are readily available, thus eliminating the need for additional hardware on small wireless devices. Moreover, model results based on RSSI provide high comparability among different wireless networks since RSSI is relative to 1 mW transmitted power (Darr and Zhao, 2008; Liechty et al., 2007; Lymberopoulos et al., 2006). Therefore, the path loss models in this paper are derived based on experimental measurements of RSSI and a statistical regression of the data.

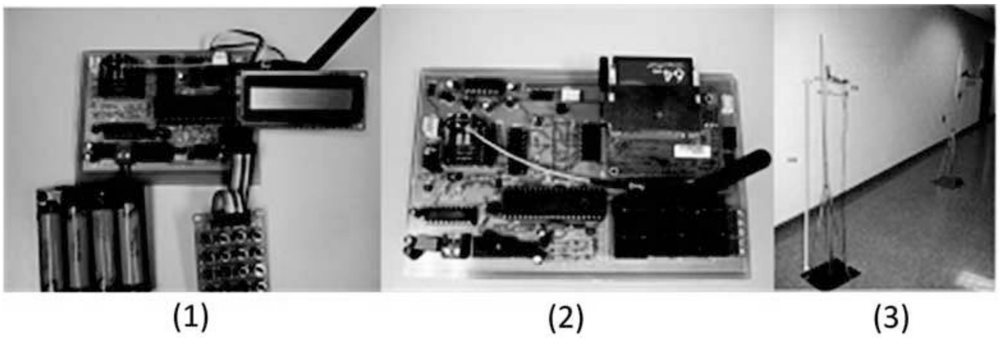


Figure 2 *The hardware and experimental setup for evaluating the wireless signal path loss: (1) Transmitter circuit board with XBee ZNet2.5 ZigBee module mounted, (2) Receiver circuit board, and (3) Custom designed test devices with circuit boards mounted.*

Design of Wireless Test Devices

In order to experimentally quantify the path loss of wireless signal within a residential house environment, a test fixture was designed and constructed by incorporating a ZigBee module with the power conditioning and microcontroller-driven data acquisition circuits. The ZigBee module was selected for the test because it provides an easy serial communication interface with microcontrollers, has multiple controlled transmission power outputs (adjustable from -8 dBm to +4 dBm), and consumes low power (up to 35 mA for transmission, 38 mA for reception if boost mode disabled, and less than 1 µA in sleeping mode). Additionally, the small size and the DIP (dual in-line package) design made it easy to embed XBee modules in custom designed circuit boards. In our tests, the transmit power was chosen to be +4dBm, which was equivalent to 2.5 mW. In our testing device, we used a standard omnidirectional antenna that provided a gain of 2.1dBi. The receiver sensitivity was -96 dBm. The functions and configurations of the XBee ZNet 2.5 module were set up through a series of AT serial commands.

A pair of the test fixture was used to determine the wireless path loss (Figure 2), including one transmitter and one receiver. A microcontroller was embedded in the transmitter board to control the wireless data transmission. A data logging board was connected to the receiver module to acquire and store the data to a compact flash card. Although the ZigBee modules are capable of establishing a mesh network, point-to-point communication was used to evaluate the performance of ZigBee for comparison with other wireless communication protocols. The microcontroller on the transmitter board initialized the transmission by sending a data packet to the receiver via the ZigBee module. Once the receiver received the data, it sent the same data back to the transmitter for acknowledgement. Then, after the transmitter received the acknowledgement, the ZigBee module on the transmitter reported the RSSI data of this link to the receiver and the receiver stored the data to the data logging module. Then, the same procedure was repeated and the transmitter sent the RSSI values to the receiver at 0.5 Hz. During the test, both the transmitter and the receiver were mounted five feet (1.52 m) above the ground to simulate the typical installation height of HVAC sensors and control units.

Test Facility Selection

Four typical two-story colonial style houses were selected for collecting wireless signal transmission data under the influence of key affecting factors. They have the size of approximately 50 feet by 30 feet (15.24 m by 9.14 m) on each floor. The height of rooms is 8 to 9 feet (2.44 to 2.74 m). The houses were built in the past 6 years with wood walls of 2×4 inch (51 × 102 mm) frame and dry-walls. The house floors are also wood structures with either carpets or wood floors. HVAC ducts were installed underneath the first floor and above ceiling in the attics. These four residential houses had similar structures and layouts (Figure 3). Houses 1, 2 and 3 were used to conduct experimental tests to develop the models so that the variation of the room layouts can be accommodated. House 4 was used to validate the developed model.

Experimental Plan and Statistical Analysis

Four factors that affect the wireless signal transmission, namely, transmission distance, wall separation, floor separation, and wireless device interference, were examined using a factorial-randomized complete block design. Measurements of RSSI were conducted within open space and space with obstructions of the houses. The path loss models were derived by experimental measurements of RSSI and a statistical regression of the measurement data.

Single Floor Attenuation. Table 1 shows the experimental test locations for testing the effects of walls and indoor open space on a single floor. The value of 0 for the number of walls represents open space. An example of the sensor locations is shown in Figure 4 (1). Although some furniture was between the transmitter and the receiver in the same space, they were lower

Figure 3 *The layouts of four typical residential houses used for the experimental tests.*

Table 1. Experimental Path Loss Measurement Plan of Locations for Single Floor

Number of Walls	Transmission Distances Tested (ft)					
0 (open space)	0.1	10	20	30	40	50
1	1	5	12	20		
2	4	9	14	19	23	
3	11	18	27			
4	28	33	37			

than the heights of the transmitter and the receiver. Indeed, their impact on the path loss was found to be negligible in our tests. Transmission distances from 0 to 50 ft (0 to 15.24 m) in the open space of a typical residential house were tested. The signals traveling through 1 to 4 walls were determined for the same consideration.

