ZigBee Propagations and Performance Analysis in Last Mile Network

Oradee Musikanon and Wachira Chongburee

***Abstract*—ZigBee is one of the alternative technologies to be adopted as the last mile media in the smart grid network. The last mile infrastructure design does require the knowledge of radio range limitation in the corresponding band. The purpose of this study is to analyze the ZigBee outdoor propagation parameters when used as a communication module in the smart grid. This study collects the received signal strength data for three difference scenarios of meter installation and analyses the path loss exponents, the variance. Then, the distribution of the received signal is verified by using Chi-square method. Additionally, the results are compared with the available propagation models.**

***Index Terms*—*Zig*Bee, last mile network, smart meter, propagation, path loss, log-normal.**

I. Introduction

Smart grid is an intelligent network infrastructure using digital technology in order to improve the efficiency, reliability, economics, and sustainability of electricity services by making use of the latest technology in Information Technology and Communication (ICT). The systems involves with automatic meter reading (AMR) and advanced metering infrastructure (AMI) system, management system, electric vehicles (PEV), distributed generation (DG), renewable energy sources and etc. [1]. Recent activities of all power authorities of Thailand including Provincial Electricity Authority of Thailand (PEA) [2] focus intensively on the smart grid technology. PEA is in charge of electricity distribution to all parts of the country except in the capital, Bangkok and in the perimeter, Nonthaburi Province and Samut Prakarn Province.

The communications infrastructure plays a key role in the smart grid. It is a necessary tool in order to real-time monitor or control power consumption, energy efficiency, data exchange and etc. Most energy organizations in Thailand already have their own communication backbone. However, the “last mile” or "last kilometer" communication link to connect to the customer electric meters is not available in all service areas. Many technologies, both wire and wireless ones, are proposed as the candidate for the link. ZigBee technology is one of the wildly mentioned technologies with low cost, low power consumption, reliability and scalable.

The frequency used worldwide by ZigBee is the 2.4 GHz ISM Band, the same frequency band of the WiFi/IEEE 802.11 standard. As a result, they are likely to interfere each other easily. There are a number of researches to improve the performance of ZigBee carried out in both experiment and simulation. Although, the previous works evaluate both indoor and outdoor environments [3-5] but it is not perfect fit to the case of PEA meter installation which has numerous in service. This work investigates the wireless link for the ZigBee when it is used in PEA smart grid.

The organization of this paper is as the follows. Sections 2 and 3 review ZigBee and propagation models, respectively. Section 4 describes the tool used to analyze the results. Section 5 shows experiment setup and provides the experimental results. The results are analyzed in Section 6 and the conclusion is drawn in Section 7.

II. ZigBee Overview

ZigBee is an international standard developed by ZigBee Alliance [6]. This standard provides a license-free and low-power, two-way wireless communications with high reliability and more extensive reliable range at an affordable cost. It is deployed in wireless control and monitoring applications with low data rate, low power consumption, allows longer life with smaller batteries. The ZigBee’s solutions will be embedded in consumer electronics, ZigBee chip with radios and microcontrollers between 60 kB and 256 kB flash memory. ZigBee operates in the industrial, scientific and medical (ISM) radio bands; 868MHz in Europe, 915MHz in the USA and Australia, and 2.4GHz in most worldwide. There are 16 channels in 2.4GHz band, with each channel requiring 5MHz of bandwidth and provides data rate up to 250kbit/s, 40 kbit/s for the 915MHz and 20kbit/s for 868MHz.

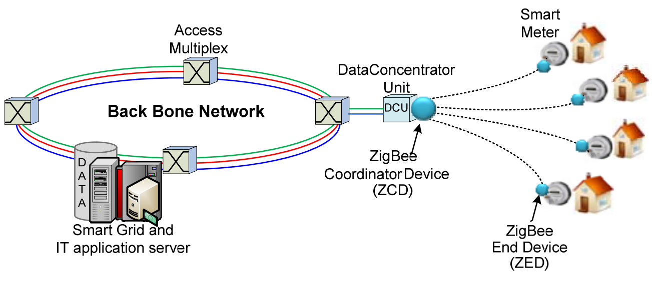

Fig. 1. An example of the last mile network design via ZigBee technology in Smart Grid Network.

