國立交通大學

電機資訊國際學位學程

碩士論文

ZigBee無線感測器網路之傳輸分析
與資料遺失補償

Propagation Analysis and Data Packet Dropout Compensation for ZigBee Wireless Sensor Networks

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Abstract

ZigBee is a low-cost and low-power, wireless communications technology that can be used widely in the wireless sensor network (WSN) for consumer electronics. It is crucial to construct monitoring systems via the ZigBee WSN by applying signal propagation analysis and data dropout compensation to improve their reliability, especially in the indoor environment. Furthermore, the data dropout is also unavoidable, irregular, and unpredictable in nature. In this thesis, the propagation model is thus obtained through experiments in complex environments where the distance and the wall effect are taken into consideration. A computer graphics interface (CGI) system has been developed for monitoring each node status of the ZigBee WSN. In present study, experimental results indicate that the intelligent message estimator (IME) integrated with proposed the combined message design (CMD) has been applied to ZigBee transmission to successfully estimate the dropout data.

Keywords: Propagation, monitoring application, data dropout .

Contents

List of Figure

List of Table

Chapter 1

Introduction

1.1 Motivation and Purposes

The wireless sensor networks (WSN) become more popular in telecommunication technologies recently. It can be recognized as a collection of nodes organized into a cooperative network and those individual nodes are able to interact with the environment by sensing or controlling the nodes [1]. Many wireless sensor networks are using the ZigBee protocol that is based on the IEEE 802.15.4 standard. Due to this, the ZigBee wireless systems are distinguished from other wireless technologies regard the lower power consumption, the lower data rate, and the lower device cost. At this moment, WSN are widely used for environmental monitoring, intelligent control, medical and health care, logistics, and various other applications [2].

While ZigBee wireless sensor networks become very attractive for monitoring and control, there still have some challenges in design and implementation of practical networks due to the unpredictable signal quality and limited reliability. These challenges are particularly evident when network infrastructures employed in the building environment [3-4].

The first challenging in this thesis for WSN is to analyze the signal propagation behavior of ZigBee modules in real operating conditions. The signal propagation is hard to predict especially inside the building environment with extensive interference and the obstacle like walls, and thus a consistent and reliable propagation model is difficult to be derived. The second challenging problem is the data dropout of communication resulting from all the effects of reflections, obstructions, and limited network reliability. The data dropout may significantly degrade reliability of the real network system. Hence, it is strongly motivated in this study to investigate the signal propagation behavior of ZigBee devices operating within a real environment and design the compensation for data dropout in ZigBee WSN.

1.2 Problem Statements

1. It requires a model to predict the propagation of the ZigBee signal, especially in building environment.
2. A monitoring system for the ZigBee WSN is required for the users to observe the link quality among all nodes and the topology of the network.
3. Since the data dropout significantly affects the reliability of the ZigBee WSN, on-line estimation of transition probability is pursued for real-time estimation of the missing messages for real applications of ZigBee WSN.

1.3 Proposed Approaches

1. By applying the received signals strength indicator (RSSI) measurement to determine the propagation model.

To investigate the RF behavior of ZigBee devices operating within a real environment, we collect the RSSI data under different conditions to characterize the main propagation features. Experimental results will be analyzed and relationship among different factors that affect the RSSI measurements such as external factors, e.g. multipath and fading, and the obstacles such as walls will be analyzed.

2. Design the network link quality monitoring software to show the real-time network link quality.

By adding the information such as extended address, network address, etc…into the transmitter messages of the end devices and router, and combining C++ builder 2010 to create a graphic interface. It helps engineers to observe the link quality for each node in the network.

3. By combining IME [5-8] and the CMD [9] as the data is missing, the dropout data in the ZigBee WSN will be resent to compensate for the missing message.

The average value substitution approach and the intelligent estimator approach are successfully applied to ZigBee WSN to compensate for the effect of data dropout. Moreover, combining IME and the CMD leads to the lowest contouring error under different dropout rate .

1.4 Organization of the Thesis

In this thesis, Chapter 1 describes the main purpose and goal of this research. Chapter 2 presents the background information of the ZigBee and its specifications. Chapter 3 develops the signal propagation model for ZigBee WSN by using the RSSI measurements in both indoor and outdoor environments. Chapter 4 and 5 present the monitoring software for network link quality and the improvement of data dropout by applying the integration of IME and CMD for the ZigBee WSN. Finally, achievements and contributions of this thesis are summarized in Chapter 6.

Chapter 2

Principle and Implementation of ZigBee

ZigBee is a new wireless technology guided by the IEEE 802.15.4 Personal Area Networks standard. It is primarily designed for the wide ranging automation applications and to replace the existing non-standard technologies. Some of its primary features are[10][11][12]:

- standards-based wireless technology
- interoperability and worldwide usability
- low data-rates
- ultra low power consumption
- very small protocol stack
- support for small to excessively large networks
- simple design
- security
- reliability

In this chapter, the ZigBee technology will be discussed in detail so that the common reader can have an overview of this technology. This thesis is carried out in corporation with FineTek, which want to evaluate the suitability of ZigBee in industrial application. The ZigBee's implementation on FineTek will also be introduced.

2.1 ZigBee Alliance

ZigBee Alliance is an association of companies working together to define an open global standard for products with low-power wireless networks. The intended outcome of ZigBee Alliance is to create a specification defining that how to build different network topologies with data security features and interoperable application profiles. The association includes companies from a wide spectrum of categories, from chip manufactures to system integration companies. Until now, the Alliance has become a large and thriving ecosystem of organizations providing everything product manufacturers need to create ZigBee products, include that radio semiconductor chips, design houses, software companies, support tools, and testing.

2.2 ZigBee and IEEE 802.15.4

The name ZigBee is said to come from the domestic honeybee that uses a zig-zag type of dance to communicate important information to other hive members. This communication dance (the "ZigBee Principle") is what engineers are trying to emulate with this protocol a bunch of separate and simple organisms that join together to tackle complex tasks.

The goal IEEE had when they specified the IEEE 802.15.4 standard was to provide a standard for ultra-low complexity, ultra-low cost, ultra-low power consumption and low data rate wireless connectivity among inexpensive devices. The raw data rate will be high enough (maximum of 250 kb/s) for applications like sensors, alarms and toys.

2.2.1 Components of the IEEE 802.15.4

The IEEE 802.15.4 networks use three types of devices:

(1) The network coordinator maintains overall network knowledge. There can be only one coordinator in a network; it has the ability to communicate with any device in the network. The coordinator is really the core component of the ZigBee network as proper working of this component is compulsory for the network to achieve the desired communication results. [13] [14].

(2) The Full Function Device (FFD) supports all IEEE 802.15.4 functions and features specified by the standard and it can be function as a network coordinator. Additional memory and computing power make it ideal for network router functions or it can be used in network-edge devices (where the network touches the real world). One other responsibility is that it searches the other FFDs and the RFDs to create the communication link so that the transfer of data can be made possible to reach the desired node. [13] [14].

(3) The Reduced Function Device (RFD) carries limited (as specified by the standard) functionality to lower cost and complexity. It is generally found in network-edge devices. The RFD can be used where extremely low power consumption is a necessity.

2.2.2 Network topologies

Figure 2.1 shows three types of topologies that ZigBee supports: star topology, peer-to-peer topology and cluster tree. which add to the properties of the network and how the data will be transferred or how the communication carried out.

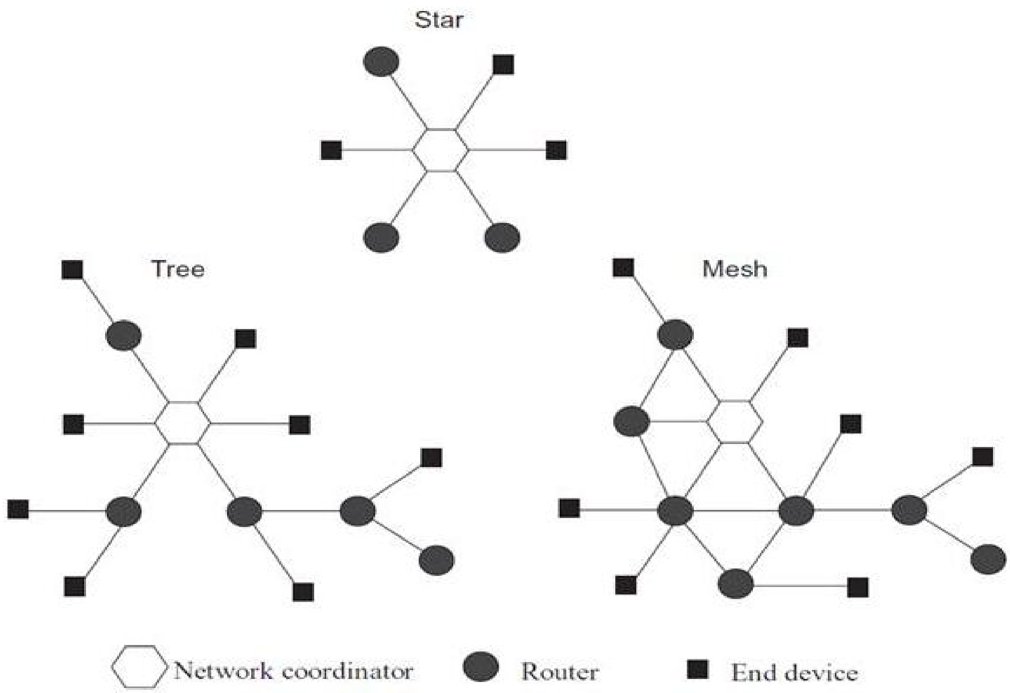


Figure 2-1 ZigBee network topologies [4]

(1) Star Topology

In the star topology, the communications are established between devices and a single central controller, called the PAN coordinator. Applications that could get benefits from this topology include home automation, personal computer (PC) peripherals, toys, and games.

After an FFD is activated for the first time, it may establish its own network and become the PAN coordinator. Each star network chooses a PAN identifier, which is not currently used by any other network within the radio sphere of influence. This allows each star network to operate independently.

(2) Peer-to-peer Topology

In peer-to-peer topology, there is also one PAN coordinator. In contrast to star topology, any device can communicate with any other device as long as they are in range of one another. A peer-to-peer network can be ad hoc, self-organizing and self-healing. Applications such as industrial control and monitoring, wireless sensor networks, asset and inventory tracking would be benefits from such a topology. It also allows multiple hops to route messages from any device to any other device in the network. It can provide reliability by employing multipath routing.

(3) Cluster-tree Topology

The cluster-tree network is a special case of a peer-to-peer network in which most devices are FFDs and an RFD may connect to a cluster-tree network as a leave node at the end of a branch. Any of the FFD can act as a coordinator and provide synchronization services to other devices and coordinators. Only one of these coordinators however is the PAN coordinator. The PAN coordinator forms the first cluster by establishing itself as the cluster head (CLH) with a cluster identifier (CID) of zero, choosing an unused PAN identifier, and broadcasting beacon frames to neighboring devices. A candidate device receiving a beacon frame may request to join the network at the CLH. If the PAN coordinator permits the device to join, it will add this new device as a child device in its neighbor list. The newly joined device will add the CLH as its parent in its neighbor list and begin transmitting periodic beacons such that other candidate devices may then join the network at that device. Once application or network requirements are met, the PAN coordinator may instruct a device to become the CLH of a new cluster adjacent to the first one. The advantage of this clustered structure is the increased coverage area at the cost of increased message latency.

2.2.3 OSI overview

The Open System Interconnection (OSI) reference model, was developed by the international organization for standardization (ISO) as a model for the computer protocol architecture, and as a framework for developing protocol standards. The entire point of the model is to separate networking into several distinct functions that operate at different levels. Each layer is responsible for performing a specific task or set of tasks, and dealing with the layers above and below it. An illustration of the general OSI-model and where ZigBee is in the model can be seen in Fig. 2-2.

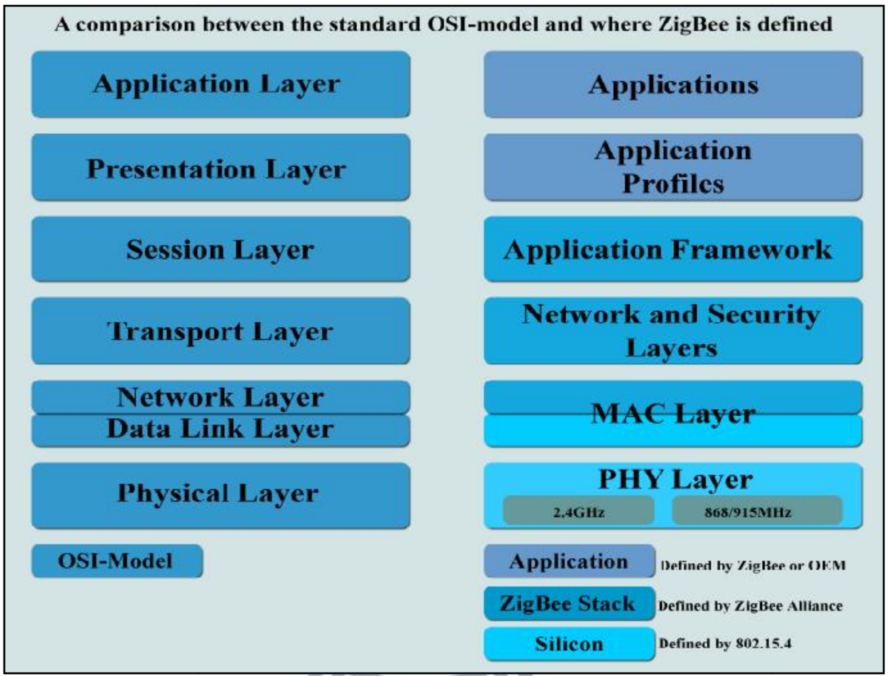


Figure 2-2 The OSI model

2.2.4 Physical layer

The IEEE 802.15.4 specification operates on three different frequency bands, in order to conform to regulations in Europe, Japan, Canada and the United States [15]. Table 2-1 describes the frequency bands and data rates. Totally 27 channels are available across the different frequency bands, as described in Table 2-2.

Table 2-1 Frequency bands and data rates [4]

PHY (MHz)	Frequency band (MHz)	Chip rate (kchips/s)	Modulation	Bit rate (kb/s)	Symbol rate (ksymbol/s)	Symbols
868	868-868.6	300	BPSK	20	20	Binary
915	902-928	600	BPSK	40	40	Binary
2450	2400-2483.5	2000	O-QPSK	250	62.5	16-ary Orthogonal

Table 2-2 Channels and center frequency [4]

Center frequency (MHz)	Number of channels (N)	Channel (k)	Channel center frequency (MHz)
868	1	0	868.3
915	10	1-10	906+2(k-1)
2450	16	11-26	2405+5(k-11)

(1) Modulation/Spreading

In the physical layer, the conversion of the binary data to a modulated signal in the 2450 MHz frequency band could describe as the functional block diagram in Fig.2-3. The numbers show how the binary data "0000b" that is converted to a baseband chip sequence with pulse shaping:

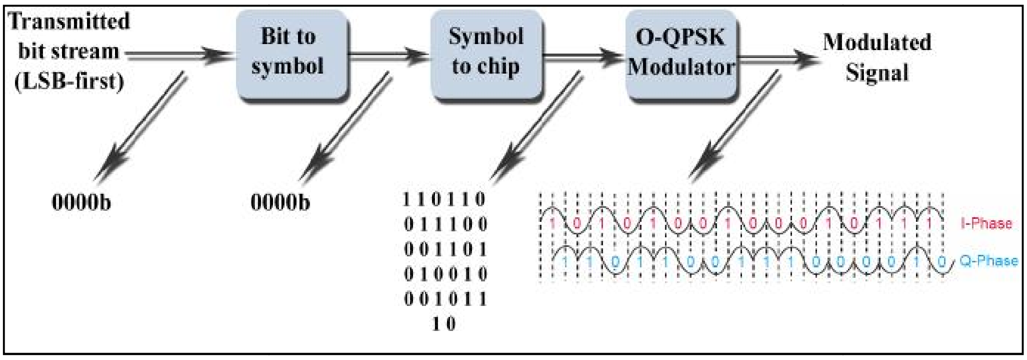


Figure 2-3 Modulation and Spreading

(2) Bit to symbol

The first step is to encode all the data in the PHY Protocol Data Unit (PPDU) from binary data to symbols [16]. Each byte is divided into two symbols and the least significant symbol is transmitted first. For multi-byte fields, the least significant byte is transmitted first, except for security related fields where the most significant byte is transmitted first.