Note that in this experiment, the distances were greater than zero to reflect physical separations of communicating nodes. At the same token, the distance in the path loss equation (Equation 5) has to be greater than zero or a result of infinity will yield.

Multi-Floor Attenuation. The transmitter and the receiver were placed at the same height (5 feet (1.52 m)) on each floor and separated by 0, 1, and 2 floors (Figure 4 (2)). The RSSI values for the link between the transmitter and receiver were measured and recorded.

Wireless Device Interference. ZigBee uses ISM (industrial, scientific and medical) band 2.4 GHz as its radio

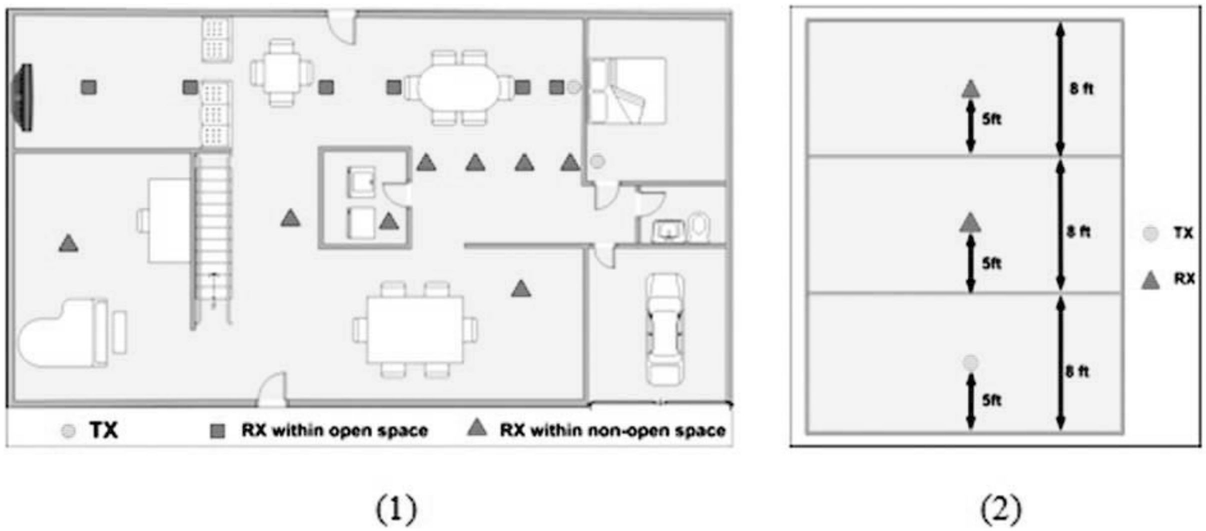


Figure 4 *An example of the sensor locations (1) within the same floor and (2) on different floors.*

Table 2. The Maximum Numbers of Co-Existing Wireless Networks with Different Protocols

	Wi-Fi	Bluetooth	ZigBee
Trial 1	3	2	3
Trial 2	2	12	8
Trial 3	1	22	12

frequency, which is also shared by Bluetooth, WiFi and 2.4 GHz cordless phone. The operation band covered by ISM 2.4 GHz is from 2.4 GHz to 2.483 GHz and is divided into different channels. To avoid interference, ZigBee, WiFi, Bluetooth and 2.4 GHz cordless phone operate in different channels. The channel bandwidth for WiFi, Bluetooth and ZigBee are 22MHz, 1MHz, and 3MHz, respectively. The entire ISM 2.4 GHz band is partitioned into 16 channels for ZigBee, 79 channels for Bluetooth, and 11 channels for WiFi in North America (Woodings and Gerrior, 2006.). The channel allocations for WiFi, Bluetooth and ZigBee are shown in Figure 5.

It can be seen from Figure 5 that the channel allocations of ZigBee, Bluetooth, and Wi-Fi overlap with each other. As a result, interference between different networks could occur. Collision-avoidance schemes were designed to deal with this issue. Both ZigBee and Wi-Fi would search a quiet channel before they start transmitting data. Bluetooth hops among 79 channels to avoid the interference. Theoretically, the optimal solution for ZigBee is to use channel 15, 20, 25 or 26, which do not overlap with the often-used Wi-Fi channels 1, 6 and 11 (ZigBee Alliance, 2007). Based on the channel allocations in Figure 5, the largest amounts of wireless networks with different protocols that can co-exist in one house are shown in Table 2. For each test in the residential houses, one WiFi router that also supported a 2.4 GHz cordless phone and several Wi-Fi adapters, several Bluetooth devices, and one group of ZigBee testing devices, were set up. The co-existence among ZigBee, Bluetooth, WiFi and cordless phone did not affect the applications since the numbers of wireless networks are less than the maximum limits in Table 2. However, a test procedure was still implemented to evaluate the wireless data transmission performance in the scenarios where WiFi, Bluetooh and cordless phone co-existed with ZigBee.

RSSI was measured when all the wireless devices were present first and then absent between the transmitter and the receiver that were separated by two walls. A two-sample t-test was conducted to compare if other 2.4 GHz wireless devices affected the ZigBee communication.