The ZigBee network layer (NWK) supports star, tree, and mesh topology and lays on top of the IEEE 802.15.4 standard. The ZigBee device can distinguish in 3 different types, ZigBee coordinator device (ZCD), ZigBee router device (ZRD) and ZigBee end device (ZED). The ZCD response for controlling, initiating and maintaining all the neighbor devices on the network while ZED communicate with the

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ZigBee coordinator. The network may be extended through the use of ZRD. In tree topology, ZRD move data and control messages through the network by using a hierarchical routing strategy.

In last mile network application, ZED will be connected to the smart meter to collect the data while ZCD be connected to the data concentrator unit (DCU). Then the DCU will carry all data to the control and processing center by PON, Wi-Fi, GPRS and etc. [7]. An example of the last mile network design via ZigBee technology in PEA Smart Grid Network as depicted in Fig. 1.

III. The Propagation Model

The target of propagation model is to determine the probability of satisfactory performance of a wireless system that depends on radio wave propagation [8]. Most radio propagation models are derived by using a combination of analytical and empirical methods. The empirical approach is based on fitting curves or analytical expressions that recreate a set of measured data. This has an advantage of taking into account the implicitly of all propagation factors, both known and unknown, through the actual field measurements. However, the validity of the empirical models is generally specific to environment. At another transmission frequency and environment other than those, additional measured data are needed.

Over time, some classical propagation models have emerged by using path loss models to estimate the received signal level as a function of distance; it becomes possible to predict the signal to noise ratio (SNR) for a radio communication system.

The free space propagation model by H. T. Friis assumes an ideal propagation condition. The model has only one clear line-of-sight path between the transmitter and receiver. Basically, the model is used to initially estimate path loss. The relationship between the transmit power, antenna gains, wavelength and distance between transmitter and receiver is as the following:

$$P_r(d) = P_T G_T G_R \left(\frac{\lambda}{4\pi d}\right)^2 \qquad (1)$$

where $P_r(d)$ is the received power; P_T is the transmitted power; G_T is the transmitter-antenna gain, G_R is the receiver-antenna gain; d is the distance between the transmitter and the receiver; and λ is the wavelength. When the antennas are assumed to have unity gain, the path loss in dB (PL) can be defined as:

$$PL(dB) = 10log\frac{P_T}{P_R} \qquad (2)$$

A. Log-Distance Path Loss Model

Propagation models, traditionally, focus on prediction of the average received signal strength at a given distance from the transmitter. Many times, the path loss is given relatively to a reference distance d_o.

$$PL(d) \propto \left(\frac{d}{d_0}\right)^n \qquad (3)$$

The path loss, as a result, can be determined in dB by:

$$PL(dB) = P_t(dBm) - P_r(dBm) = PL_0 + 10nlog\text{—} \qquad (4)$$

By this definition, *PL(dB)* is the overall path loss which includes the antenna gains of transmitting and receiving sides.

In practice, received signal strength indicator (RSSI) represents the measured received signal. Its values relate to equivalent transmit power (including transmit antenna) by [9]:

$$RSSI = P_{Tx}(dBm) - PL(dBm) \qquad (5)$$

B. Log Normal Shadowing

Slow shadowing in wireless network is the attenuation caused by buildings or any obstacles between a transmitter and a receiver. In the model with shadowing, the shadowing value $X\sigma$, typically defined in dB, is added to (or subtracted from) the average received power in equation (4). $X\sigma$ is a zero means Gaussian distributed random variable with standard deviation σ, the random shadowing path loss becomes:

$$PL(dB) = PL(d_0) + 10nlog\left(\frac{d}{d_0}\right) + X_\sigma \qquad (6)$$

C. Two-Ray Model

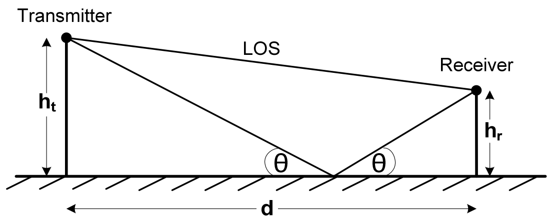

Fig. 2. Two-ray model.