(3) Symbol to chip

Each data symbol is mapped into a Pseudo-random (PN) 32-chip sequence. The chip sequence is then transmitted at 2 MChip/s with the least significant chip (c_0) transmitted first for each symbol. Table 2-3 shows the data symbol with corresponding chip values.

Table 2-3 Symbol to chip mapping

Data symbol (decimal)	Data symbol (binary) (b_0 b_1 b_2 b_3)	Chip values (c_0 c_1 … c_{30} c_{31})
0	0 0 0 0	1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0
1	1 0 0 0	1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0
2	0 1 0 0	0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0
3	1 1 0 0	0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1
4	0 0 1 0	0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0 0 0 1 1
5	1 0 1 0	0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1 1 1 0 0
6	0 1 1 0	1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1 1 0 0 1
7	1 1 1 0	1 0 0 1 1 1 0 0 0 0 1 1 0 1 0 1 0 0 1 0 0 0 1 0 1 1 1 0 1 1 0 1
8	0 0 0 1	1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1
9	1 0 0 1	1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1
10	0 1 0 1	0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1
11	1 1 0 1	0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0
12	0 0 1 1	0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1 0 1 1 0
13	1 0 1 1	0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0 1 0 0 1
14	0 1 1 1	1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0 1 1 0 0
15	1 1 1 1	1 1 0 0 1 0 0 1 0 1 1 0 0 0 0 0 0 1 1 1 0 1 1 1 1 0 1 1 1 0 0 0

(4) QPSK Modulation

The modulation format is Offset -Quadrature Phase Shift Keying (O-QPSK) with half-sine pulse shaping, equivalent to Minimum Shift Keying (MSK). QPSK is an efficient way to use the often limited bandwidth. Each signal element represents two bits, the equation below shows how the O-QPSK can be expressed. By using Oset, phase changes in the combined signal never exceeds 90º. In the case, using QPSK the maximum phase change is 180 º. O-QPSK provides a greater performance than QPSK when the transmission channel has components with significant nonlinearity.

$$p(t) = \begin{cases} \sin\left(\pi \frac{t}{2T_c}\right), & 0 \le t \le 2T_c \\ 0, & otherwise \end{cases} \qquad (2.1)$$

(5) Error-vector magnitude

The modulation accuracy of an IEEE 802.15.4 transmitter is determined by an Error Vector Magnitude (EVM) measurement, see Fig. 2-4. EVM is the scalar distance between the two phasor end points representing the ideal and the actual measured chip positions. Expressed in another way, it is the residual noise version of the signal and distortion remaining after an ideal version of the signal has been stripped away.

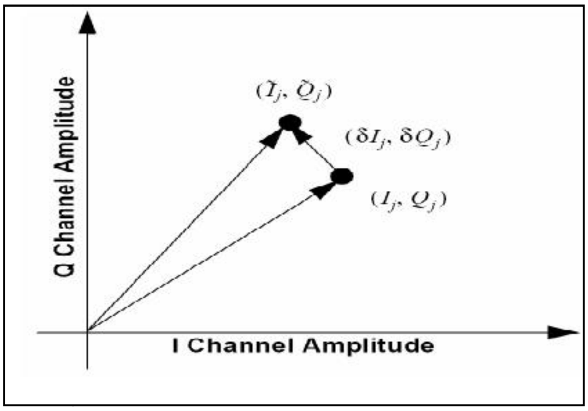


Figure 2-4 Error vector

$$(\tilde{I}_j, \tilde{Q}_j) = (I_j, Q_j) + (\delta I_j, \delta Q_j) \tag{2.2}$$

The EVM for IEEE 802.15.4 is defined as shown in Eq. 2.3.

$$EVM \equiv \sqrt{\frac{\frac{1}{N}\sum_{j=1}^{N}\left(\delta I_j^2 + \delta Q_j^2\right)}{S^2}} \times 100\% \tag{2.3}$$

where S is the magnitude of the vector to the ideal constellation point, $(\delta I_j, \delta Q_j)$ is the error vector. The transmitter shall have EVM values of less than 35% when measured with 1000 chips.

(6) Transmit power

The transmitter should be capable of transmitting at least -3 dBm. Also, the device should transmit as low power as possible to reduce interference to other devices and systems. The definition of dBm is shown in Equation 2.4.

$$Power_{dBm} = 10 log \frac{Power_{mW}}{1mW} \tag{2.4}$$

Note the following relationships:

$$0dBm = 1mW \tag{2.5}$$

$$+30dBm = 0dBW \tag{2.6}$$

$$0dBm = -30dBW \tag{2.7}$$

(7) Receiver sensitivity

The receiver sensitivity is defined by two terms. One is Packet Error Rate (PER) which is the average fraction of transmitted packets that are not detected correctly. The other term is the threshold input signal power that yields a specified PER. In IEEE 802.15.4 a compliant device shall have a sensitivity of -85 dBm or better.

(8) Receiver Engineering Detection (ED)

The receiver Energy Detection (ED) is intended to be used by the network layer as part of a channel selection algorithm. It is an estimate of the received signal power within the bandwidth of an IEEE 802.15.4 channel. No attempt is made to identify or decode signals on the channel. The ED time shall be equal to 8 symbol periods [17].

(9) Link quality Indication (LQI)

The LQI is a characterization of the strength and/or quality of a received packet. The measurement may be implemented using receiver ED, a Signal to Noise Ratio (SNR) estimation, or a combination of these methods. The use of the LQI result by the network or application layer is not part of the IEEE 802.15.4 standard [17].

(10) Received signal strength indicator (RSSI)

The received signal strength indicator can be used as a measure of the signal quality. The RSSI is a measure of the total energy of the received signal. The ratio of the desired signal energy to the total in-band noise energy (the signal-to-noise ratio , or SNR) is another way to judge the signal quality. As a general rule, higher SNR translates to lower chance of error in the packet. Therefore, a signal with high SNR is considered a high-quality signal[17].

(11) Clear Chanel Assessment (CCA)

The CCA is used to decide whether the channel is busy or idle and one of the following methods must be supported [17].

- CCA Mode 1: Energy above threshold. CCA shall report a busy medium upon detecting any energy above the ED threshold.
- CCA Mode 2: Carrier sense only. CCA shall report a busy medium only upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4. This signal may be above or below the ED threshold.
- CCA Mode 3: Carrier sense with energy above threshold. CCA shall report a busy medium only upon the detection of a signal with the modulation and spreading characteristics of IEEE 802.15.4 with energy above the ED threshold.

A busy channel shall be indicated by the Physical Layer Management Entity Con-firm (PLME-CCA.confirm) primitive with a status of BUSY. A clear channel shall be indicated by the PLME-CCA. confirm primitive with a status of IDLE.

2.2.5 Medium Access Control Layer

Media Access Control (MAC) has different responsibilities [16]:

- The main function of MAC is to carry out the association and disassociation of the network involved. A large number of devices are managed or handled by this layer.

- It generates the network beacons according to the device, if it is a coordinator
- It also performs the function of synchronizing the beacons.
- It uses the CSMA-CA channel access mechanism
- It uses Guaranteed Time Slot (GTS) mechanism.
- It allows different mechanisms to conserve energy like collision avoidance using CSMACA and allowing the device to go into sleep mode.

2.3 Hardware

The Smart development kit from FineTek company were used in this thesis, as show in Fig. 2-5.

Figure 2-5 FineTek ZigBee equipments

The board complete with CC2430 chip complied to system-on-chip (SOC) ZigBee®/IEEE 802.15.4 standard, an industry-standard enhanced 8051 MCU with 128 KB flash memory and 8 KB RAM and with AN040 whip antenna. The board supports the Z-Stack™ protocol stack .

2.4 FineTek's Level Measurement [18]

FineTek designed level measurement system using ZigBee WSN to perform smart monitoring of the level of tanks as show in the Fig. 2-6. The data are collected by level transmitters such as electromechanical level measurement, magnetostrictive level transmitter, capacitance level transmitter, magnectic level transmitter, pressure level transmitter. Then data is transmitted via ZigBee communication protocol.

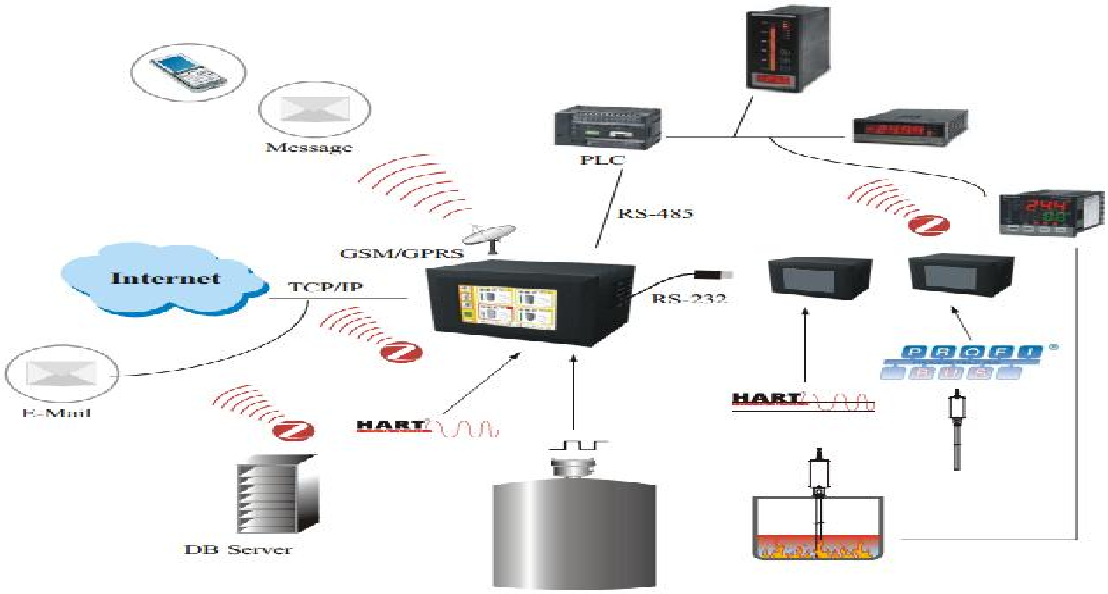


Figure 2-6 FineTek's Level Measurement System

The FineTek system is really is a good monitoring application to observe all levels in the tanks and silos. However, the developed system does not support information of the WSN such as communication reliability and topology of the network. In addition, the application does not deal with the data dropout in the ZigBee WSN.

Chapter 3

Propagation Analysis for ZigBee

In this chapter, the radio frequency behavior of ZigBee devices operating within a real environment will be studied. Three different RSSI measurement models have been carried out to characterize the main propagation features. On the basis of the experimental results, different factors that affect the measurements, such as external factors (e.g. multipath, fading) or internal ones (e.g. hardware device, integrated antennas) have been analyzed. The first approach, made in the outdoor environment, was performed to study both the internal and external factor effects, the second one was performing in the corridor of the building to investigate the signal characteristics in the indoor environment. And the last one is to study how obstacles such as the walls affect signal intensity in indoor environments. Furthermore, to deeply analyze the ZigBee behavior, we have compared the measurements with a suitable propagation model to prove it's effectiveness. Thus, the ZigBee signal propagation in a complex environment can be predicted by applying the obtained model.

3.1 The Propagation model

The effectiveness of a propagation model depends on how the theoretical approximation can fit with the real measurements. The Log-Distance Path Loss Model [19, 20] has been used extensively in literatures as:

$$P(d)_{dB} = P(d_0)_{dB} - 10.n.\log_{10}\left(\frac{d}{d0}\right) \qquad (3\text{-}1)$$

As the reference power at 1m, the equation becomes:

$$P(d)_{dB} = P(1m)_{dB} - 10.n.\log_{10}(d) \qquad (3\text{-}2)$$

Where, $P(d)$ is the power in dB to estimate at some particular distance d, $P(d_0)$ is the known power at distance d_0, n is the path loss exponent, which indicates the decreasing rate of signal strength in an environment, d_0 is a reference distance which is close to the transmitter, and d is the distance between the transmitter and the receiver. In general, the exponent n is environment-dependent and in a free space its value is close to 2 [20]. In the indoor case, it will be larger than this value.

However, the Log-Distance Path Loss Model does not show the effect of obstacles such as the wall effect. Therefore, the Wall Attenuation Model [21] is adopted in this analysis and it considers the number of walls of certain types between the transmitter and receiver. This model suggests that a certain wall causes a particular and fixed dB loss in the signal strength irrespective of the distance of transmitter or receiver from the wall [22] :

$$P(d)_{dB} = P(d_0)_{dB} - 10.n.\log_{10}\left(\frac{d}{d0}\right) - \sum_{i=1}^{p} a_i \cdot N_i \qquad (3\text{-}3)$$

For the reference power at 1m, the equation becomes,

$$P(d)_{dB} = P(1m)_{dB} - 10.n.\log_{10}(d) - \sum_{i=1}^{p} a_i \cdot N_i \qquad (3\text{-}4)$$

Where α is the wall attenuation factor for the wall type i , and N is the number of walls of type i between the transmitter and the receiver, and p is the number of different types of walls between transmitter and receiver.

This model added the term $\sum_{i=1}^{p} \alpha_i . N_i$ that represents the total loss due to the walls in different types. Many researchers worked on different types of walls and their attenuation factors. The wall attenuation effect for different wallsbased on the material conductivity was presented in [23]. Wall Attenuation Model is the most commonly used nowadays for indoor signal strength estimations, and also used by RADAR [23].

Radio Signal Strength Indication (RSSI) ranging system is constructed by measuring the received signal strength. The RSSI value is inversely proportional to the signal strength, so the Log-Distance Path Loss Model can be further expressed as:

$$RSSI(d)_{dBm} = RSSI(1m)_{dBm} - 10.n.log_{10}(d) \qquad (3\text{-}5)$$

And the Wall Attenuation Model also can be expressed as:

$$RSSI(d)_{dBm} = RSSI(1m)_{dBm} - 10.n.log_{10}(d) - \sum_{i=1}^{p} \alpha_i . N_i \qquad (3\text{-}6)$$

where *RSSI (d)* is the measured value at distance *d. RSSI(1m)* is measured value at 1m distance .

3.2 Linear Regression Modeling

The Path Loss Exponent Analysis method determines the Log-Distance Path Loss Model and the Wall Attenuation Model with the linear least squares curves fitting [24]. To obtain the path loss exponent (*n*), and wall attenuation factor α. This method is a process of constructing a curve, or mathematic function that has the best fit to a series of data points, possibly subject to constraints with some degree of randomness in curve fitting. 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 received power in *dB* and the distance on the logarithmic scale are preferred.

3.3 Experimental setup

In the present experiments, the smart development kits from FineTek company are used. The board complete with CC2430 chip complied to system-on-chip (SOC) ZigBee®/IEEE 802.15.4 standard, an industry-standard enhanced 8051 MCU with 128 KB flash memory and 8 KB RAM, plugged in AN040 whip antenna are adopted. The board supports the Z-Stack™ protocol stack [25].

Measurements have been carried out as follows: the ZigBee end device sent packets to the receiver, and the ZigBee coordinator measured the RSSI of the received packet. We extracted RSSI data byte from the received packet by a query of the coordinator which was connected to the PC via RS232 port. In the experiment, the ZigBee coordinator is placed at a fixed location while the ZigBee end device is placed at different distance as show in Fig.3-1.