Data Collection and Statistical Analysis

Determining the Sample Size. Due to fading and path loss variation in houses with different layouts and structures, the sample size was designed to maintain the confidence interval within an acceptable level, ±1dB. RSSI data were continuously collected from the transmitter and reported to the receiver every two seconds in an outdoor environment where no obstructions were around the transmitter and the receiver and thus could be an approximation of free space. The transmitter and the receiver were placed 52 feet (15.85 m) away from each other and 3000 packets were collected. The statistical analysis for RSSI data in the outdoor environment

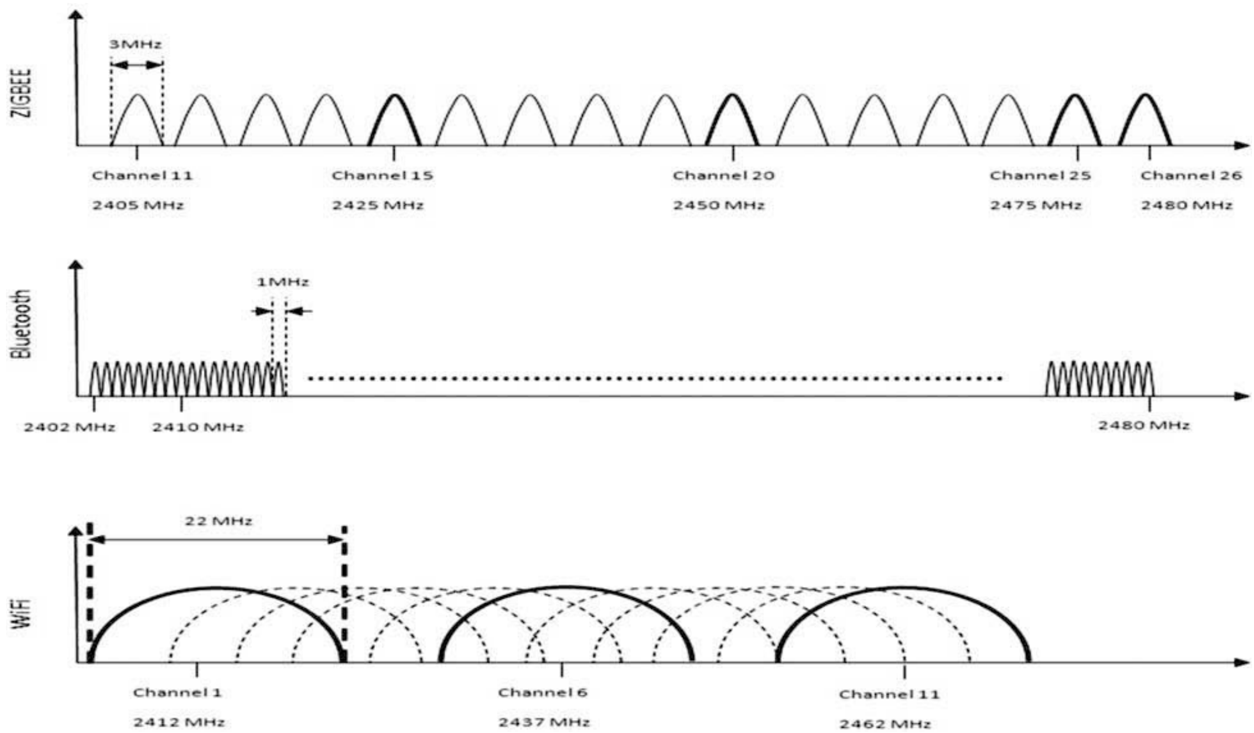


Figure 5 *Channel allocations of (1) ZigBee, (2) Bluetooth, and (3) WiFi protocols in the ISM 2.4 GHz band (Woodings and Gerrior, 2006).*

indicated that the mean value of RSSI was -72.501 dBm and the standard deviation was 0.751 dBm. Then, the transmitter and the receiver were placed 52 feet (15.85 m) apart in an indoor environment where there were walls and furniture between the transmitter and the receiver. 2994 packets were collected and our statistical analysis showed that the mean RSSI was -80.602 dBm and the standard deviation was increased to 1.787 dBm. It was clear that the RSSI was reduced at the same distance in indoor environment compared to outdoor free space. Also, the variance was increased, which indicated that the walls and furniture did contribute to the variation of path loss of the electromagnetic wave.

To ensure proper sampling, the methodology to determine the sample size for the t-distribution is determined using Equation 6, where S is the estimated population standard deviation determined from our preliminary study and has a value of 1.787.

$$n = \left(\frac{t_{\alpha/2,\,df} \times S}{1}\right)^2 \tag{6}$$

For statistical significance level of 0.05, the calculation trials based on t-distribution indicated that the right-hand-side of Equation 6 is approximately 15. Thus, at least 15 samples should be collected for each point where RSSI was measured. To ensure the factor of safety regarding the application of t-distribution, a sample size of 60 was selected.

RESULTS AND DISCUSSIONS

Confirmation of Free Space Path Loss Model

The free space path loss prediction using Friis' model (Equation 2) is shown in the Equation 7 below, where d is the transmission distance with a unit of feet. For our system, the ZigBee operating frequency was 2.4GHz and the antenna gain was 2.1 dBi.

$$PL(\mathrm{dB}) = 25.53 + 20 \times \log_{10} d \tag{7}$$

The regression model of the path loss for free space from our experiment data was given by

$$PL(\mathrm{dB}) = 44.37 + 18.40 \times \log_{10} d \tag{8}$$

A 73.8% difference in the offset evaluation and an 8% difference in the slope evaluation were found between the empirical regression model and the theoretical model. It was indicated in Figure 6 that there always existed errors between these two models. This could be explained by the fact that the real environment where the experiment was conducted was surrounded by trees, ground, grass and other objects instead of ideal free space and these objects could cause reflection, diffraction, and multipath error (Darr, 2007). However, the trend of the regression model was very close to the theoretical free space path loss model because the two slopes were close

