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The design and evaluation of Wireless Sensor Networks for applications in industrial locations

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THE DESIGN AND EVALUATION OF WIRELESS SENSOR NETWORKS FOR

APPLICATIONS IN INDUSTRIAL LOCATIONS

An Abstract of a Dissertation

Submitted

in Partial Fulfillment

of the Requirements for the Degree

Doctor of Technology

Approved:

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ABSTRACT

In manufacturing industries, there exist many applications where Wireless Sensor Networks (WSN's) are integrated to provide wireless solution for the automated manufacturing processes. It is well known that industrial environments characterized by extreme conditions such as high temperature, pressure, and electromagnetic (EM) interference that can affect the performance of the WSN's. The key solution to overcome this performance issue is by monitoring the received Signal Strength Index (RSSI) at the received sensor of the WSN device and track frame error rate of wireless packets.

ZigBee is a wireless sensor network (WSN) standard designed for specific needs of the remote monitoring sensor system. Zigbee networks can be established by three different topologies: start, hybrid, and mesh. In this research project, the interest in analyzing the characteristics of the Zigbee performance was completed using a star topology network. Three performance parameters were obtained: the RSSI signal to monitor the received wireless packets from the sending node, path-lost exponent to determine the effect of industrial environment on wireless signals, and the frame error rate to know the discontinue time. The study was in three phases and took place in two settings: The first was at the manufacturing laboratory at the University of Northern Iowa, the second and the third were at the facility of a Midwestern manufacturing company. The study aimed to provide an analytical tool to evaluate the performances of Zigbee networks in industrial environments and compare the results to show that harsh environments do affect its performance.

The study also involved testing the performance of WSN. This was done by simulating input/output Line passing with digital and analog data. Packets were sent from one node and counted at the receiving side to measure the packet error rate of WSN in industrial environment.

In conclusion, investigating the WSN's systems performance in industrial environment provides is crucial to identify the effects of the harsh conditions. It is necessary to run similar investigation to prevent the malfunction of the manufacturing applications. Testing a simple WSN in industrial environment can be capable of predicting the performance of the network. It is also recommended to have an embedded approach to WSN applications that can self-monitor its performance.

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I want to take another moment to show my admiration to people who have been supportive to me in every step in my life. I want to express my deepest feelings to my wife Nawal for she has been very supportive during my doctoral journey. I want to dedicate this work to my wife and to my family members. Finally, I want to thank my parents who supported my decisions in academic and nonacademic life.

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CHAPTER 1

INTRODUCTION

The use of conventional cables in industries is causing problems such as high cost of maintenance, limited mobility of workers, and potential hazards. With the Wireless Sensor Networks (WSN) technology, workers can operate and monitor processes beyond the limitation of cables.

Zigbee is a standard form of wireless sensor networks (WSNs) based upon the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard. ZigBee protocol was engineered by the ZigBee Alliance to provide original equipment manufacturers OEM's and integrators with low-power consumption wireless data solution with multiple network structures and secure connections for monitoring applications (Sumi, Ebrahim, Rajan, & Harikrishnan, 2009).

Although WSN applications are becoming well-known technology for industries, the harsh industrial environments such as electro-magnetic interferences (EMI) may affect the stability and reliability of the wireless network. As a result, the performance of the wireless network under the harsh industrial environments must be investigated before the deployment of the wireless WSN nodes.

This paper describes an experimental study for the design and implementation of WSN to offer low power and low cost wireless networking applications in industrial settings. In order to overcome the problems associated with the cables and to investigate the performance of the wireless network under the harsh industrial environments, a proposed project has been started in the Industrial Technology Department at a

Midwestern University in the United States. This investigation will verify that the harsh manufacturing environment will not affect the performance of the wireless sensor network when implemented.

Statement of the Problem

The problem of this research study is to find and implement a wireless sensor network to study its performance in industrial applications, and to determine its viability in comparison with the different industrial environments.

Purpose of the Study

The purpose of this study is to validate the WSN for industrial applications and manufacturing processes that are influenced by external interferences. The objectives of this study supporting this purpose are:

1. To develop a simple wireless sensor network strategy using peer-peer network.
2. To transmit analog data using the designed WSN
3. To compare the model results from one environment to another.
4. To validate the use of the wireless sensor network by displaying the performance in a real time procedure using LabView™ software available by National Instruments.
5. To test the performance of the WSN by monitoring the packet error rate.