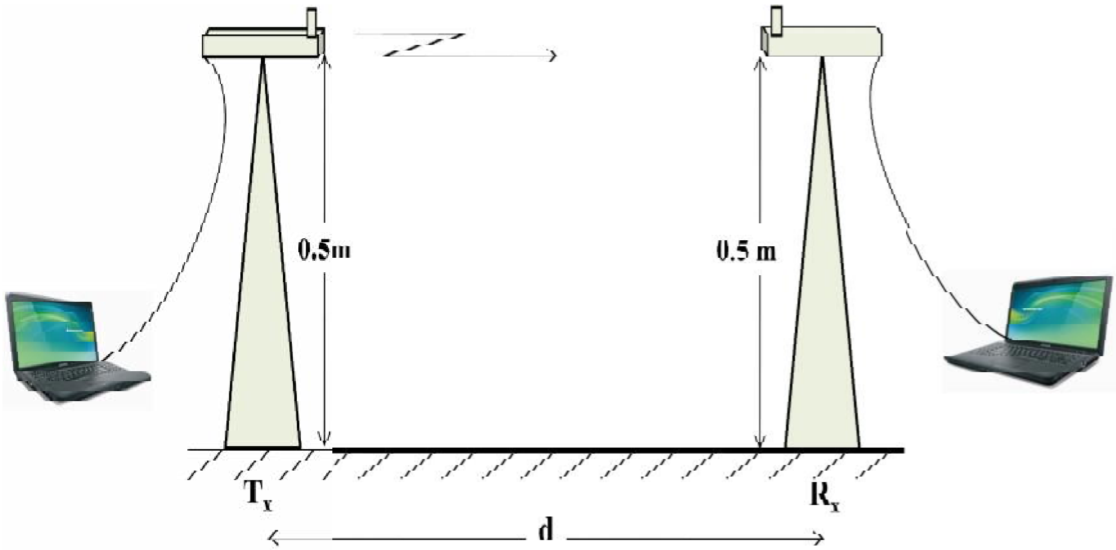


Figure 3-1 The experiment setup at various Tx-Rx distance of *d*

In each distance, the relocating ZigBee end device transmits 1000 strength packets on Channel 11 (2405 MHz) at the output power of -0.1 dBm, the minimum allowed by the program. The fixed-location ZigBee coordinator records the RSSI. The average value of RSSI is recorded.

The ZigBee devices are placed in 3 different scenarios ranging from the closest link to the user:

- **Scenario 1: Outdoor without obstacle**

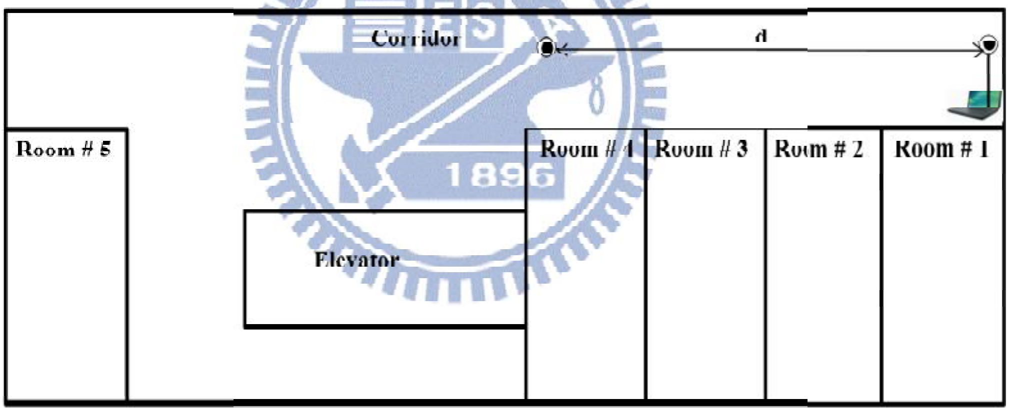
This experiment was taken placed on the walking path without obstacle as show in Fig. 3-2

Figure 3-2 Outdoor data was collected in an open walking path without obstacles.

- **Scenario 2 : Indoor without obstacle**

This experiment was taken placed at the corridor at ninth floor of Dormitory Building in NCTU without obstacle as show in Fig. 3-3. In this scenario, the setup is similar to the first but the devices are placed in less open area with walls surrounded.

(a)



(b)

Figure 3-3 Indoor data was collected at the corridor of the building without obstacle

- **Scenario 3: Indoor with obstacle**

The experiment also was taken place at ninth floor of Dormitory Building in NCTU. As shown in Fig. 3-4, measurement were carried-out at the corridor with a fixed obstacle, the brick wall. The ZigBee coordinator is placed at fixed distance in front of the brick wall, while the ZigBee end device is placed at different distance behind the wall.

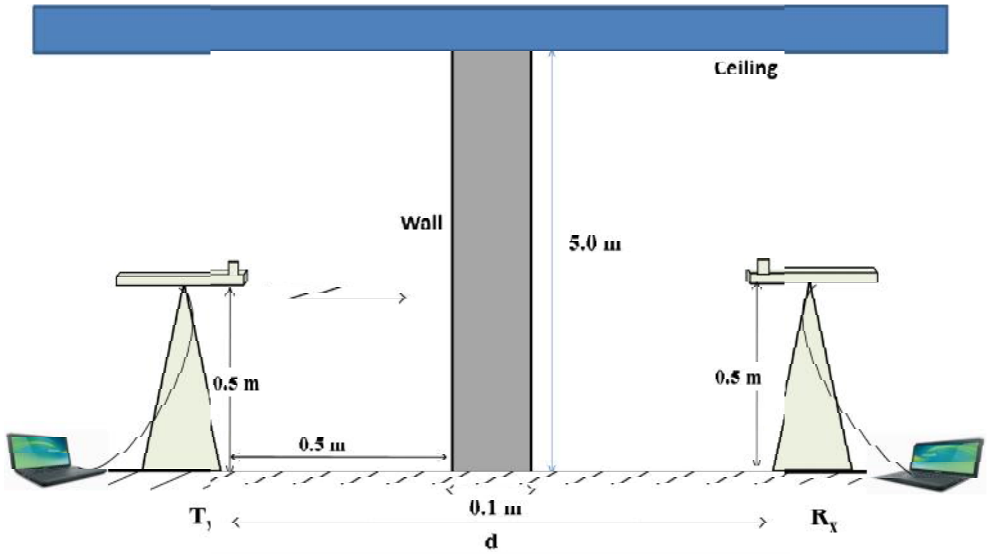


Figure 3-4 Indoor data was collected at the corridor of the bulding with a fixed obstacle (brick wall)

3.4 Experimental results

3.4.1 Outdoor without obstacle

The experiment was taken place on the walking path in NCTU campus without obstacle. The ZigBee end device transmits 1000 packets to the ZigBee coordinator, and each received packet contains the RSSI value. Fig. 3-5 shows that the RSSI are measured by the coordinator when the distance between transmitter and receiver is 1 m.

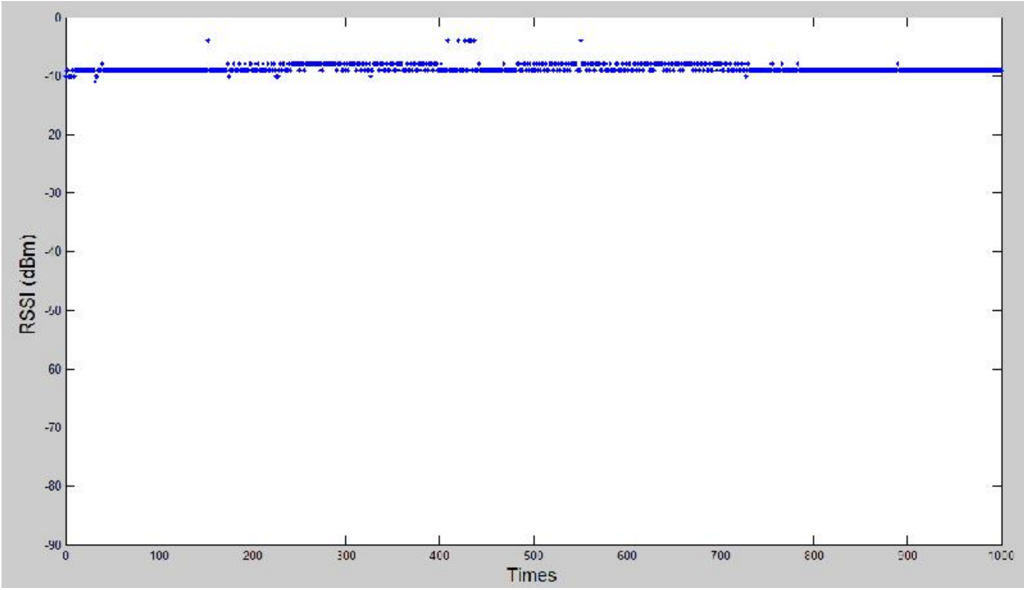


Figure 3-5 RSSI with 1m distance

The average of RSSI is calculated to determine the parameter of Eq. (3-5). For example, the average of RSSI is -8.68 dBm and 1 m is between two devices. Table 3-1 below shows the average RSSI and PRR with different distances.

Table 3-1 Average RSSI with distances

Distance (m)	1	10	20	30	40	50	60	70	80
RSSI(dBm)	-8.68	-28.08	-35.02	-37.94	-39.68	-40.53	-44.57	-45.38	-47.07
PRR (%)	100	100	99.5	99.3	98.4	96.4	93.4	92.3	90.6

By applying the least square curve fitting from MATLAB curve fitting tool in a graphical user interface, Fig 3-6 shows the curve fitting results for collected data.

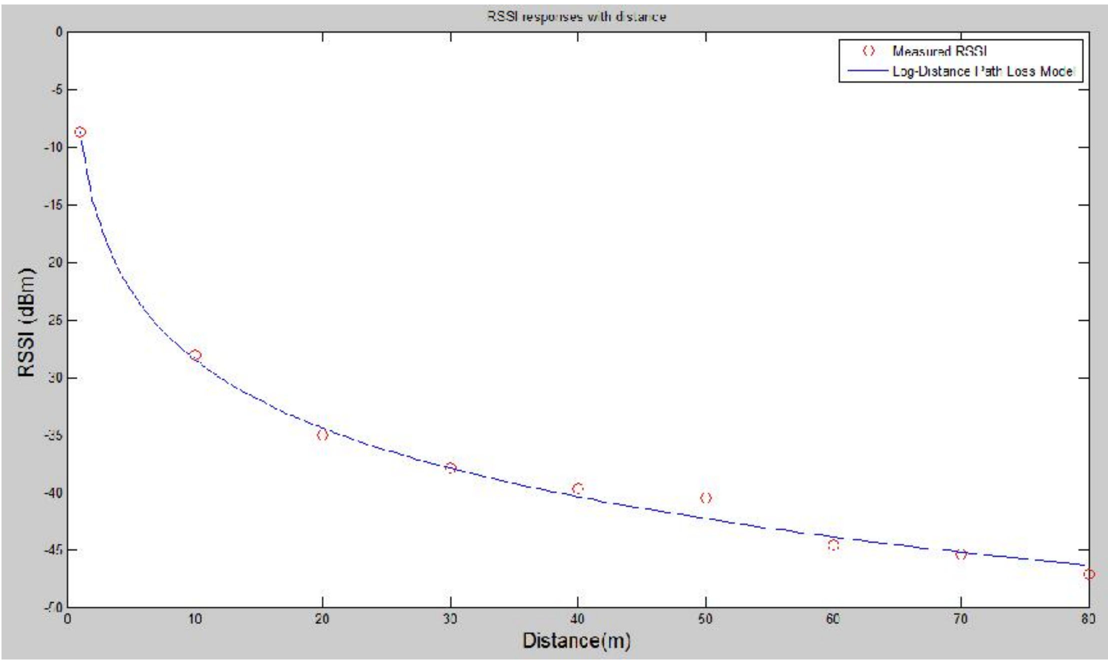


Figure 3-6 RSSI responses with distances

The strength of signal attenuates when we increase the distance from coordinator and end device. Due to signal attenuation, the packet reception rate proportional decreases with signal attenuation. The result shows in the Fig. 3.7

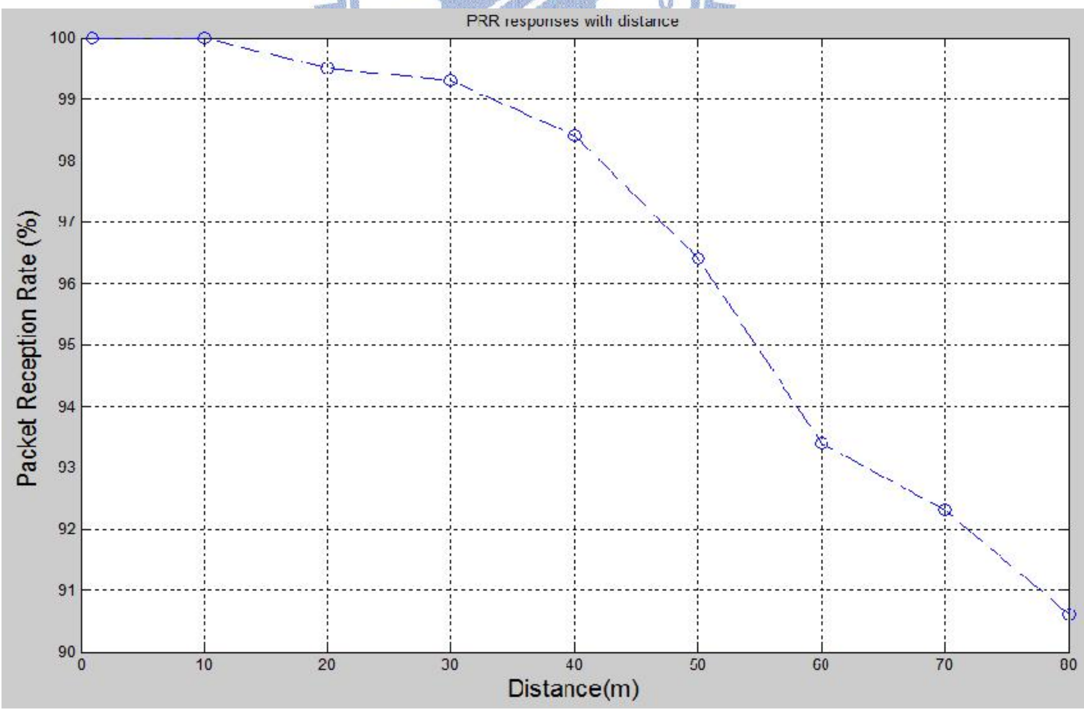


Figure 3-7 PRR responses with distances

The circle mark is the average of measured RSSI with the different distance and the line is the curve fitting results. In the Log-distance Path Loss Mode, the path loss exponent *n* is 1.98.

Thus, the Log-distance Path Loss Model in the scenario of the devices taken place without obstacle can be rewritten as:

$$RSSI(d)_{dBm} = -8.68 - 19.8*log_{10}(d) \qquad (3\text{-}7)$$

3.4.2 Indoor without obstacle

The indoor end device also transmits 1000 packets to ZigBee coordinator, each received packet all contains the RSSI value as recorded in Fig. 3-8 as the distance between transmitter and receiver is 1 m.

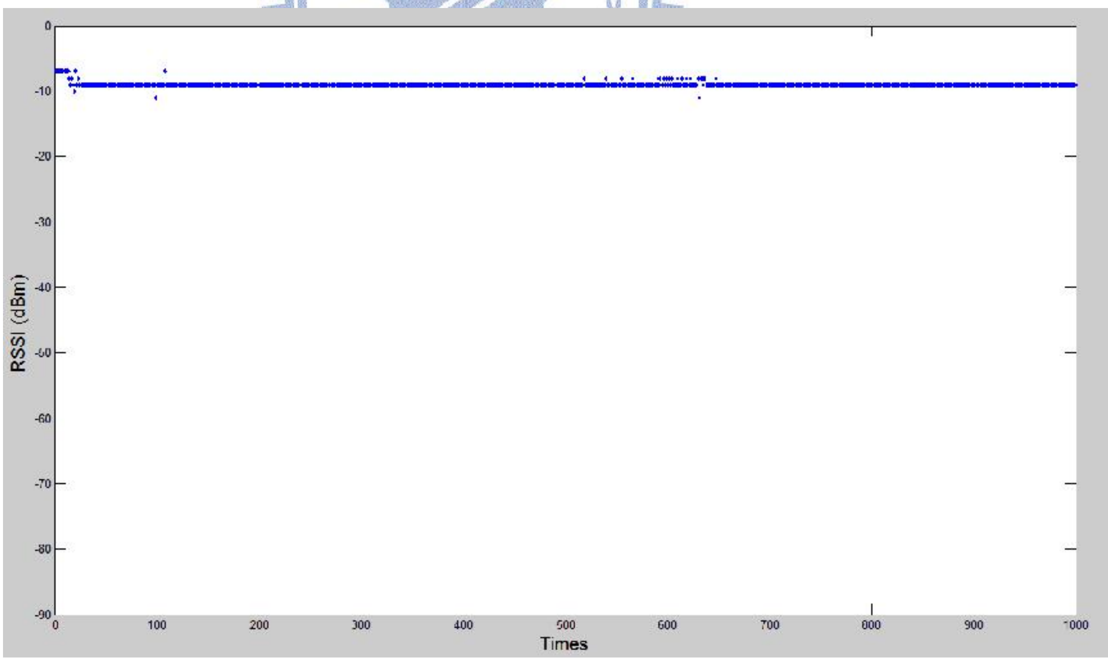


Figure 3-8 Indoor RSSI with 1m distances without obstacle

The average of responses with 1m distance is -8.67 dBm in the scenario 2: the experiment was taken place at the corridor of ninth floor of Dormitory Building in NCTU without obstacle. Table 3-2 below shows the average of RSSI measured indoor with different distances. The least squares method was also applied to obtain the curve fitting as shown in Fig. 3.9.