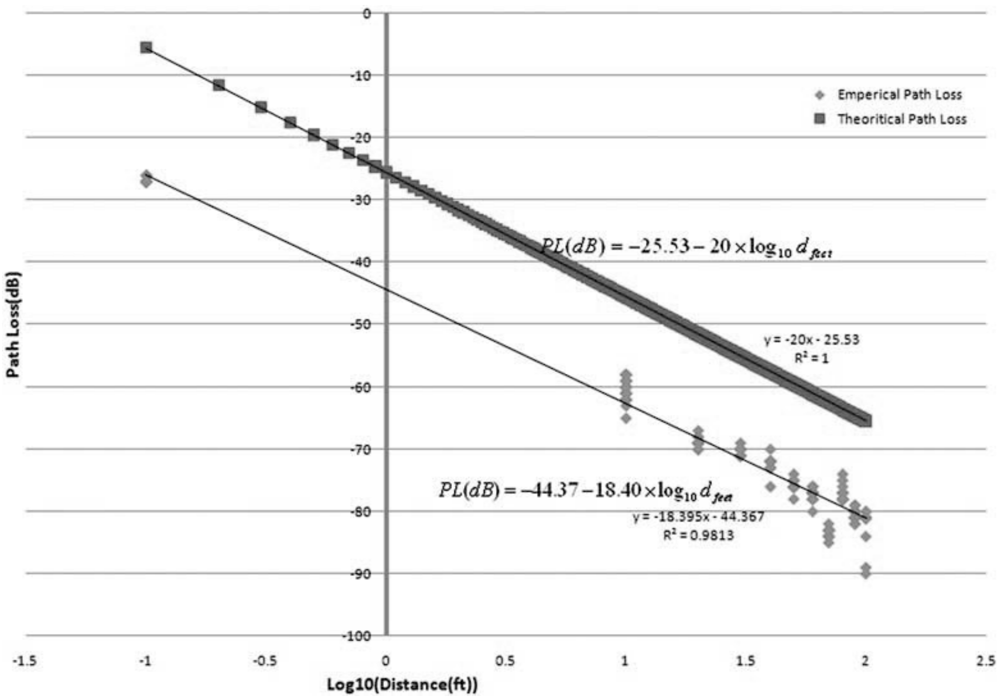


Figure 6 *The comparison between the theoretical free space path loss model and the empirical free space path loss model.*

to each other. It was noted that the errors had a value of around 15 dB within the distance of approximately 100 ft (30.48 m).

We note that the use of the Friis free space model requires that $d >> d_f$, where d_f is termed “far-field” distance. According to Rappaport (2002), d_f can be computed as $d_f = 2D^2/\lambda$, where D is the largest physical linear dimension of the antenna and λ is the wavelength. Additionally, to be in far-field region, d_f must satisfy $d_f >> D$ and $d_f >> \lambda$. In our testing environment, our antenna dimension is approximately 0.1 m and the wireless devices were working in the ISM 2.4 GHz band. This leads to $D = 0.1$ m, $\lambda = 0.125$ m, and $d_f = 0.16$ m. Also, the distance d is in the range of [3.0 30.5] (in meter), which is obviously far greater than d_f. On the other hand, d_f is greater than D and λ although it is not far greater. This slight violation of the restrictions also partly explains why there is a gap between our experimental data and the theoretical values.

Path Loss within Open Space of Residential Houses

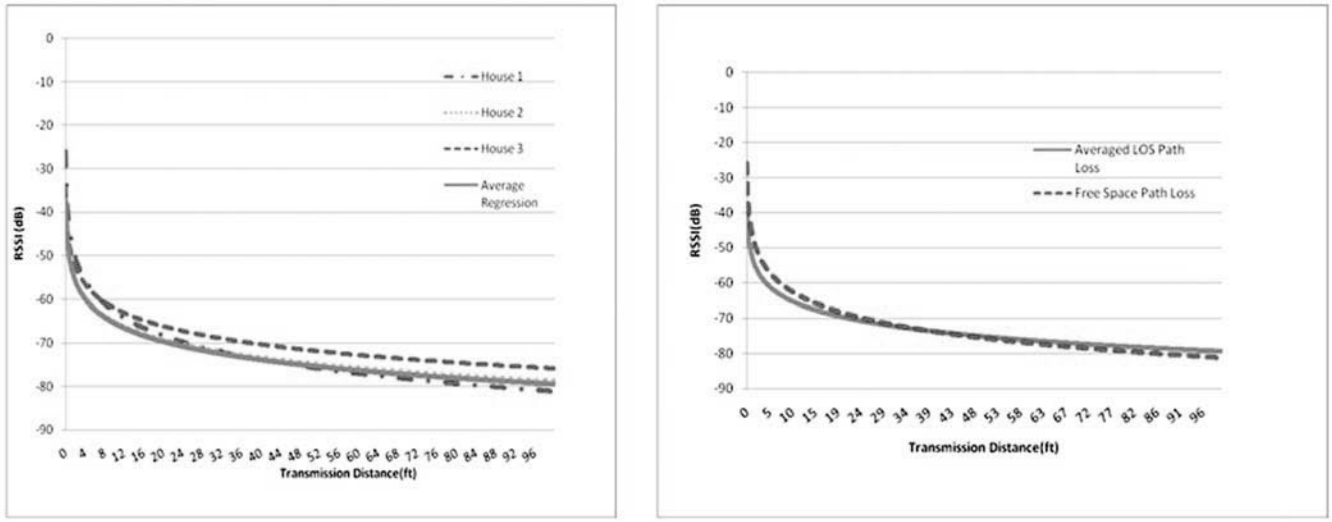
It can be observed from Figure 7(1) that the open space path losses measured in the three houses were not statistically different. The averaged regression model between the path loss and the logarithmic open space transmission distance yielded an offset of 51.39 dB and a slope of 14.01. This resulted in an n value of 1.4. An n value less than 2 indicated that less attenuation occurred in open space within a residential house than in open-air free space. The offset of 51.39 dB was close to the offset of the 44.37 dB in the empirical free space path loss model (c.f. Equation 10). It can also be observed that the path loss model in the house open space behaves similarly to that in outdoor free space environments (Figure 7(2)).