Need for the Study

The need of this study was based on the lack of an available model to test the performance of a WSN operating at 916 MHz frequency band using a peer-peer ZigBee network. Although there are many models developed for a performance study, most of them were focused on the 2.4 GHz frequency bands, as these are considered the most commonly available products (Pekhteryer, Sahinoglu, Orlik, & Bhatti, 2005). Studies focused on investigating WSN performance against the WLAN interferences due to the operation on the same frequency band of 2.4 GHz (Shuaib, Boulmalf, Sallabi, & Lakkas, 2006). Similar studies developed an interference analysis model to detect signal degradation by estimating the packer error rate (PER; Gyuang & Yu, 2009) or formulated a mathematical model to evaluate the ZigBee performance against the WLAN performance (Chong, Hwang, Jung, & Sung, 2007). The packet error rate (PER) is also obtained in related research from the bit error rate (BER) and the signal-to-noise ratio (SNR; Shin, Park, Choi, & Kwon, 2007).

Another approach for the study is the introduction of a real time environment to monitor the system performance through a graphical programming environment, LabView™. LabView™ offers to sample real-time information with the ZigBee and simultaneously transmits data to PC (Guofang, Lidong, Yubin, Shengtao, & Junyu, 2010). LabView™ has the capability to develop a GUI user interface to monitor and control applications such as controlling a wireless household-electric network (de Sousa, do Prado, & Schulz, 2007). Thus, using LabView™ in this model will give the user more control over the external variables affecting the ZigBee network. This approach will assist the user with the following benefits:

1. RSSI data can be visualized
2. Unexpected results can easily be detected or repeated due to the real time simulation of the data.
3. Signal charts simulating the performance variables are directly represented in the LabView™ graphical user interface (GUI).
4. LabView™ is a programmable environment and therefore can be expanded to include additional variables.

The industrial environments are considered to contain harsh constraints on wireless signals due to interference with existing equipment and signal multiple path propagation (Carcelle, Dang, & Devic, 2006). In a previous study, the received signal strength index (RSSI) was proven lower in industrial areas where interferences such as metallic objects, electro-mechanical disturbances, and high temperature values (Madwar, 2008). This proposed research will also produce a more in depth study of the RSSI performance.

Research Questions

The goal of this research is to develop and evaluate the WSN performance in industrial environment. The research questions for this study were:

1. Would the interference found in industrial environment affect the performance of WSN?
2. Would the average frame error rate measured from the wireless packets received show distinguished difference between two different environment characteristics?
3. Would the path-lost exponent and the signal strength index (RSSI) average values be different from one location to another?
4. How to establish analog and digital wireless transmission using WSN and how to measure packet error rate?

Assumptions of the Study

For this study certain assumptions are made that will serve as the basis for ensuring the performance analysis. These assumptions are:

1. The signal values generated by the development kit are relatively accurate.
2. Each node in the development kit will produce exactly the same values.
3. The time spent to generate data will be the same in each location.
4. Unexpected disturbances and uncontrollable influences have insignificant effect on the process and may be rounded or deleted from the analysis.
5. The commercial application supported by the development kit is correctly developed and assumed to be a standard for all the processes.

Delimitations of the Study

This study is delimited to:

1. The Meshnetics Development Kit ZigBit 900 and XB24-DKS.
2. The BitCloud functionality allowing the users to control the BitCloud stack without any need to program the microcontroller directly.
3. The use of three wireless nodes only, two at a time to measure the specific system parameters.

Limitations of the Study

The following limitations are to be applied to this study:

1. The study is limited to existing industrial locations.
2. The study is performed using one development kit with only one year of technical support from the vendor due to the operation cost that includes larger wireless nodes and product support.
3. The variables that can be measured by the Zigbit are the frame counter (FC), and the received signal strength index (RSSI).
4. Specific details such as location name and detailed description of surrounding equipment are not provided due to the sensitive application of this research.
5. Companies where the proposed project will take place is to remain undisclosed.

Definition of Terms

Although certain terms used throughout this research proposal are not unique to this study, they are defined to have a common basis for understanding of their use within the context of this proposal. The following terms are defined:

RSSI: is the received signal strength indicator is an indicator of the strength of the received signal measured in dBm depending on the card model (Marti-Gamboa, 2006).