Table 3-2 The Indoor RSSI and PRR responses with different distances without obstacle

Distance (m)	1	2	3	4	5	10	15	20	25
RSSI(dBm)	-8.67	-13.25	-17.45	-19.92	-21.48	-26.87	-29.48	-32.45	-34.13
PRR (%)	100	100	99.7	99.7	99.4	99.5	99.2	99.2	99.0

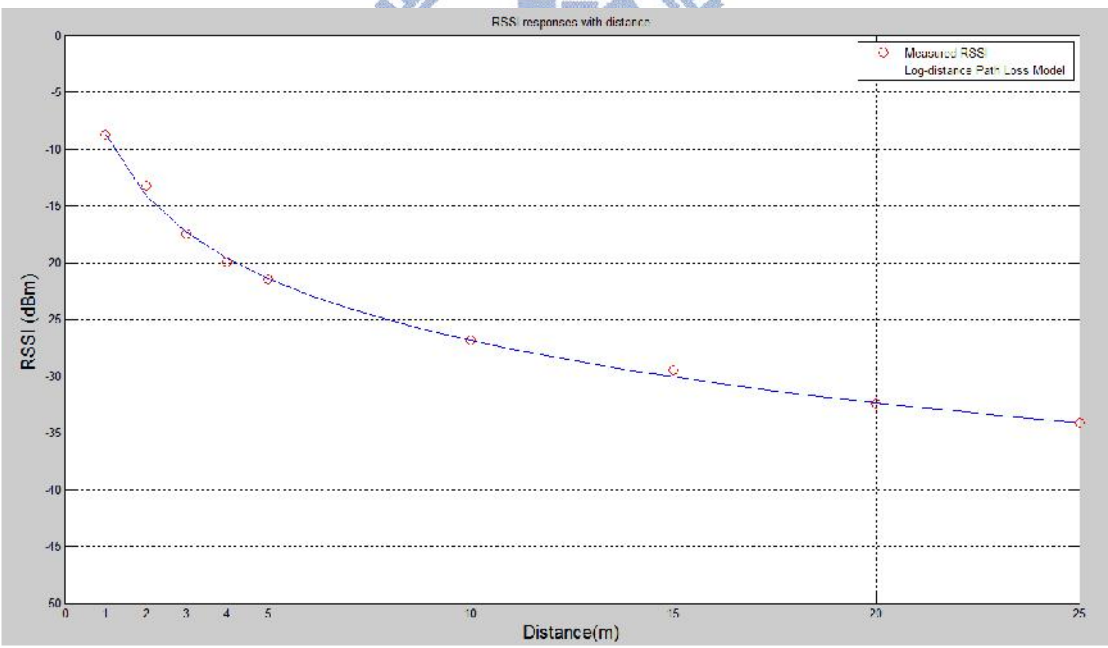


Figure 3-9 The indoor RSSI with distances (without obstacle)

Fig.3-10 shows the packet reception rate proportional decreases with distance between coordinator and end device.

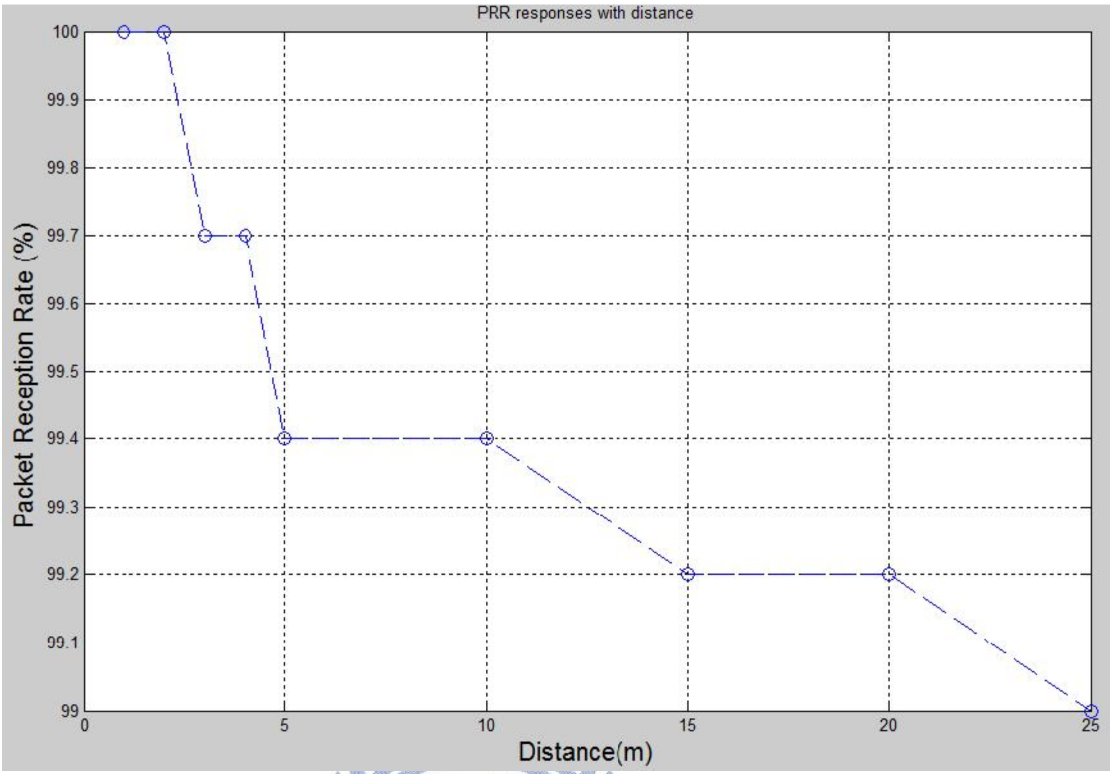


Figure 3-10 PRR with distances (without obstacle)

The circular mark is the average of measured RSSI with the different distance and the line is the curve fitting results using the least squares method. In this indoor experiments, the Log-distance Path Loss Model can be represented as

The path loss exponent *n* is 1.82.

Thus, the Log-distance Path Loss Model in this scenario can be rewritten as:

$$RSSI(d)_{dBm} = -8.67 - 18.2 * log_{10}(d) \quad (3\text{-}8)$$

3.4.3 Indoor with a brick wall

Obstacles are one of the major concerns in RSSI ranging system. Radio signals lose strength when traveling through obstacles such as wall. Large obstacles can even block a signal completely. In this section, we show how the wall affect the signal strength behavior. By applying the Wall Attenuation Model as in Eq. (3-6), the path loss exponent n and the wall attenuation factor α can be determined from experiments. In this scenario, the number of wall is 1, so the equation (3-5) can be expressed:

$$RSSI(d)_{dBm} = RSSI(1m)_{dBm} - 10.n.log_{10}(d) - \alpha \qquad (3\text{-}9)$$

We locate the coordinator behind the brick wall still with the distance as 1 m. The end device locates in front of the wall with the different distance from the coordinator. At each position of the end device, the coordinator receives 1000 RSSI from the end device. The average of RSSI is used to determine the parameters n and α of the model. By adopting the value the same with the scenario 2 and RSSI (1m) is -8.67 dBm, Table 3-3 shows the average of RSSI with different distances.

Table 3-3 RSSI with distances with an obstacle (one brick wall)

Distance (m)	2	3	4	5	10	15	20	25	30
RSSI(dBm)	-20.02	-24.68	-28.93	-31.85	-39.06	-45.67	-47.18	-50.92	-52.96
PRR (%)	99.9	99.3	99.2	99.0	98.5	98.1	98.0	97.6	97.2

By applying the least square method, Fig. 3-11 shows the measured RSSI and the curve fitting in good agreement.

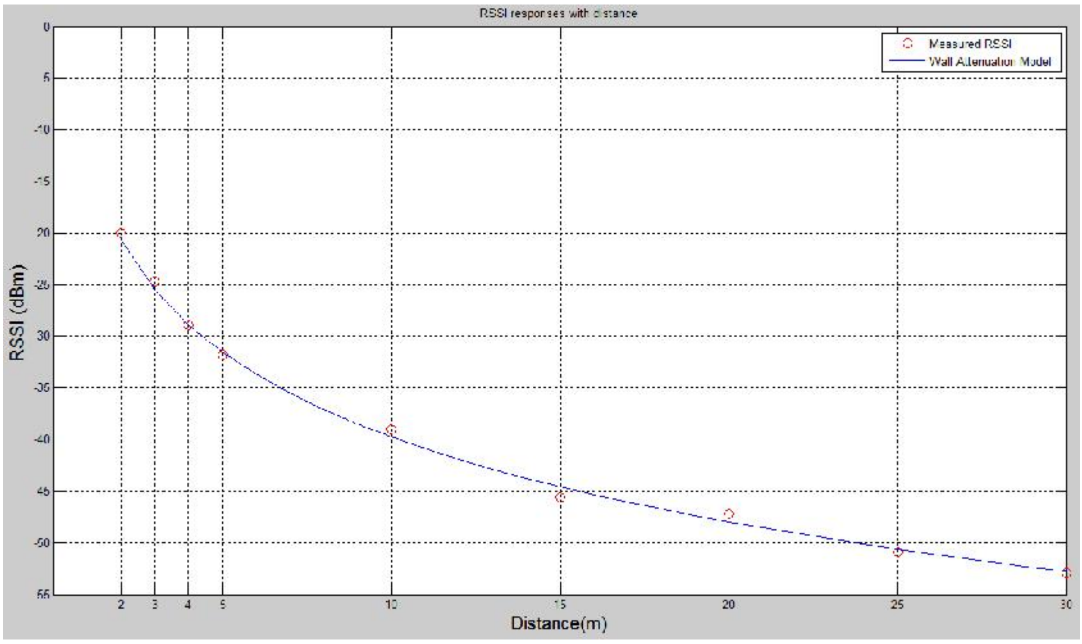


Figure 3-11 RSSI responses distances (with a brick wall)

Fig.3-12 shows the packet reception rate proportional decreases with distance between coordinator and end device.

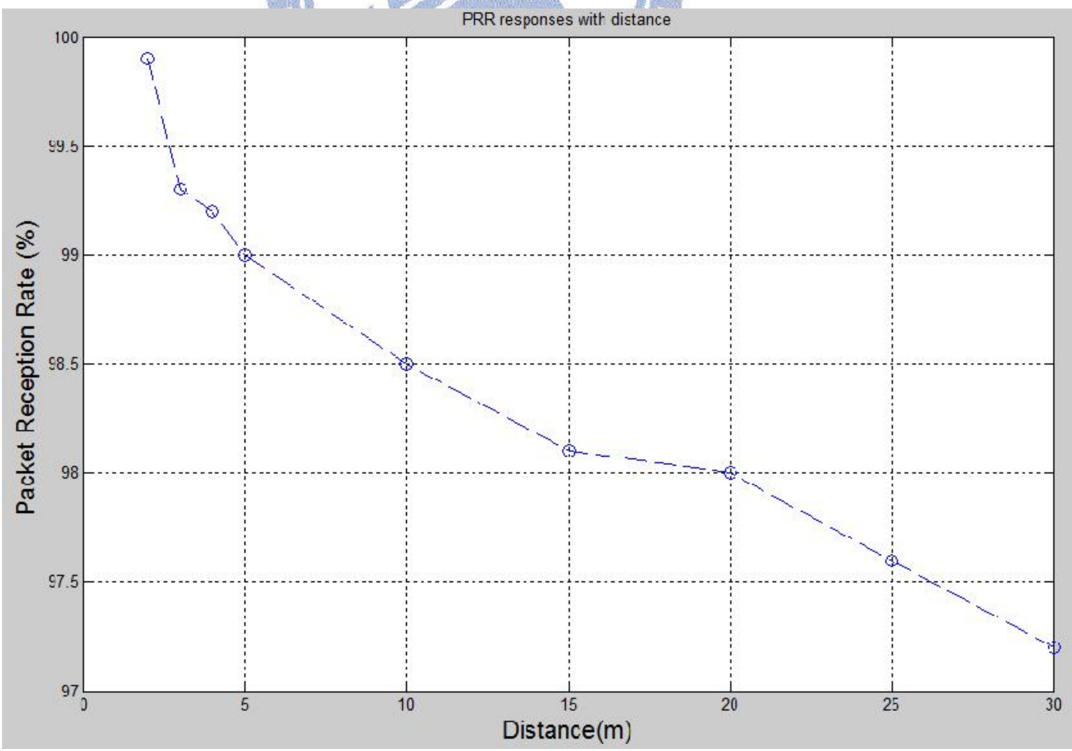


Figure 3-12 PRR with distances (with a brick wall)

By using the least square method to fit the measured RSSI, parameters of the model are obtained as:

The path loss exponent: n= 2.73

The wall attenuation factor α = 3.78 dBm.

The Table 3-4 and Fig 3-13 prove the accuracy of model in the indoor environment with a brick wall, the Wall Attenuation Model with path loss exponent n= 2.73 and wall attenuation factor α=3.78 dBm leads the least mean absolute error.

Table 3-4 The error of estimate the Wall Attenuation Model

Path loss exponent n	Wall attenuation factor α	Mean absolute error
1.98	11.11	2.63451
1.82	13.67	3.02230
2.37	3.78	0.78218

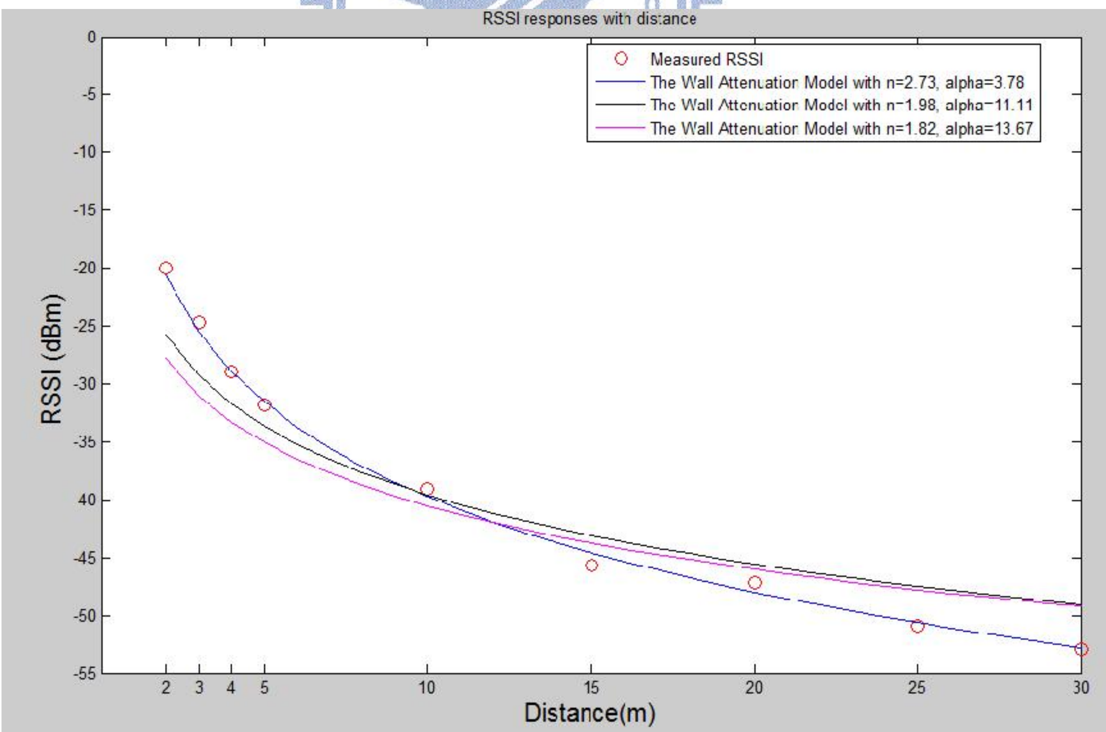


Figure 3-13 The Wall Attenuation Model

Thus, the Wall Attenuation Model in the equation (3-6) in this scenario can be rewritten as:

$$RSSI(d)_{dBm} = -8.67 - 27.3*\log_{10}(d) - 3.78 \qquad (3\text{-}10)$$

or

$$RSSI(d)_{dBm} = -12.45 - 27.3*\log_{10}(d) \qquad (3\text{-}11)$$

3.5 Summary

In this chapter, we have demonstrated that how signal strength behaves in both indoor and outdoor environments. Present achievements are summarized as follows.