Effects of Wall Separation on Signal Strength

For wall separation effect investigation, the transmitter and the receiver were placed on the same floor (i.e., without signal loss due to floor-attenuation-factor). A new term called wall attenuation factor was added to the path loss model, as proposed by Liechty et al. (2007) to account for the wall effect. The new model is shown in Equation 9, where q represents the number of walls that the wireless signals transmitted through, and AF_w represents the wall attenuation factor. Three path loss regression equations for the three houses were yielded from the experimental results (Table 3). The 95% confidence interval for AF_w and n were also given in Table 3.

$$PL = PL(d_0) + 10n\log_{10}\frac{d}{d_0} + qAF_w \tag{9}$$

The final regression model for path loss of wall separation was derived by combining three sets of data from three houses and conducting the analysis based on the linear relationship with wall separation and $\log_{10}$ of transmission distance. Results yielded a PL (d_0) of 52.9 dB, an n of 1.37 and an AF_w of 1.92. Compared to the house LOS path loss model, the values of n were very close (1.37 for wall attenuation path loss model versus 1.4 for open space path loss model). However, compared to the open space path loss model, the wall attenuation effect resulted in a loss of 8.53 dB (52.9 dB for wall attenuation path loss model versus 44.37 dB for open space path loss model).



(1) (2)

Figure 7 *(1) Cumulative regression results within open space of the three houses and (2) the comparison between the averaged house open space path loss and free space path loss.*

Table 3. Summary of Regression Models for Path Loss Due to Wall Separation in Houses 1, 2, and 3

	Regression Equation	95% CI of $PL(d_0)$	95% CI of AF_w	95% CI of $10n$
House 1	PL(dB) = 55.5 + 0.85q + 14.4log$_{10}$d	(4.84, 56.16)	(0.6, 1.1)	(13.91, 14.89)
House 2	PL(dB) = 54.7 + 1.04q + 11.7 log$_{10}$d	(54.20, 55.20)	(0.79, 1.29)	(11.31, 12.09)
House 3	PL(dB) = 48.3 + 3.51q + 15.5 log$_{10}$d	(47.58, 49.02)	(3.27, 3.75)	(14.87, 16.13)
Overall	PL(dB) = 52.9 + 1.92q + 13.7log$_{10}$d	(52.51, 53.29)	(1.77, 2.07)	(13.38, 14.02)

Table 4. Summary of Path Loss due to Floor Separation in Houses 1, 2 and 3

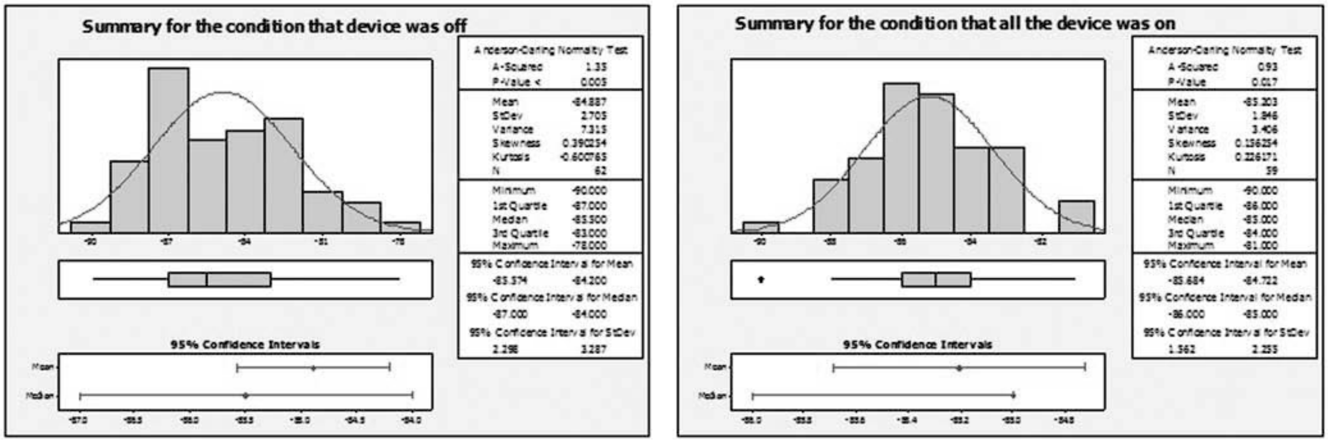
	FAF through 1 Floor	95% CI	Additional FAF through 2 Floors	95% CI
House 1	21.26	(20.337, 22.183)	4.127	(2.9769, 5.2771)
House 2	16.06	(15.483, 16.637)	9.5667	(9.0092, 10.1241)
House 3	21.343	(20.834, 21.853)	3.9167	(3.2870, 4.5464)
Overall	19.592	(19.054, 20.129)	5.8415	(5.2339, 6.4491)