The two-ray ground reflection model as shown in Fig.2 takes into account both direct and a ground reflected path. The analysis shows that, in a certain setup, the received power at distance d is predicted by:

$$P_r(d) = P_t G_t G_r \left(\frac{h_t h_r}{d^2}\right)^2 \qquad (7)$$

where h_t and h_r are the height of the transmit and receiving antennas, respectively. This model gives more accurate prediction at a long distance than the free space model.

IV. Method of Analysis

There are two major tools used in this study to analysis the result. One is to determine the path loss exponent and the other is to verify the statistics of the model.

A. Path Loss Exponent Analysis

The analysis method to determine the log-distance path loss model is a linear least squares curve fitting. It is used to calculate the path loss exponent (n). This method is a process of constructing a curve, or mathematical function that has the best fit to a series of data points, possibly subject to constraints. Since the collected data has some degree of randomness, the curve fitting used does not constrain to exactly fit all data on the curve. As a consequence, a linear regression analysis is used instead. Once the curve is fitted, the path loss parameters can then be determined. According to the propagation model assumed, the linear curve fitting, the received power must be in dBm and the distance must be on the logarithmic scale.

B. Statistic Test

Chi-squared distribution is one of the most widely used tool in inferential statistics. It is also used in the analysis of wireless propagation model [10-11]. In communication, once the path loss parameters (path loss exponents and shadowing values) are determined, Chi-squared test is used to test the goodness of the fitting of observed data and model parameters.

Computation of the chi-square goodness-of-fit, all data, in this work, is carried out by dividing the collected data into k bins. Then the chi-square figure defined by:

$$X^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)}{E_i} \quad (8)$$

O_i is frequency of observed data fitted in the bin i and E_i is the expected frequency calculated from the model for bin i.

V. The Experiment

In this section, the experimental setup is described followed by the corresponding results. The result is analyzed in the next section.

A. Experimental Setup

In the experiments, Smart RF04EB development kit, the Chipcon products from Texus Instruments are used. The board complete with CC2430EM complied to system-on-chip (SOC) ZigBee®/IEEE 802.15.4 standard, the CC2420 RF transceiver, an industry-standard enhanced 8051 MCU with 128 KB flash memory and 8 KB RAM and plug in AN040 whip antenna. The board supports the Z-Stack™ protocol stack [12]. The board connects to a PC via USB port, and can be configured, controlled and monitored the transmit and receive power by SmartRF 7, a 32-bit Windows 7 PC application program provided by the manufacturer. The main specifications of the EB are summarized in the Table I

TABLE I :ZIGBEE MAIN CHARACTERISTICS

Parameter	Symbol	Value
Modulation	DSSS /QPSK	2 bit/symbol
Operational Band	BW ISM	2.4GHz
Bit Rate	Rb	250 kbps
Transmitted Power	P_{TX}	-25 dBm to 0.6 dBm adjustable
Receiver Sensitivity	RSSI	-90 dBm

The received power data is collected in outdoor environments in 3 different scenarios ranging from the closest link to the user

- Scenario 1 – ZigBee meters are installed on electric power poles along the street in front of the 2-story detached houses in a community. It is assumed that the ZigBee modules are embedded in the smart meter and are to communicate with another ZigBee module installed on a data concentrator unit (DCU) located in the line of sight, probably around the corner.
- Scenario 2 – ZigBee meters are installed on electric power poles along the main entrance 4-lane street of the community. In this scenario, the setup is similar to the first but the meters are placed in more open area with no buildings surrounded like in the first.
- Scenario 3 – ZigBee meters are installed on electric power poles along an 8-lane public main road outside the community. This scenario, simulate the radio link between the meter and PEA backbone network.

In the experiment, as shown in Fig. 3, one ZigBee module is placed at 1.8 meters from the ground at a fixed location while another one is placed at 1.2 meters from the ground and relocated to get different Tx-Rx separations.

For each Tx-Rx separation, the relocating ZigBee module transmits 100 data packets on Channel 11 (2405 MHz) at the output power of -0.1 dBm, the minimum allowed by the program. Note that 0 dBm is not allowed. The fixed-location ZigBee module records the RSSI. The experiment is repeated 20 times. The sample of scenario 3-ZigBee meters are installed on electric power poles along an 8-lane public main road outside the community as shown in Fig.4.