BER: is the bit error rate or the percentage of bits that have errors relative to the total number of bits received in a transmission, usually expressed as ten to a negative power (IEEE Consumer Electronics Society, 2007)

FER: is the frame error rate is the rate of data received with errors to total data received that is used to determine the quality of a signal connection.

Averaged Link Quality Indicator (LQI) is defined as the measure of chip error rate (Srinivasan & Levis, 2006).

WSNs: are wireless sensor networks defined as individual nodes that are able to interact with their environment by sensing or controlling physical parameters; these nodes have to collaborate to fulfill their tasks as usually, a single node is incapable of doing so; and they use wireless communication to enable this collaboration (Karl & Willig, 2007).

ZigBee: is a standard form of wireless sensor networks (WSNs) based upon the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard. ZigBee protocol was engineered by the ZigBee Alliance to provide OEMs and integrators with low-power consumption wireless data solution with multiple network structures and secure connections for monitoring applications (Sumi et al., 2009).

APL: It is the top layer in the Zigbee protocol stack consisting of the Zigbe Device Object (ZDO), and Application Support Sublayer (APS)

ZDO: Zigbee Device object (ZDO) is a protocol that defines the overall device management and security keys within the Zigbee network such as initiating and/or responding to binding and discovery requests, establishing a secure relationship between network and devices (Daintree Networks, 2008)

APS: it is known as the Application Support Sublayer that provides a data service to the Zigbee application and manages binding services (Daintree Networks, 2008)

NWK: known as Network Layer it handles tasks related to network addresses such as starting the network, assigning, adding and removing network addresses, and applying security (Daintree Networks, 2008).

MAC: known as Medium Access Control responsible for providing reliable communications between nodes (Daintree Networks, 2008).

CHAPTER II

REVIEW OF LITERATURE

This research focuses on the advancement of the wireless sensor networks and the ZigBee technology in industries and the surrounding issues related to harsh conditions such as temperature variations, electromagnetic interferences and the existence of many materials and blocks in the industrial settings affecting the performance. This chapter will review the major advances of the WSN, and will list its characteristics based on previous research and literature that lead up the development of the technology. The chapter begins with an overview of the history and characteristics of ZigBee, and the most recent fundamental concepts and issues surrounding the ZigBee. The chapter will also include a review of the commercially available advanced ZigBee devices that are related to this applied study.

Wireless communication in general has been around for a long time. For example, the US army was authorized to setup a nationwide radio net whereas stations were located at major cities or at headquarters of each corps areas (Callaway, 2004). Each corps area had its own internal subsystem and connections that communicate with other stations. Since the development of wireless communication, disturbances were found to be a challenging part for the communication systems. For example, the atmospheric disturbances were found to have a huge impact on the military relayed messages from Fort Leavenworth, Kansas, and Fort Douglas to the West Coast. “A good message meant that a message filed in Washington reached the West Coast by the following day.” As a result of this success, two major establishments were formed at the US Army. The first was on March 1923 and was called the War Department Message Center that combined the War Department's telegraph with the signal Corps' own telegraph office and radio station. The department was able to handle messages for more than fifty federal agencies. The second was the formation of the Army Amateur Radio System with the net control station at Fort Monmouth. This system did not operate in the summer due to the great static interferences. Figure 1, represents the structure of the Army Amateur Radio Net. Messages generated at the leaves were transmitted in hierarchal order to a node (station) that had the destination in its nodes or leaves. Thus, the system was very close to what is known today as a master/slave network operating together to cover a large physical area. In a Master/Slave system, the Master can send/receive data from/to slave nodes. However, slave nodes cannot communicate with each other. They can only talk to Master nodes (Laughton & Warne, 2003).