Effects of Floor Separation

The attenuation caused by floor is quantified by the *FAF* (floor attenuation factor), which is a function of the number of the floors. The overall path loss model is the sum of the wall separation loss (Equation 9) and FAF, which can be written as

$$PL = PL(d_0) + 10n\log_{10}\frac{d}{d_0} + qAF_w + FAF \qquad (10)$$

In this work, FAF of one floor is determined by subtracting the predicted path loss at the distance that is equal to the floor height (8 feet (2.44 m)) in free space from the experimental path loss through one floor. The path loss at 8 feet (2.44 m) in the free space is 60.99 dB according to Equation 8. The mean and 95% confidential interval of FAF through one floor in three houses are shown in Table 4. Additional FAF when signal were transmitted through two floors were obtained by subtracting the path loss through one floor from that through two floors. The mean and 95% confidential interval of the additional FAF were also shown in Table 4. The overall FAF was derived by combining three sets of data from three houses and conducting the analysis. Results yielded an FAF value of 19.59 dB for one floor separation and 5.84 dB



(1) (2)

Figure 8 *Statistical summary of RSSI measurements of the transmission with all 2.4 GHz devices off (1) and on (2).*

for each additional floor separation. Our results statistically agree with the previous research result that FAF is about 15 dB for one floor separation and an additional 6 dB to 10 dB for every additional floor separation (Panjwani et al., 1996).

Interference of 2.4GHz Devices in Homes

Figure 8 shows the effects of home wireless device operations on the signal attenuation of the ZigBee network signal transmission. The statistical analysis of the measured RSSI data were collected separately when the home wireless devices were turned off and on. The power levels of the interference sources are: 1) Bluetooth: 4 dBm (2.5 mW); and 2) Wi-Fi: 20 dBm (100 mW), respectively. Statistics of the data shows that two means were very close to each other (84.887 dB versus 85.203 dB) while the 95% confidence interval for two means almost covered the same range ((85.574 dB, 84.200 dB) versus (85.684 dB, 84.722 dB)). The results of the two sample t-tests showed that the 95% confidence interval of the difference between these two conditions was (0.521, 1.154) and the P-value was 0.456. This indicated that the path loss in these two conditions were not significantly different between the 2.4 GHz devices in homes being off or on. In other words, these wireless devices did not interfere with the wireless transmission of the ZigBee network. However, the limitation of this test was that the number of 2.4 GHz wireless devices was much less than the potential number of wireless devices that could incur large amount of data traffic. Further research was needed to study the RSSI performance of ZigBee in co-existence with a large number of wireless devices.

Overall Path Loss Model

By adding FAF to the overall path loss model shown in the last row of Table 3, the overall path loss model is given below in Equation 11. The ranges of all the parameters are shown in Tables 3 and 4.

$$PL(\mathrm{dB}) = 52.9 + 1.92q + 13.7\log 10(d) + \begin{cases} 0 & \textit{same floor} \\ 19.59 & \textit{one floor} \\ (19.59 + 5.84) & \textit{two floors} \end{cases} \tag{11}$$

Comparing our model to that proposed by Ghassemzadeh and Tarokh (2003), 5.9 dB and 0.33 differences were found for the path loss at the reference distance of 1 m from the transmitter ($PL(d_0)$), and the path loss exponent (n), respectively. The Ghassemzadeh and Tarokh model was developed for 5GHz transmission and had ($PL(d_0)$= 47 dB and n=1.7 for LOS). These differences were attributed to the difference between the transmission frequency of Ghassemzadeh and Tarokh model (5GHz) and that of the developed model (2.4GHz) discussed in this paper. Regarding the floor attenuation factor (FAF), researchers reported that FAF is about 15 dB for one floor separation and 6-10 dB for every additional floor (Panjwani et al., 1996; Andersen et al., 1995; Seidel and Rappaport, 1992). Our findings of 19.59 dB for one floor separation and 5.84 dB for every additional floor as shown above are in general agreements with what have been reported.

Validation of the Predictive Models

To validate the model derived by the procedure discussed above, RSSI data was collected in House 4. The difference between the model prediction and field-measured signal strength is defined as the prediction error. Normalized Mean Error (NME), Normalized Mean Square Error (NMSE) and Fractional Bias (FB) were used to evaluate the performance of the model. They are defined in Equation 12.

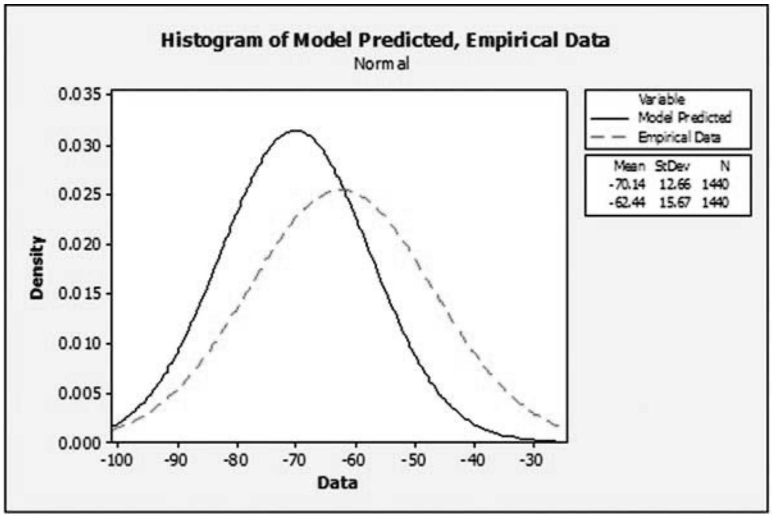


Figure 9 *The histogram of the model predicted data and empirical data.*

$$NME = \sum|P_{pi} - P_{mi}|/\sum P_{mi},$$
$$NMSE = \sum(P_{pi} - P_{mi})^2/(nP_pP_m), \quad (12)$$
$$FB = 2(P_p - P_m)/(P_p + P_m)$$

where

P_{pi} = model predicted value

P_{mi} = measured value

n = number of corresponding pairs of measured and predicted values

P_p = mean predicted value

P_m = mean measured value

The NME was calculated to be 15%, the NMSE was 2.6% and the FB was 11.8%. Although the NMSE indicates that the variance of the errors is small, the mean of the model predicted value is biased to the left tail for the empirical values with 15% bias rate as shown in Figure 9. The FB value shows that the model over-predicts the path loss by 11.8%.