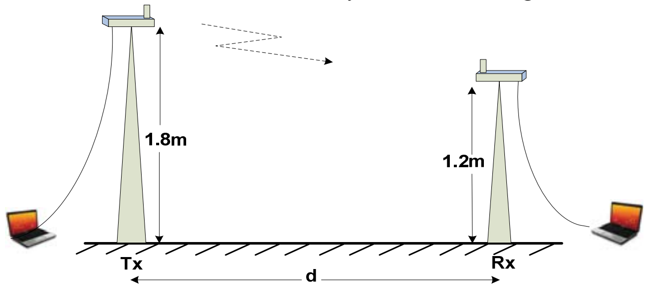

Fig. 3. The experiment setup with h_t = 1.8 m and h_r = 1.2 m at various Tx-Rx separation of d.

Fig. 4. Test setup for scenario 3-ZigBee meters are installed on electric power poles along an 8-lane public main road outside the community.

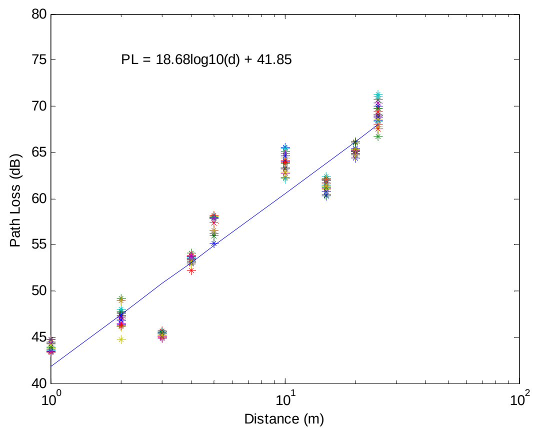

Fig. 5. The path losses and the curve fitting for Scenario 1: ZigBee in front of the houses.

VI. Experimental Results

The RSSI are collected at different distances for each scenario. The path losses are calculated by subtracting RSSI from the transmit power of -1 dBm. The results are shown in Fig. 5-7. The x-axis is in a logarithmic scale.

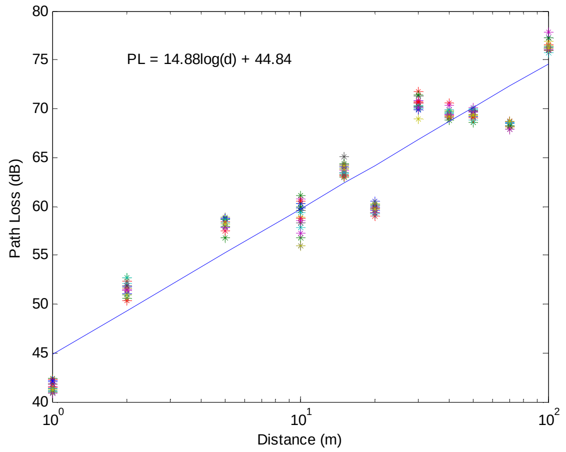

Fig. 6. The path losses and the curve fitting for Scenario 2: ZigBee in the community entrance, more open area.

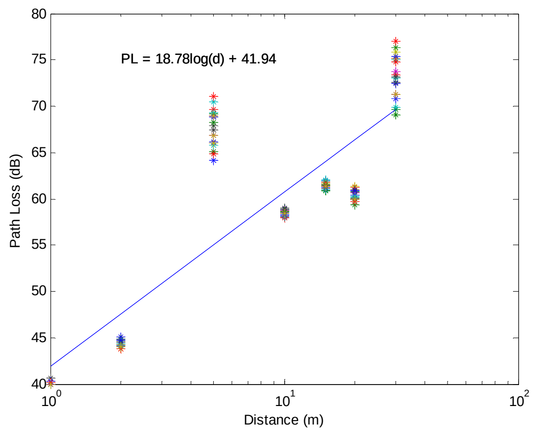

Fig. 7. The path losses and the curve fitting for Scenario 3: ZigBee in an 8-lane main road.

VII. Result Analysis

Two analyses are performed in this section: path loss exponents for each scenario and Chi-squared test to verify the distribution.

A. Determination of Path Loss Exponents

The path loss exponents shown in Fig. 5-7 are analyzed by using the linear regression. The path loss exponents n are summarized as the follows:

Scenario 1: $n = 1.87$

Scenario 2: $n = 1.49$

Scenario 3: $n = 1.88$

The corresponding standard deviations (σ) in dB versus the distances for all three scenarios are depicted in Fig. 8.