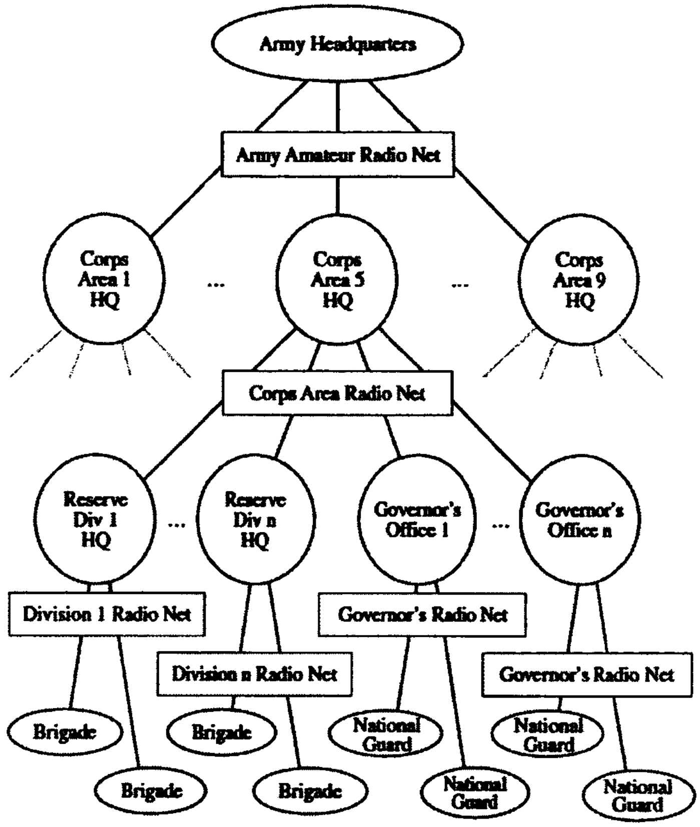

Figure 1: The Army Amateur Radio, 2004
(Modified from Callaway, 2004)

The first successful data wireless communication networks were the ALOHA system at the University of Hawaii employing a random channel access protocol and operating at two radio frequency (RF) at 4000MHz each to provide a link to computer users on the Hawaiian Islands. Messages were sent and received in the form of packets each of fixed length of 704 bits characters (8 bytes characters, 32 bits identification bits, and 32 parity bits) and a data rate of 24,000 baud as shown in Figure 2. (Abramson, 1970).

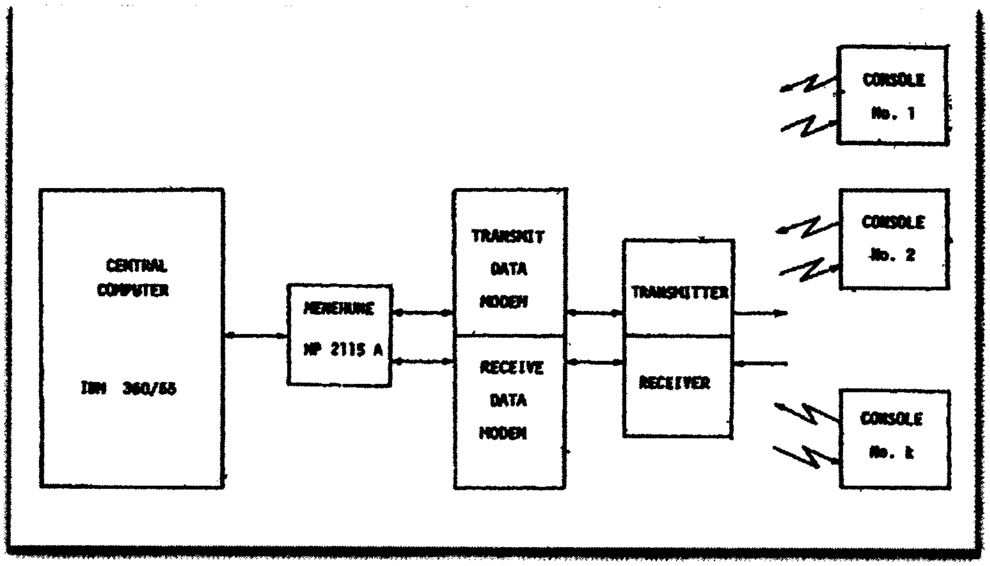

Figure 2: The ALOHA system
(Modified from Abramson, 1970)

The Aloha system was based on random access radio communication for k active users. Thus, the average rate of message packets from all users depends on the average rate occurrence of the message packets according to the following formula:

$$r = k\gamma \tag{1}$$

Where r is the average number of message packets per unit time, k is the number of active users, and γ is the average rate of occurrence of message packets from a single active user.

Abramson Aloha system contained two types of errors for employing the random access channel protocol. The random access protocol sends an acknowledgement only and only if the message packet was received by a Console without any error. The transmitter waits a certain time for an acknowledgement. If none was received, the transmitter resends the message packet and so on until the package is received. The errors that can be resulted of this system are identified as follows: "random noise error" due to external interference that cannot be controlled by the user. According to Abramson these errors are not serious as "errors caused by interference with a packet transmitted by another console". The problem in this case is that multiple users are attempting to access the channel at the same time. This means that the channel utilization in the Aloha system is proportional to the number of active users and was found to be:

$$r\tau = R_\tau e^{-2R_\tau} \qquad (2)$$

Where, τ is the duration of each packet, and R_τ is the channel traffic.