(1) The Log-distance Path Loss Model can be used to estimate signal attenuation both indoor and outdoor of the building, with and without obstacles as walls.

(2) The Wall Attenuation model can be used to estimate signal attenuation inside the building with obstacles such as walls. The Wall Attenuation model considers the number of walls and their certain types. This model suggests that a certain wall causes a particular and fixed dB loss in the signal strength is mainly determined by the distance between the transmitter and the receiver if the wall exists between them. Based on obtained models and specific environment-dependent parameters as in Table 3-5, the signal strength in various environments can be thus predicted.

Table 3-5 Path loss exponent and wall attenuation factor under different environments

Environment	Path loss exponent n	Wall attenuation factor α
Outdoor, free space	1.98	
Inside of building, line of sight	1.82	
Inside of building with a wall obstacle	2.73	3.78

Chapter 4

The Monitoring Systems for ZigBee

ZigBee has been developed to meet the growing demand for wireless networking between low-power devices. It has been widely deployed for wireless monitoring and control applications [26-28]. Moreover, some other research work has been extensively implemented in monitoring green-house environment [29], home automation [30], distributed solar panels [31], high voltage switch gears in substations [32]. However, most research results only monitor the physical parameters such as temperature, water quality, position location, etc. The internal communication conditions of the network such as: topology, packet receive rate, and signal strength are unknown in real application.

The main aim of this chapter is to design a network link quality monitoring system. The main functions of this design are:

- continuous monitoring of data values of nodes.
- designing of GUI window.
- displaying the topology of the ZigBee wireless sensor network.
- displaying signal strength of all node-to-node connectivity in the network.
- calculating the packet receive rate of the network.
- showing the the status of connectivity of the nodes such as connection, disconnection.

A comparison between the currently available monitoring system such as level measurement system (LMS) [18] of FineTek and the present network link quality monitoring system is listed in Table 4-1

Table 4-1 The available monitoring systems and the present monitoring system

Function	Available monitoring system[18][29][31]	Present monitoring system
Real time data	Yes	Yes
Show topology network	No	Yes
Indicate the fail communication	Limited	Yes
Extend the network	Limited	Yes
Suitable network	Star topology	Star, mesh topology

4.1 The transmitted messages

The format of transmitted message are designed as in the following:

ID	Extended address	Short address	RSSI	The order of message	Length of data	Data

Figure 4-1 The ZigBee transmitted message format

They are defined as:

ID: Identification of device. ZigBee's addressing scheme supports 255 active nodes per network coordinator, each active node has ID from 1 to 255. The coordinator can recognizes the resource of message through the ID parameter.

Extended address or IEEE address: The 64-bit address is a globally unique address and is assigned to the device for its lifetime. It is usually set by the manufacturer or during installation. These addresses are maintained and allocated by the IEEE.

Short address: The 16-bit address is assigned to a device when it joins a network and is intended for use while it is on the network. It is only unique within that network. It is used for identifying devices and sending data within the network.

Through extend address and short address, the topology of the network can thus be determined.

RSSI: Received signal strength indicator.

The order of the message: We use this parameter to calculate the packet receive rate.

Length of data: It presents the byte of data in the message.

Data: it contains transmitted value information.

4.2 Implementation

In this section, implementation results of the present network link quality monitoring system will be discussed. The developed monitoring programs are implemented in PC using C++ builder. To construct the ZigBee networks, FineTek devices with CC2530 (IEEE 802.15.4 radios) accompanying Z-Stack were adopted. One of them is configured as the coordinator, two other devices are configured as the routers, and two are configured as the end devices. The experimental setup is shown in Fig. 4-2.

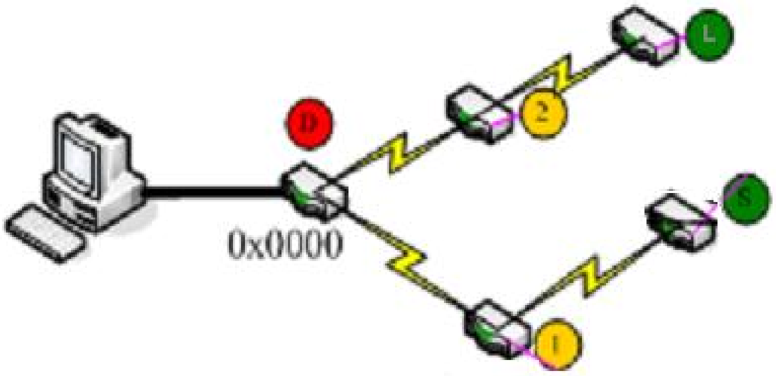


Figure 4-2 Experimental setup

When the coordinator starts communication functions, it initializes all internal ports and waits for transmitted messages from other nodes within the network. The format of transmitted messages are designed the same as Fig. 4-1. The devices are considered as disconnected when ten consecutive messages are lost during the transmission.

4.3 Examples

- **Example 1 :** A ZigBee mesh network in normal condition

  The mesh network is setup as show in Fig. 4-3

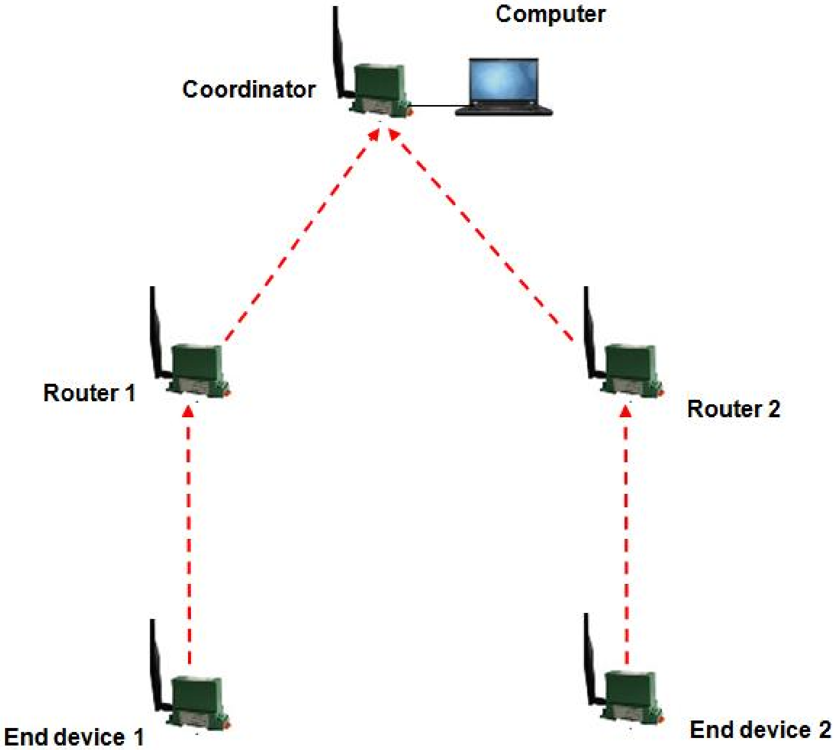


Figure 4-3 The mesh network in normal condition

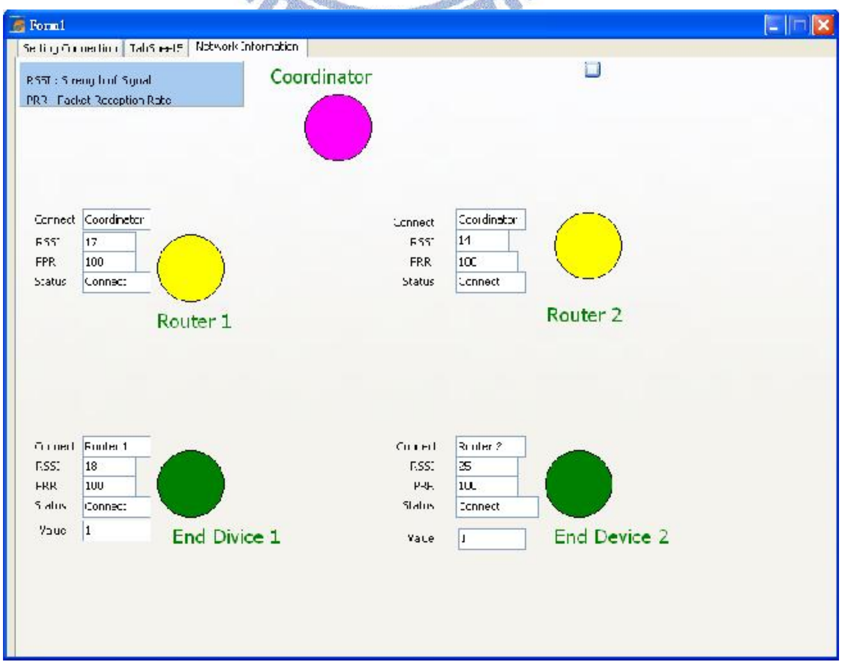


Figure 4-4 GUI of the developed monitoring system in the normal condition

The GUI of the present system as shown in Fig. 4-4 expressed as:

- The signal strength of the node to node connectivity in the network: this parameter presents the link quality between 2 nodes.

- The topology of the network.

- The packet reception rate .

- The real-time data values of nodes.

- Connectivity status of the nodes.

- **Example 2**: The end device is disconnected from the network.

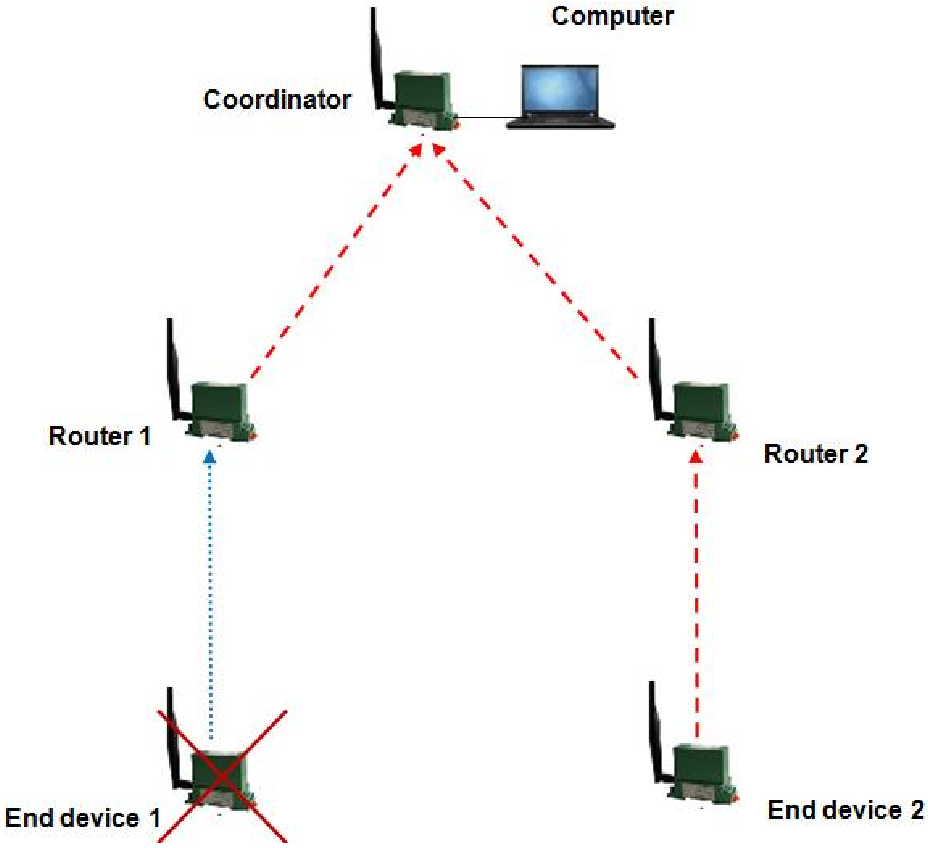


Figure 4-5 The ZigBee mesh network when the end device 1 is disconnected from the network

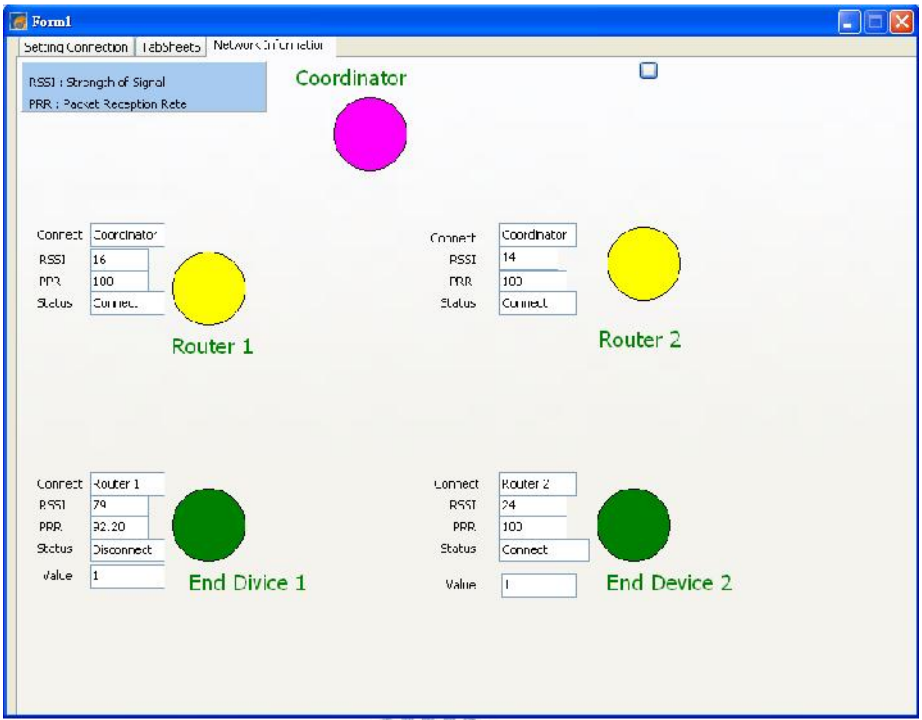


Figure 4-6 GUI of the developed monitoring system when router 1 is disconnected

The “status” of end device 1 expresses the end device 1 is disconnected from the network.

The software helps network manager can detect the disconnection of the nodes such as end device 1 in this example as show in Fig.4-5.

- **Example 3:** The router is disconnected

This example expresses the change of network topology when the router 1 is disconnected (caused by power shutdown or router remove out of the network). Then, end device which connected with disconnected router will search for new path for the message to be passed.