It is noted that in Scenario 3, the setup is surrounded by many moving vehicles. The data are collected under a dynamic environment. As a result, the data are not as expected.

B. Chi-squared Test for Normal Distribution

For each distance, Chi-squared test is performed to verify if the received signal strengths are normal distributed. For example, as shown in Table II, the Chi-squared test at $d = 1$ m in Scenario 1 yields an X^2 of 52.603 with a degree of freedom *df* of 19.

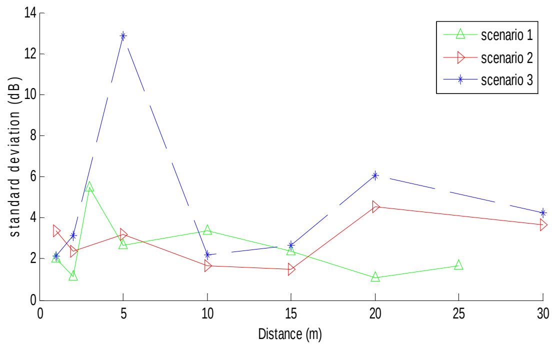

Fig. 8. The standard division σ in dB versus the distances in scenario 1-3

According to the Chi-square distribution table, X^2 of 52.60320 is greater 38.582 which is corresponding to a probability (p) at of 0.005. As a result, the received signal strengths can be said to be likely normal distributed. For other distances and scenarios, the Chi-squared test yields positive for being normal distributed.

TABLE II: Sample Expected and Chi-square Value of Scenario 1 (d = 1 m)

BIN	Number of Observed Samples	Expected Probability	Chi-square value
-45.19 to -45.00	0	0.0178	0.00032
-44.99 to -44.80	2	0.0521	3.79431
-44.79 to -44.60	1	0.1237	0.76790
-44.59 to -44.40	2	0.2389	3.10147
-44.39 to -44.20	1	0.3749	0.39075
-44.19 to -44.00	2	0.4783	2.31557
-43.99 to -43.80	4	0.0521	15.58591
-43.79 to -43.60	4	0.4180	12.83072
-43.59 to -43.40	4	0.2864	13.79082
-43.39 to -43.20	0	0.1594	0.02541

C. Comparison to Two Ray Model

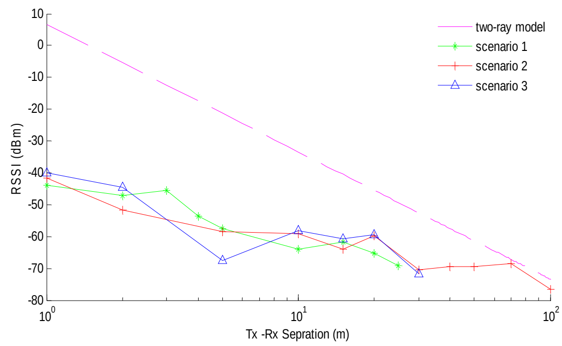

Fig. 9. Path loss comparison of the empirical data and the prediction by the Two-Ray model.

The comparison of the empirical data and the prediction by the two ray model is shown in Fig. 9. In the model, the path loss exponent is found to be 4 while the analysis of the data yields about 2. Although the experiment setup possibly fit to the model, the condition that Tx-Rx separation must be significantly greater than the height of the antennas does not satisfied. Consequently, the model does not apply to this setup. However, if the longer Tx-Rx separation is test, it could fit to the model.

VIII. Conclusion

In this study, ZigBee propagation characteristics are investigated by setting up experiments in the environment similar to installation of smart meters in PEA smart grid. The empirical data are collected from the distances up to 30 meters and are used to determine the path loss exponents for 3 different scenarios. It is found that in all scenarios, the path loss exponents are less than 2, which is the path loss of free space propagation. The results suggest that for the distance under 30 meters, free space propagation fits ZigBee link well. So, it can be used as the installation guide for the PEA.

The Chi-square tests suggest that the received signals are normal distributed with standard deviations under 5 dB. It is noted that when ZigBee is operated in an environments with full of moving objects like in the 8-lane case, both path loss and standard deviation significantly increase. Further study is needed to mitigate the effects in this situation.

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