The predicted values and the measured values of RSSI are plotted in Figure 10. Except for the large errors found in predicting the signal prediction of short transmission distances, most of the predicted signal attenuation was close to the measured signal attenuation.

The statistical summary shows that the mean prediction error is 7.7 dB and the standard deviation of the prediction errors is 7.12 dB (Figure 11). The range of the prediction errors is from 0 dB to 25.4 dB. Larger errors were found at the transmission distance of 5 feet (1.52 m) with one wall separation. Within this area, the path loss prediction errors ranged from 15 to 25.4 dB. The large errors might be caused by the errors of the electrical hardware or the noise from wireless devices in House 4. Other than this, the prediction errors are small in the other areas of House 4. It can be concluded that the model worked accurately to predict the path loss of ZigBee wireless signals in residential houses.

Application of the Developed Path Loss Model

The developed path loss model can be used to help strategically locate the wireless sensors in residential house environments according to the predicted transmission signal strength. Although ZigBee modules can be mesh networked, all ZigBee transceivers in the network in this research work were set as SEDs (sleep end devices) and they made up a star network. All communications of the network go through the coordinator. Therefore, it is necessary to determine the sensor locations to assure the data transmission reliability with the coordinator for successful communications. To successfully establish a link between a sensing module and the coordinator, the received signal power must be greater than the receiver sensitivity, which is defined as the minimum required signal power for a receiver to decode the transmitted message. Equation 13 shows how the received signal power can be computed.

$$P_r = P_t - PL \quad (13)$$

where

P_r = received power

P_t = transmitted power

PL = path loss

As an example, the power received can be plotted in a 3D space that simulates a residential house. The locations where the power received is greater than the receiver sensitivity (-96 dBm for the ZigBee module used in this paper) are preferred for the sensing modules. On the other hand, those locations where the power received is less than the receiver sensitivity should be avoided. The transmit power of the ZigBee module

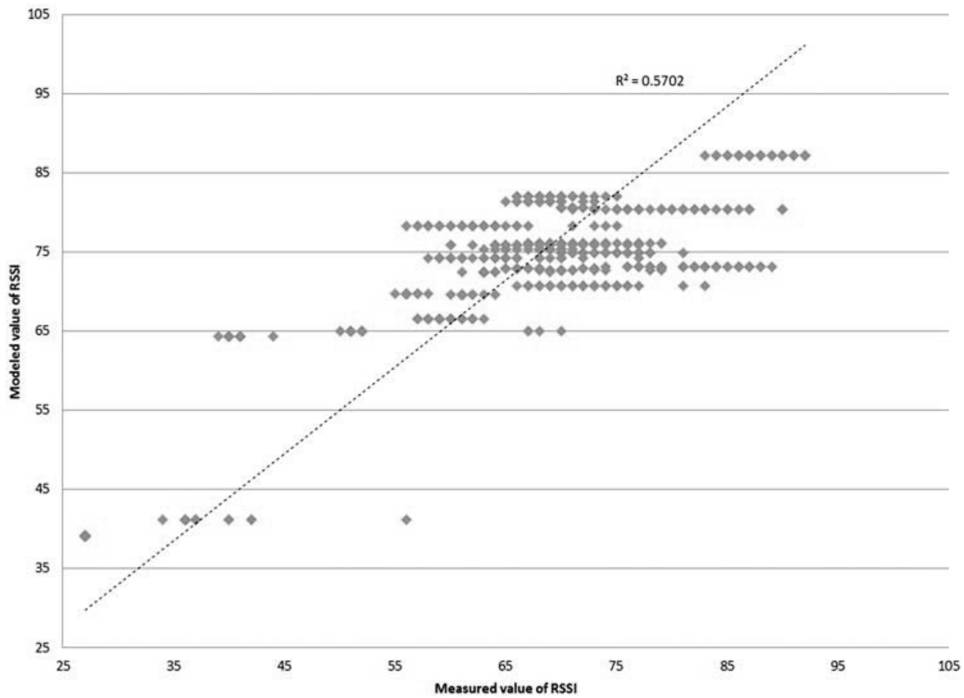


Figure 10 The model predicted and the measured wireless signal attenuation expressed in received signal strength indication (RSSI).

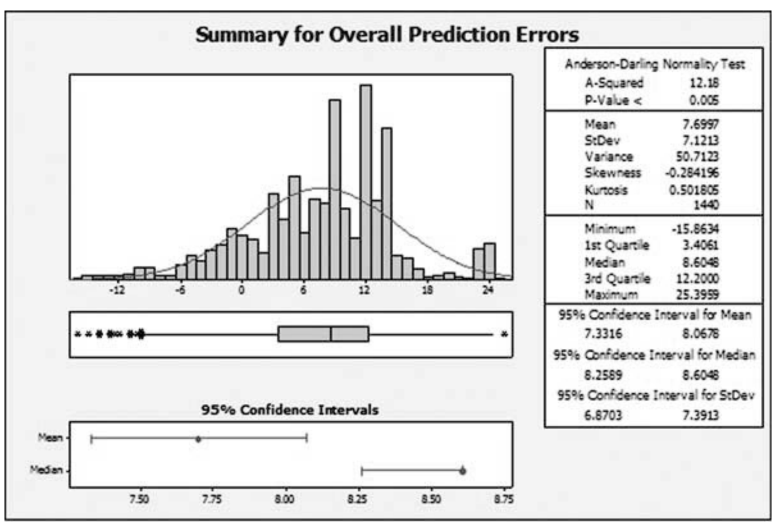


Figure 11 The statistical summary of the prediction errors.