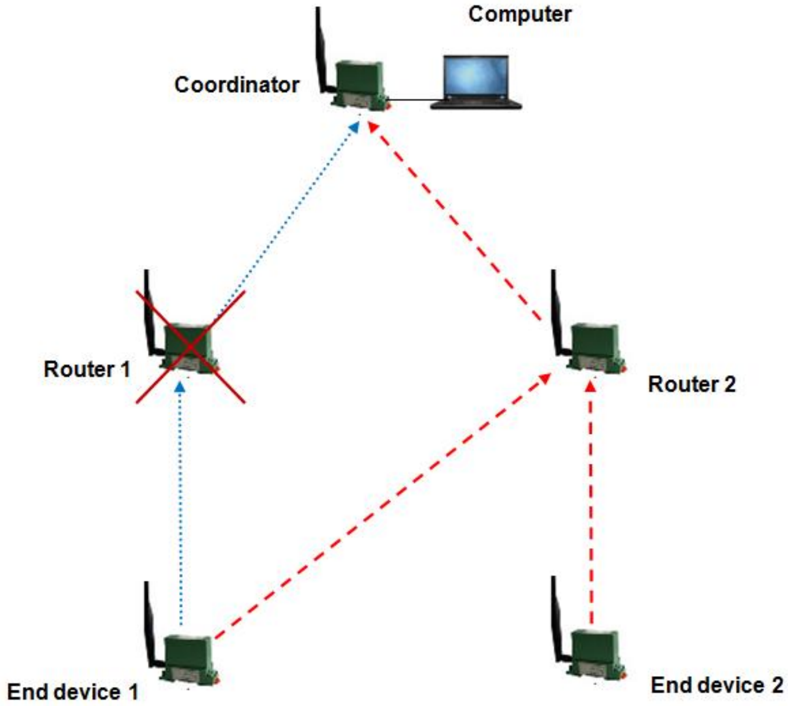


Figure 4-7 The ZigBee mesh network when the router 1 is disconnected

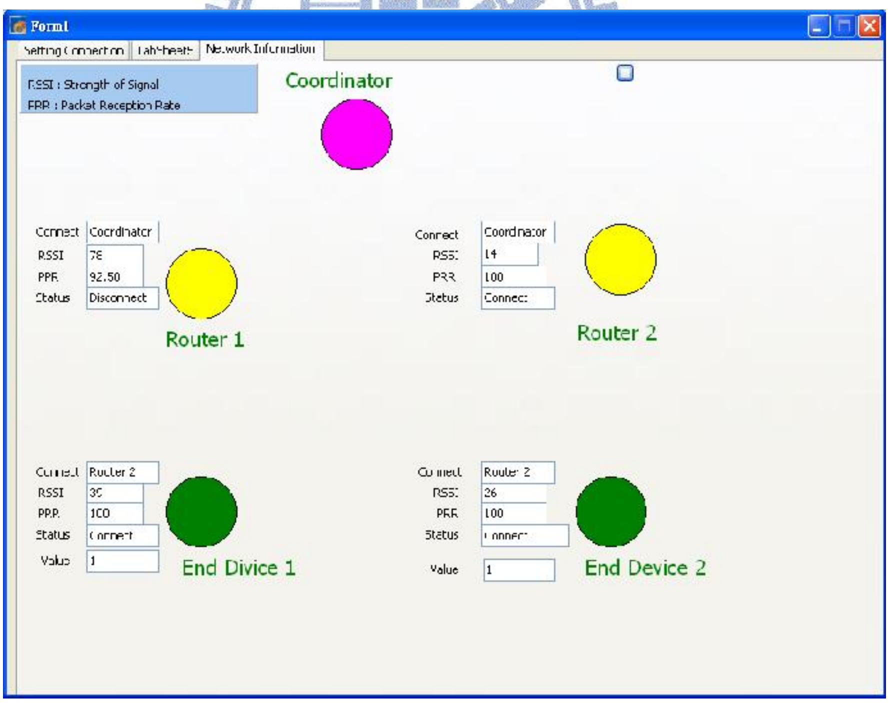


Figure 4-8 GUI of the developed monitoring when router 1 is disconnected

The GUI shows that when router 1 is disconnected from network, the end device 1 will connect automatically to router 2 to transmit messages continuously.

- **Example 4:** The route between router 1 and end device 1 fails because of the barrier

If a route between router and device fails, then ZigBee's self-healing mechanism will allow the end device to search for an alternate path for the message to be passed

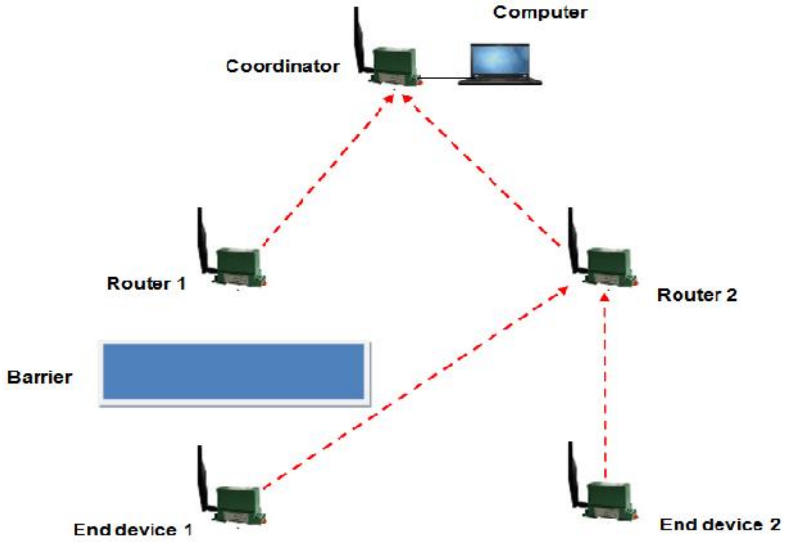


Figure 4-9 The mesh network when the route between router 1 and end device 1 fails because of the barrier

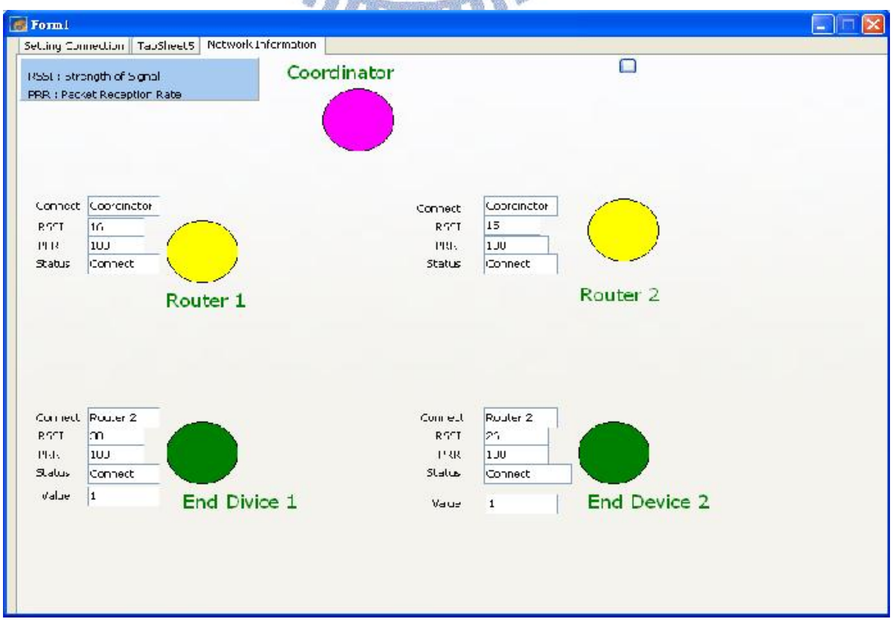


Figure 4-10 GUI of the developed monitoring system as connection between router 1 and end device 1 fails

By observing GUI, we recognize that the end device 1 connected to router 2 instead of router 1.

- **Example 5:** The route between router 1 and coordinator fails because of the barrier

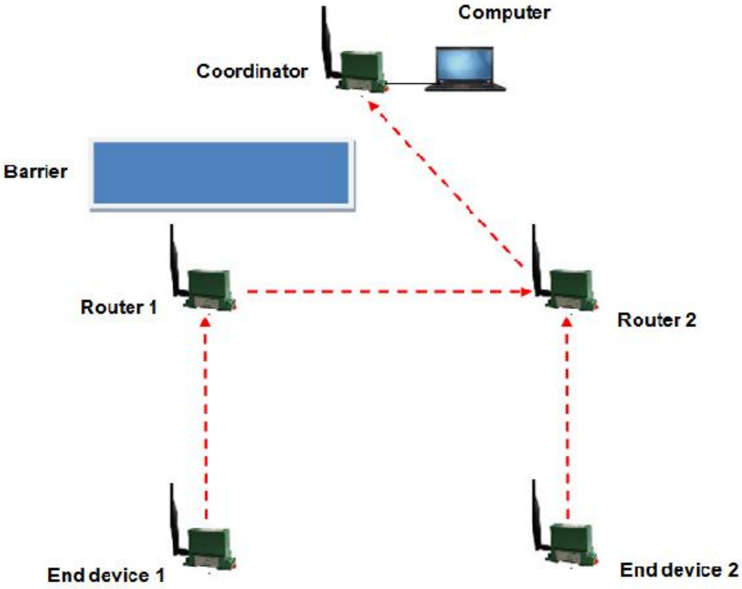


Figure 4-11 The mesh network when the router between router 1 and coordinator fails

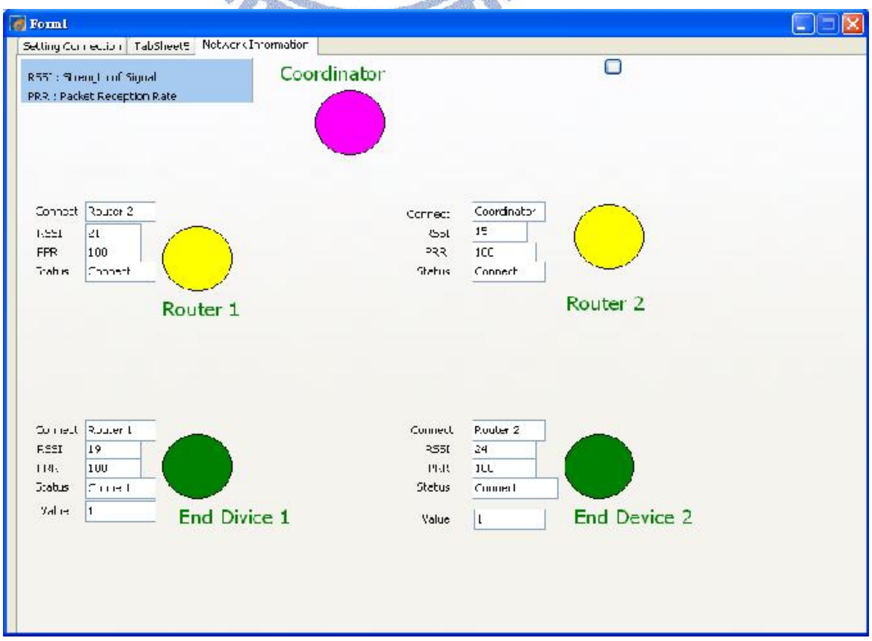


Figure 4-12 GUI of the developed monitoring as connection between router 1 and coordinator fails

When the route between router 1 and the coordinator is blocked, the router 1 will connect to the coordinator through neighbor router 2. As show in above five examples, the present developed monitoring software can completely obtain the status of desired targets.

4.4 Summary

In this chapter, a software is designed for obtaining both the ZigBee wireless sensor network monitoring and management applications. Results indicate that the monitoring software which helps managers know that both the quality of the ZigBee network and the changing of network topology are thus obtained.

Chapter 5

Estimation of the data packet dropout

In the ZigBee wireless sensor network, sensors send their data to coordinator. It is reasonably assumed that the transmitted data may be lost or corrupted due to reasons such as power outage at the sensor node, random occurrences of local interferences, or a higher bit error rate of the wireless radio transmissions as compared with wired communications. To estimate the missing values to restore it during transmission is a challenge of the present research.

5.1 Average value substitution

The average value substitution [33] is one of the most frequently used method in estimation of missing messages in networks. The missing value is replaced by the average value of all past known values at the instance with the missing feature belongs. Observation window (OW) is defined as a finite length of previous network messages which contain the previous known values to estimate the missing value of the current missing message. For example, if the length of observation window is five, and time index k=10 then OW(10)={$x[5]$,$x[6]$,$x[7]$,$x[8]$,$x[9]$} is an observation window where x[k] is the received values [34]. $x[10]$ is the missing value for the current missing message can be predicted as :

$$x[10] = \frac{1}{5}\sum_{i=5}^{9} x[i] \qquad \text{(5-1)}$$

The advantages of this method are: (i) nearest neighbor data values can be simply used to estimate the missing value without a predictive model, and (ii) it can be easily applied to instances with multiple missing values. The choice of OW, is the observation window based on accuracy of estimation. The choice of a small OW produces a deterioration in performance of estimation due to overemphasis of a few dominant instances in the estimation process of the missing values. On the other hand, an observation window with a too large size would include instances that are significantly different from the instance containing missing values. In other words, the sudden change of the data will not be reflected from the estimation results. In the present study for ZigBee, the observation window OW =5 can be suitably determined.

5.2 Intelligent messages estimator

The intelligent messages estimator [34] is an estimation method based on the transition probability to compensate for the missing data in network control system (NCS). The intelligent messages estimator renders the best performance as compared to the one-delay and the Taylor estimators in motion NCS. We use the two-state Markov chain network model [35] to express the nature characteristics of network signals.

5.2.1 Two-state Markov chain network model

The two-state Markov chain network model and the Bernoulli model [36] are the probabilistic models for describing a random outcome that either is received or lost. In both models, the data dropout rate, ρ, describes the probability of received or dropout data. However, only the two-state Markov chain network model can characterize burst packet loss adequately in the ZigBee wireless sensor network. The two-state Markov model captures this bursty behavior because the success or failure at any instant is independent of all other outcomes. For a two-state Markov chain which is used to model the network in this thesis, two parameters describe the distribution of packet dropouts. In our notation for success (*D*) and failure (*R*) of the network at each sampling period, the parameters of the probabilities are given by

$$\rho_{ij} = \Pr[\alpha(k+1) = j \mid \alpha(k) = i] \; for \; i, j \in \{R, D\} \qquad (5\text{-}2)$$

where $\rho_{D,R}$ is the probability of transitioning from a *D* (dropout) state to a *R* (received) state. Likewise, $\rho_{R,D}$ is the transition probability from an *R* state to a *D* state. The probabilities of all transitions can be conveniently represented pictorially as shown in Fig. 5-1

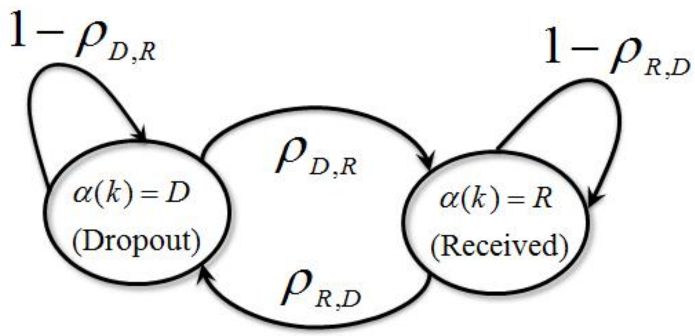


Figure 5-1The two-state Markov chain network

5.2.2 The least-square estimator

The intelligent messages estimator (IME) is proposed based on the integration of the least-square estimators with different orders based on the on-line measured local transition probability ($\hat{\rho}_{DD}$). Since the online estimation of the missing data is time-consuming, all parameters of the real-time least-square estimation (LSE) can be obtained in advance. Thus, to achieve an online estimation and compensation algorithm for the missing data in the ZigBee wireless sensor network, the IME is proposed based on past messages within a short window by applying the least-square approach. For a general time sequence x[0],x[1],….x[M,], a polynomial sequence can be suitably described as

$$x[k] = c_0 + c_1 k + c_2 k^2 + \cdots + c_N k^N \tag{5-3}$$

Thus,

$$\begin{aligned} x[1] &= c_0 + c_1 + c_2 + \cdots + c_N \\ x[2] &= c_0 + c_1 2 + c_2 2^2 + \cdots + c_N 2^N \\ &\vdots \\ x[M] &= c_0 + c_1 M + c_2 M^2 + \cdots + c_N M^N \end{aligned} \tag{5-4}$$

By rearranging Eq. (5-4) as

$$\begin{bmatrix} x[1] \\ x[2] \\ \vdots \\ x[M] \end{bmatrix} = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ 2^0 & 2 & \cdots & 2^N \\ \vdots & \vdots & & \vdots \\ M^0 & M & \cdots & M^N \end{bmatrix} \begin{bmatrix} c_0 \\ c_1 \\ \vdots \\ c_N \end{bmatrix} \equiv x = A \cdot c \tag{5-5}$$

The normal equation from the least-square approach can be applied to the data to obtain coefficient vector ***c*** as

$$c = (A^T A)^{-1} A^T x \tag{5-6}$$

Thus, the missing value for the current missing message can be predicted as

$$
\begin{aligned}
x[M+1] &= c_0 + c_1(M+1) + c_2(M+1)^2 + \cdots + c_N(M+1)^N \\
&= \left[(M+1)^0 \quad (M+1)^1 \quad \cdots \quad (M+1)^N\right] \cdot c \\
&= \left[(M+1)^0 \quad (M+1)^1 \quad \cdots \quad (M+1)^N\right] \cdot (A^T A)^{-1} A^T x \\
&\equiv LSE(M,N) \cdot x
\end{aligned}
\tag{5-7}
$$

The estimator matrix *LSE(M,N)* can thus be pre-calculated for real-time implementation. *M* indicates the data number of the observation window length to be counted, and *N* is the order of polynomial functions.

To achieve an online estimation for ZigBee wireless sensor network, parameters should be determined in advance. Therefore, the order and the data number of the least-square estimator should be determined with practical concerns. The length of OW can be properly chosen to as large as five to suitably estimate the different curves [34][37].

Three useful *LSE(M,N)* are pre-calculated for real-time applications as follows:

- $LSE(5,3) = 3.2z^{-1} - 2.8z^{-2} - 0.8z^{-3} + 2.2z^{-4} - 0.8z^{-5}$ (5-8)

- $LSE(3,2) = 3z^{-1} - 3z^{-2} + z^{-3}$ (5-9)

- $LSE(2,1) = 2z^{-1} - z^{-2}$ (5-10)

5.2.3 The intelligent messages estimator architecture

The intelligent messages estimator (IME) uses switching law according to Eq.(5-11) based on the estimated $\hat{\rho}_{DD}$:

$$\begin{cases} 0 \le \hat{P}_{11}(K) \le 0.2, & LSE(5,3) \text{ is adopted} \\ 0.2 < \hat{P}_{11}(K) \le 0.4, & LSE(3,2) \text{ is adopted} \\ 0.4 < \hat{P}_{11}(K) \le 0.6, & LSE(2,1) \text{ is adopted} \\ 0.6 < \hat{P}_{11}(K) \le 1, & 1\text{-delay estimator is adopted} \end{cases} \quad (5\text{-}11)$$

5.3 Combined messages design

This proposed method, the combined messages design (CMD) uses the circular buffer to store the sensor data when failure transmission occurs. The data of this message will be inserted into the next following message, and if the coordinator can receive the following message, it also updates the previous data. The previous data is not useful in the real-time monitoring application, however, it improves the performance of dropout data. The below flowchart shows the CMD algorithm with implementation on the ZigBee as:

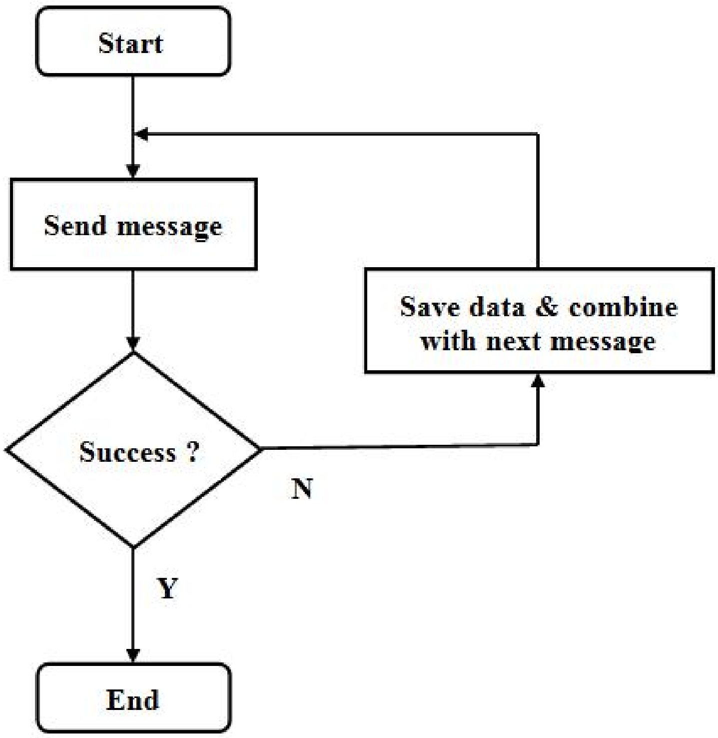


Figure 5-2 Algorithm of CMD on ZigBee

5.4 Experimental results

The size of the original message is eight bytes, in which one byte is reserved for the data value. The interval time of transmission is one second. ZigBee network operates at channel 11 (2405 MHz) .The ZigBee WSN is established in the indoor environment as shown in Fig. 5-3. The distance between end device and coordinator varies, and end device transmits message to coordinator via 2 routers which both located at 2m distance from coordinator.

Three estimation methods were applied to present experiments to ZigBee wireless sensor network as: (a) the average value substitution, (2) the IME, and (3) the integration of IME and CMD.

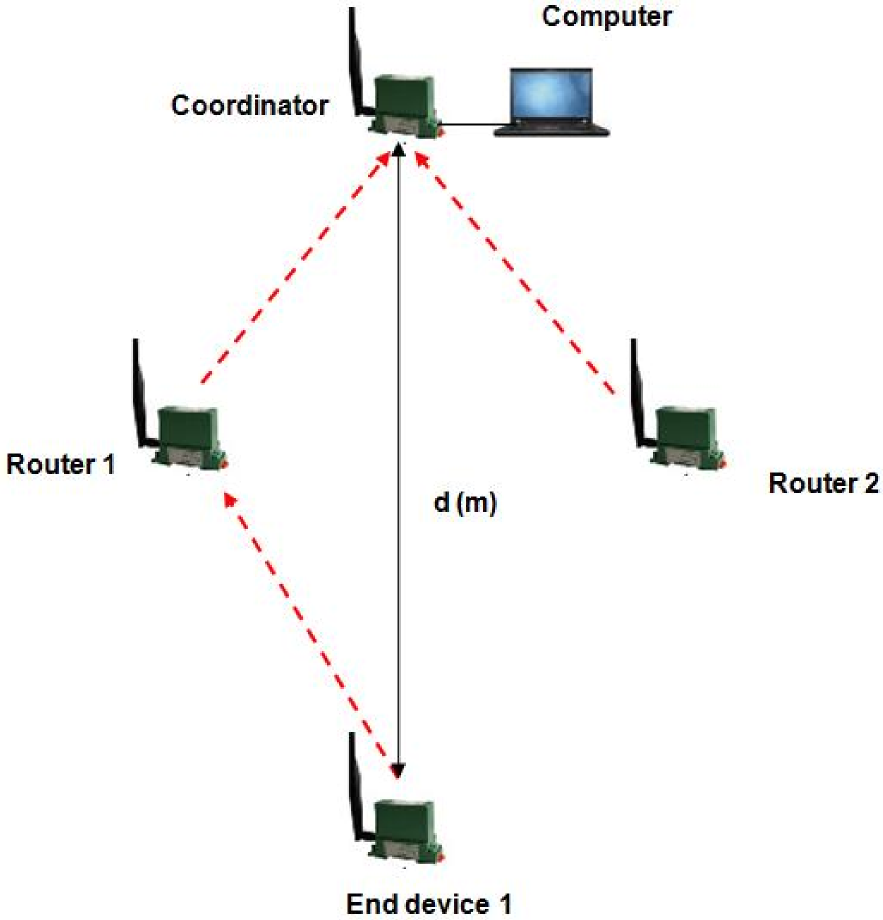


Figure 5-3 Experimental setup

- **Example 1 :** The low-frequency sinusoidal signal

The transmitted and received signals are shown as in Fig 5-4.

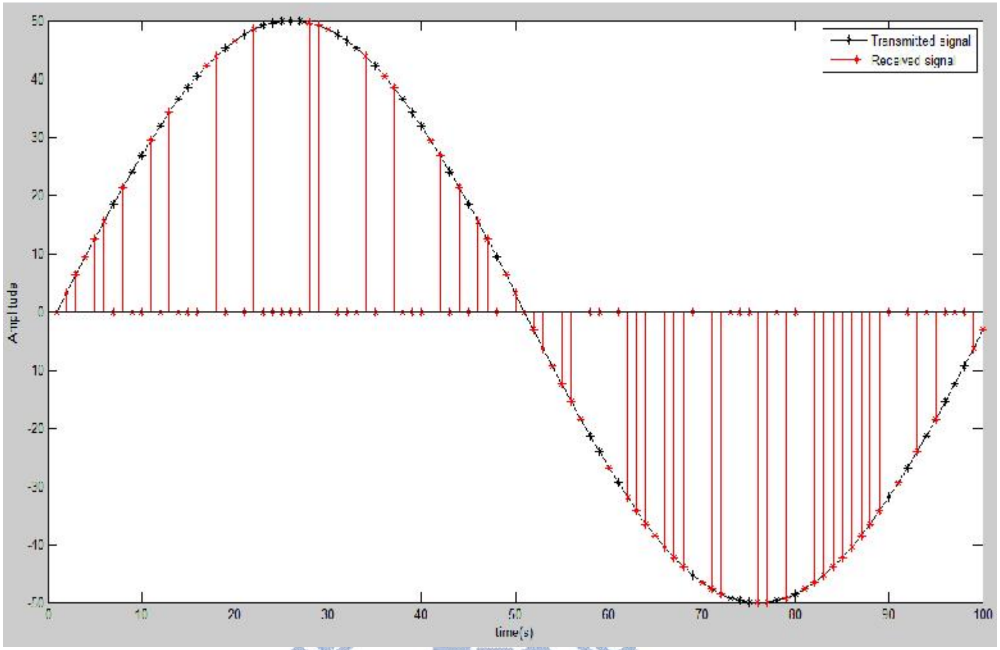
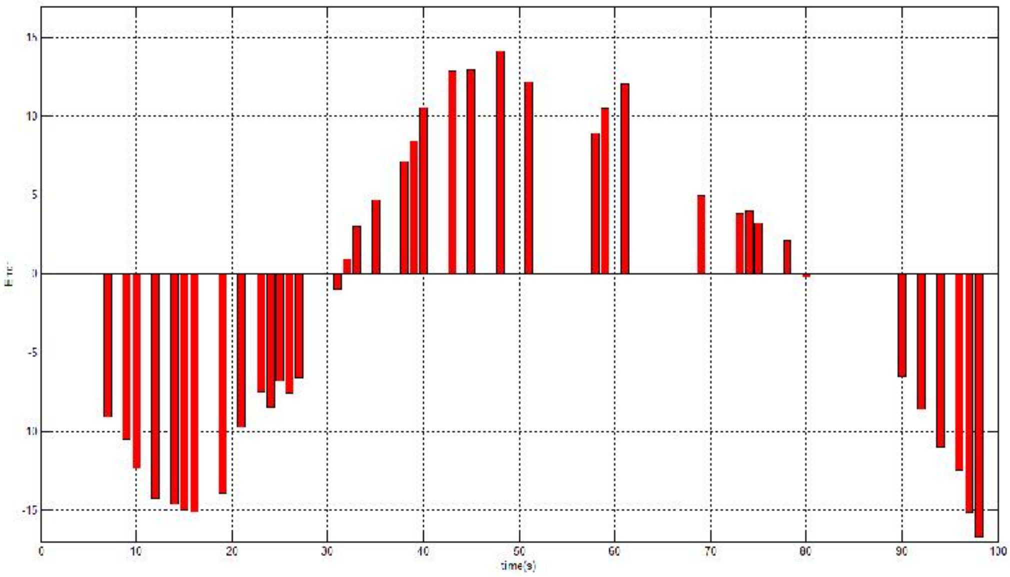
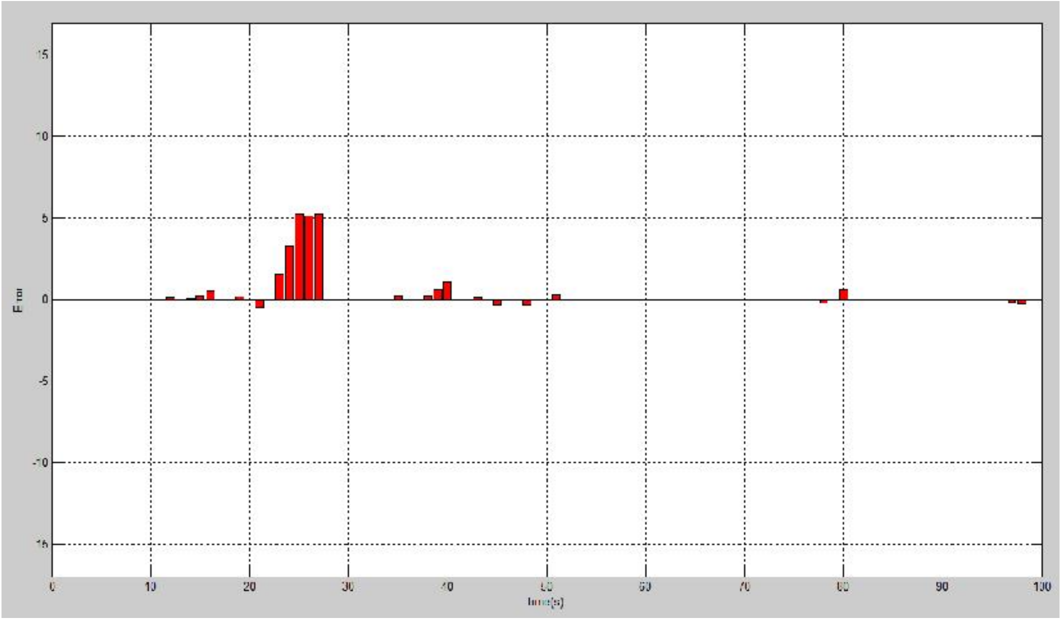


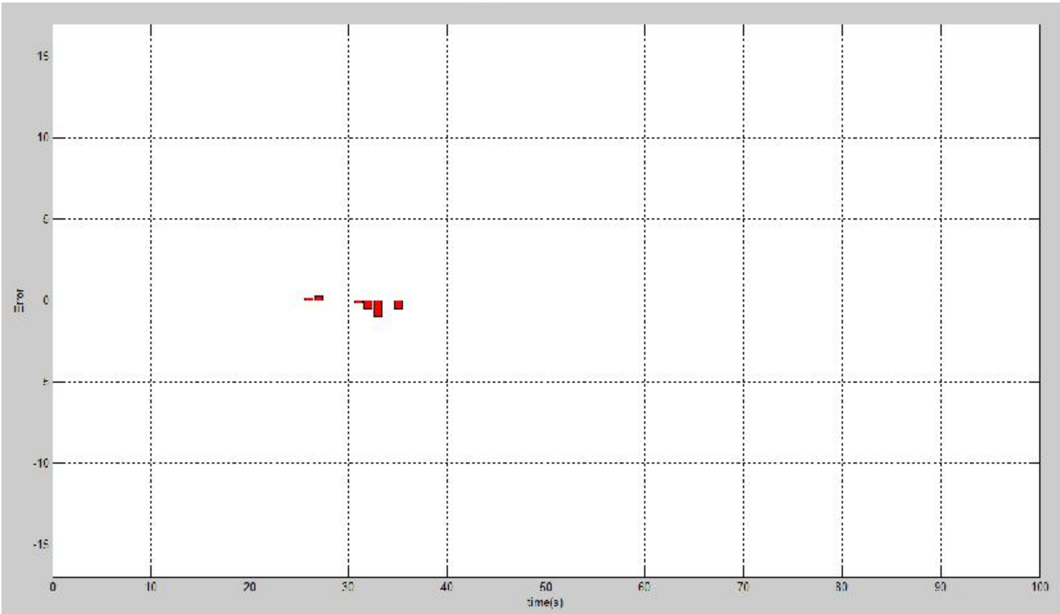
Figure 5-4 The transmitted and received signals with a low frequency



(a)



(b)



(c)

Figure 5-5 The tracking error with (a) AVS, (b) IME, and (c) IME+CMD

(40% dropout rate)

The results of the estimations are summarized as the following table:

Table 5-1 Results of dropout data compensation (Example 1)

Distance (d)	Dropout rate	AVS	IME	IME+CMD
10 m	4%	0.24561	0.00006	0.000006
12 m	5%	0.41724	0.00081	0.00076
28 m	13%	0.84655	0.00406	0.00343
40 m	17%	1.20427	0.07324	0.00673
51 m	27%	1.72350	0.16325	0.01856
68 m	40%	3.59583	0.26447	0.026401