used in this work is +4 dBm. Therefore, the received power can be derived based on the path loss model as below.

$$P_r = +4 - 52.9 - 1.92q - 13.7\log 10(d) - \begin{cases} 0 & same\ floor \\ 19.59 & one\ floor \\ (19.59 + 5.84) & two\ floor \end{cases} \tag{14}$$

Assuming that the coordinator is located at the center of the basement of a residential house as shown in Figure 3, we plot the received power of the SEDs on the first floor and second floor in Figure 12. The point (0, 0) on the x-y plane represents the center of the floor. It is clear that the received power is greater than -96 dBm at all the locations of the first floor and within the range of 25 feet (7.62 m) on the second floor. Therefore, the sensing modules can be installed anywhere on the first floor. In the dark areas in Figure 12(b),

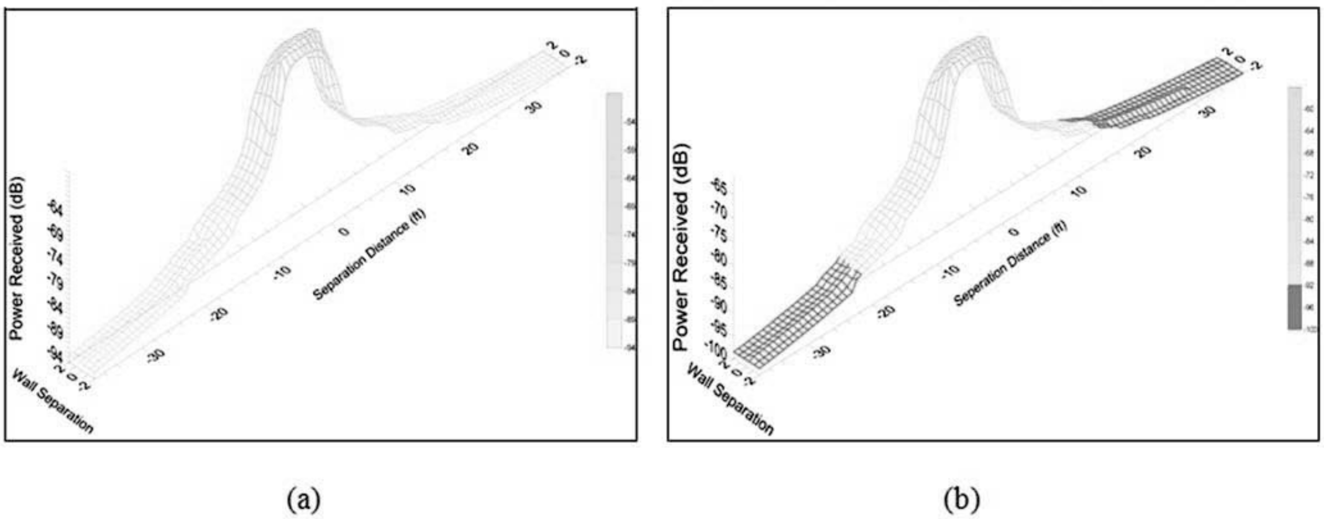


Figure 12 *The received power on (a) the first floor and (b) the second floor.*

the power received is less than -96 dBm, therefore, no successful communication can be established and sensors should not be installed at these locations.

Our path loss model can also be used to improve the design of wireless transceivers. The receiver sensitivity can be reduced if the minimum power received determined by the path loss model is greater than the nominal receiver sensitivity so that the cost of a wireless transceiver can be reduced. For example, consider the communication between a transmitter and a receiver in a residential house with only one floor. The maximum distance on the same floor is 50 feet (15.24 m), the largest number of separation walls is 4, and the minimum transmitted power is -8 dBm. The minimum received power can be calculated by applying Equation 15 as the follows:

$$P_r = -8 - 52.9 - 1.92 \times 4 - 13.7 \log 10(50) = \quad -91.8 \text{ dBm} \tag{15}$$

Therefore, a receiver sensitivity of -92 dBm is sufficient to overcome the path loss in this one-floor house such that the receiver can reliably decode transmitted messages. In this way, the cost of the wireless transceiver can be reduced by using a receiver with lower sensitivity.

CONCLUSION

A wireless signal path loss prediction model was developed for applications of emerging ZigBee wireless networks in residential house environments. The models can be used to configure reliable wireless sensor network, which will lay a solid foundation for the adaptation of wireless multi-zone HVAC control systems for residential houses. The path loss model can also be used to improve the design of wireless transceivers and reduce the cost by selecting an appropriate receiver sensitivity based on the received power determined by the path loss model and the transmitted power.

Significant factors affecting wireless transmission in residential housing environment are mainly indoor open space, wall separation, and floor separation. The path loss in open space inside a house was found to behave similarly to that in outdoor free space environments. The impact of some common household ISM (industrial, scientific and medical) 2.4 GHz wireless devices on the ZigBee transmission was tested and no interference with the ZigBee network was found.

Performance analysis showed that the path loss model's mean error was about 7.7±7.1 dB. The Normalized Mean Error (NME), Normalized Mean Square Error (NMSE) and Fractional Bias (FB) were 15%, 2.6%, and 11.8%, respectively. The mean and the standard deviation of the prediction errors were comparable to previous literature research findings. Therefore, the model can be used to predict the path loss of ZigBee wireless signals in residential houses.

The path model established in this study is applicable for typical wood structure housing environment. Wireless signal transmission in houses with different building materials other than wood need to be to studied in the future to expand the application of the path loss model.

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