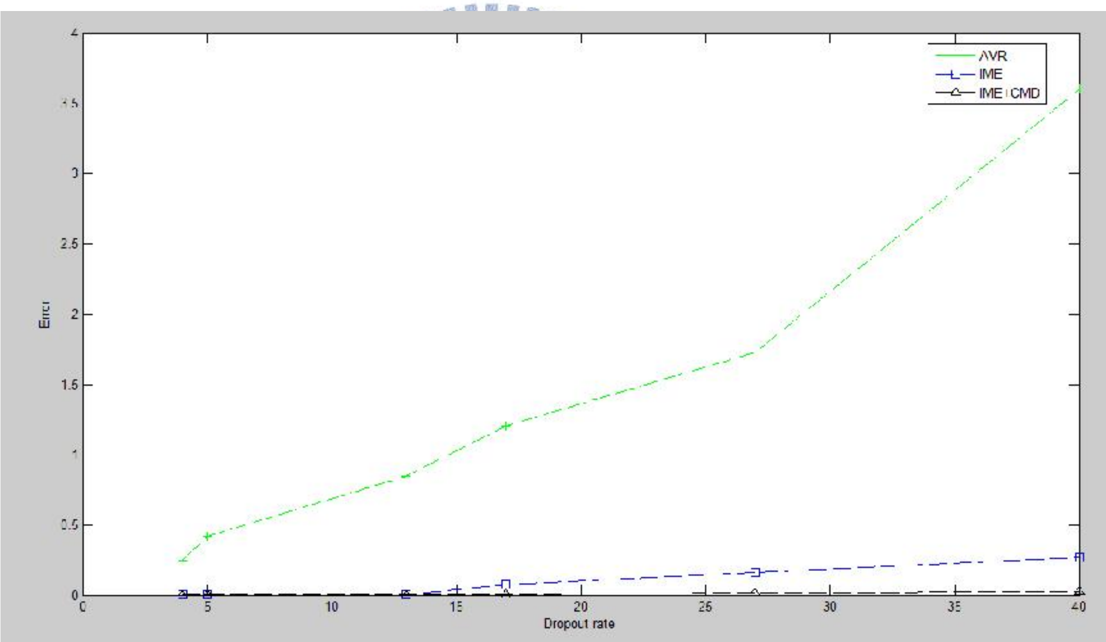


Figure 5-6 The mean absolute error (MAE) of three estimation methods (Example 1)

As shows in Table 5-1 and Fig. 5-6, the proposed method (IME+CMD) achieves the least contouring error

- **Example 2** The high-frequency sinusoidal signal

Another example will be tested and the transmitted and received signals are shown as in Fig. 5-7

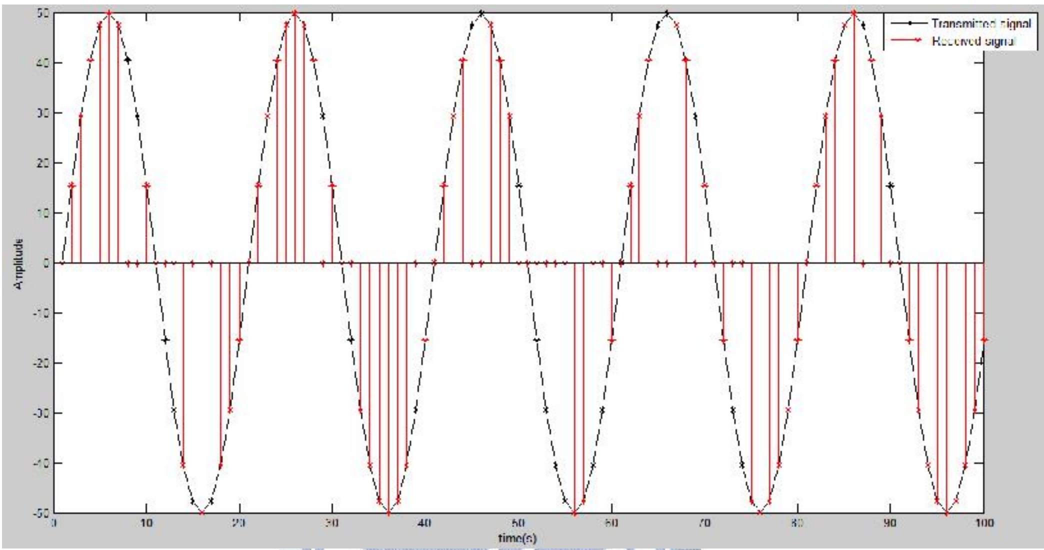
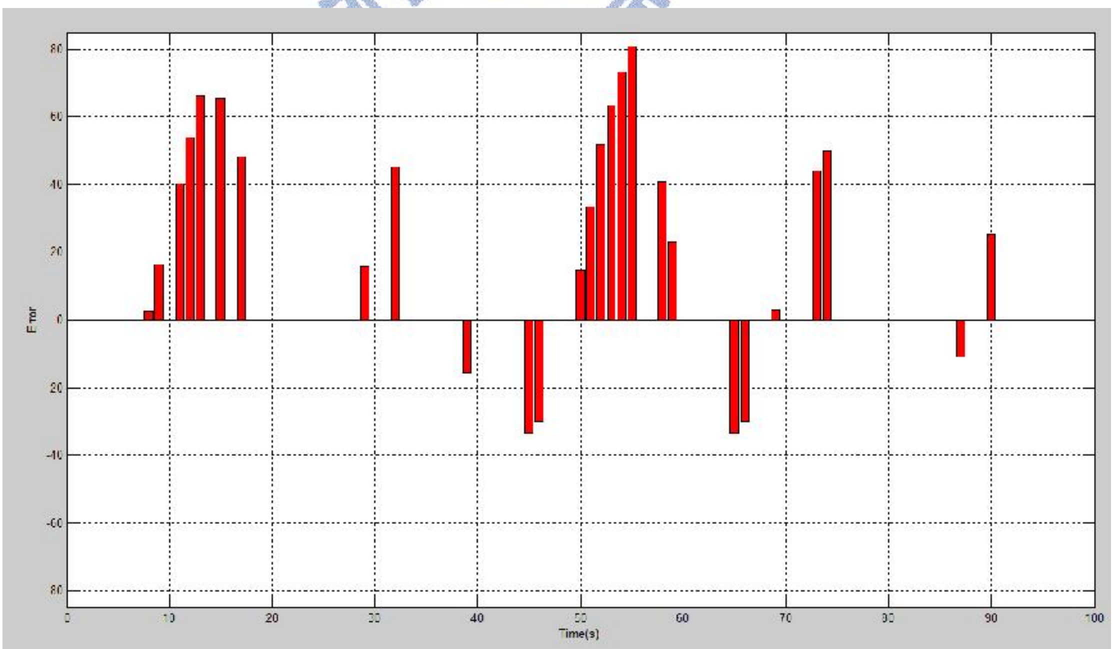
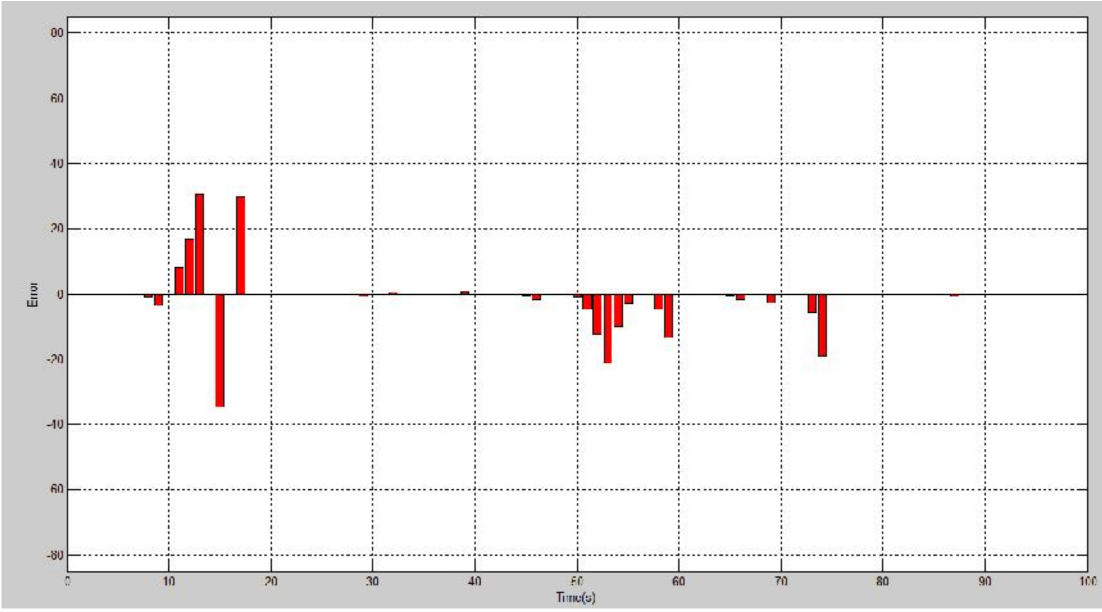


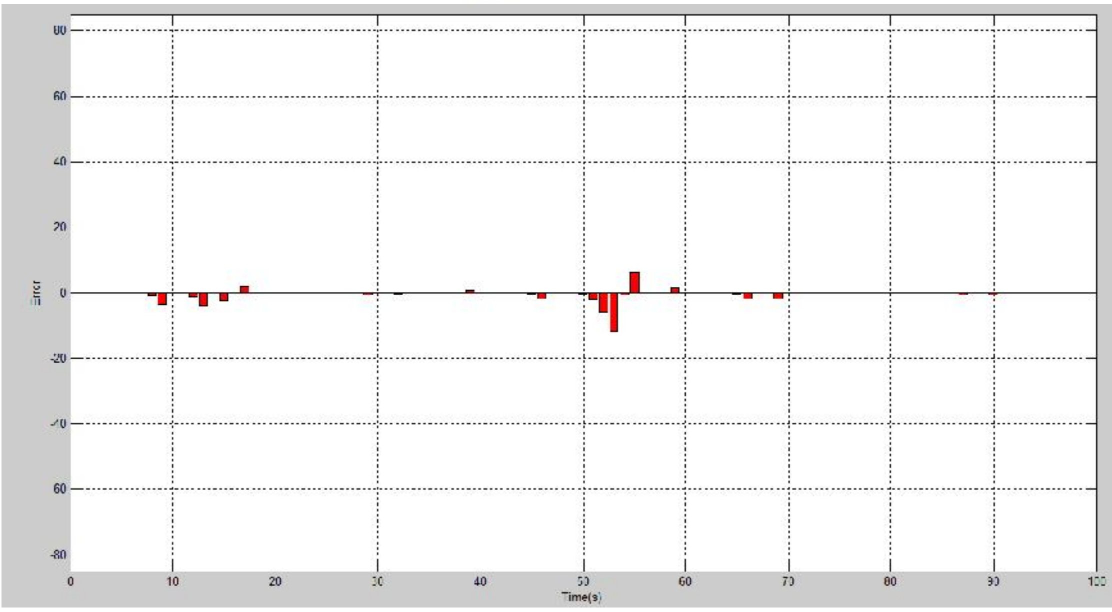
Figure 5-7 The transmitted and received signals with high frequency



(a)



(b)



(c)

Figure 5-8 The tracking error with (a) AVS, (b) IME, and (c) IME+CMD

(31% dropout rate)

The result of dropout data compensation with different estimation approaches are summarized in Table 5-2:

Table 5-2 Results of dropout data compensation (Example 2)

Distance (d)	Dropout rate	AVS	IME	IME+CMD
10 m	2%	0.26673	0.03452	0.03452
12 m	7%	1.27015	0.12082	0.12082
15m	9%	1.48275	0.16610	0.15135
51 m	27%	4.64832	2.29375	0.53313
60 m	31%	7.26352	2.37142	0.57286
68 m	44%	10.75584	3.34062	0.76454

And the results are plotted as below Fig 5-9

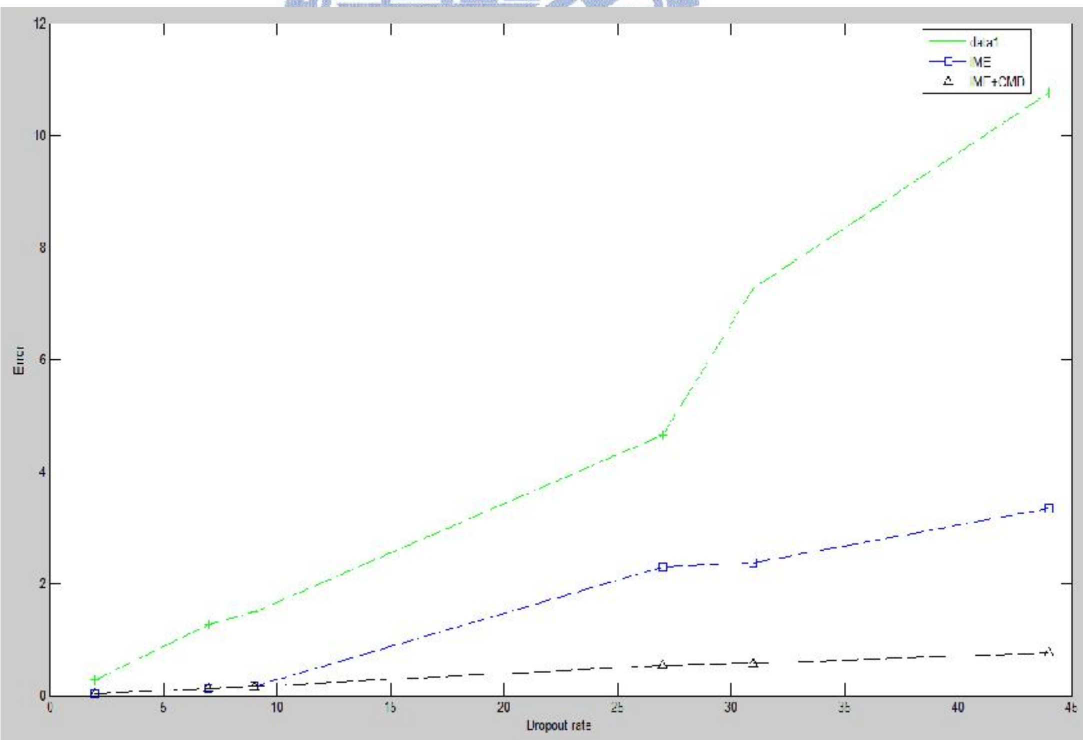


Figure 5-9 The mean absolute error (MAE) of three estimation methods (Example 2)

5.5 Summary

In this chapter, the transmitted signal has been successfully measured with different transition probability in ZigBee wireless sensor network. The missing messages can be also properly estimated by combining the intelligent messages estimator (IME) and the combined messages design (CMD).Experimental results indicate that by applying the method, the error of the estimation is significantly improved as follows:

(1) The proposed method by combining IME and CMD leads to the least mean absolute error under different dropout rates.

(2) The proposed method significant improves performance of ZigBee under medium and heavy dropout conditions.

Chapter 6

Conclusion

In this work, the signal strength and propagation in both indoor and outdoor environments with obstacles as the walls have been analyzed. Moreover, the varied data dropout rate in ZigBee network communication have been successfully estimated by applying the integration of the IME and the CMD. Thus, the quality of service of the ZigBee network is significantly improved. Conclusions of this thesis are as follows:

(1) The Log-distance Path Loss Model and the Wall Attenuation Model are properly adopted to analyze the signal attenuation both inside and outside the building with obstacles as the wall effect. The path loss exponent n and the wall attenuation factor α can be thus determined in real environment. Moreover, the signal strength in various environments can be predicted by applying the obtained model.

(2) The developed network link quality monitoring system is useful to indicate both the reliability and topology change of the network. In this system, all the signal strength of node-to-node connectivity, the data packet receive rate, the connection statement of each node are directly presented and the status of the network can be observed easily.

(3) Integration of the IME and the CMD is effective to estimate the missing messages in the ZigBee wireless sensor network. Results indicate that by applying the integration method, it leads to the least contouring error under different dropout data rates. This method improves performance of network dropout data estimation particularly under medium and heavy dropout conditions.

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