The ALOHA system pioneered the development of two new systems. The first called the Packer Radio Network (PRNET) system operating at 1800 MHz and providing a network of 138 host computers or entities. The data rate, based on the link quality, ranged between 100 and 400 kb/s using a 32-bit cyclic redundancy checksum (CRC)

(Vinton, 1981). The second is known as the Amateur Packet radio Networks operating at 1200 Baud frequency shift keying (FSK) to transmit identification beacon every five minutes. The Amateur Packet Radio helped the development of the Multiple Access with Collision Avoidance (MACA) channel access protocol based on the Carrier Sense Multiple Access (CSMA; Phil, 1990).

The first standard for the Wireless Local Area Network (WLAN) was first established in 1997 by the Institute of Electrical and Electronics Engineers (IEEE) requiring fixed access points between networks (Marks, Gifford, & O'Hara, 2001). However, the first experiment in wireless local area network goes back to 1979 that was done by Gfeller who published a paper describing a protocol using diffused infrared diffusion in the same room (Gfeller & Bapst, 1979). Using the infrared technology was limited due to its inability to pass through solid objects according to the resulted formula:

$$F(\tau) = \begin{cases} \frac{2\tau_0^2}{\tau^3 \sin^2(FOV)}, \tau_0 \leq \tau \leq \frac{\tau_0}{COS(FOV)} \\ 0, \quad elsewhere \end{cases} \tag{3}$$

Where τ_0 is the minimum delay and FOV is the field of view of receiver. Although the protocol had less than 1 megabit per second of data rate (64 kbps using phase-shift key), the protocol was considered a step forward to the development of wireless networks that doesn't require a license to operate. (Benton, 2010).

Wireless Sensor Networks

Sensor Networks have been very useful in manufacturing applications for it has been researched in recent studies to assist in machining grinding operations (Konig, Altinas, & Memis, 1995). The criterion was to measure the acoustic emission (AE) signals in RMS value to produce smooth surface finish in a minimum grinding time. They used the AE sensor and transmitted the signals to a receiver where a rectifier is used to rectify and analyze the signals. The results of using sensors in the grinding operations have found a correlation between the sensors and the surface roughness. This means that sensors can be used as process monitoring devices report the quality of operations in manufacturing. Furthermore, the research indicated an increase of 5-10% of productivity in using such an on-line monitoring technique which shows that sensors can play an important role in manufacturing processes if they are managed well for specific purposes. For example, instead of using just one sensor to measure the parameters, a multi-sensor system can be used to give a reliable system that indicates the tool wear state. Such system will be able to measure several features simultaneously (Wilkinson et al., 1999); they investigated the AE frequency, AE energy, and surface finish as inputs for tool wear prediction in milling operations measured by neural network nodes. Their study was empirical because the experiment showed that the performance of the neural network has improved when combining features together simultaneously and consequently using multiple sensors. A similar research by Govekar, Gradisek, and Grabek (2000) ensures using the multiple sensor system to measure the AE signal of machining processes as an approach to improve the experiment characterization while application of nonlinear time series analysis (off-line analysis) is used to analyze the cutting process characterization. Such applications would open the eyes to more useful research of sensors in the manufacturing field and expects more possibility of using such technology in the future research according to Chung and Geddam (2003, p.17): "Multi-sensor systems remove the drawback since loss of sensitivity in one sensor domain can be offset by information from other sensors within the system, thus allowing high decision making capability over a wide range of process conditions to be possible."

The modern sensor networks may contain extremely small sensors. This made sensor networks to be highly mobile and efficiently powered. Currently, sensor networks are integrated in data acquisition systems to monitor and report certain conditions or physical phenomena of events:

> The purpose of data acquisition is to measure an electrical or physical phenomenon such as voltage, current, temperature, pressure, or sound. PC-based data acquisition uses a combination of modular hardware, application software, and a computer to take measurements. While each data acquisition system is defined by its application requirements, every system shares a common goal of acquiring, analyzing, and presenting information. Data acquisition systems incorporate signals, sensors, actuators, signal conditioning, data acquisition devices, and application software (National Instruments, 2011).

Data acquisition systems require to be interfaced with computers in order to report the data simultaneously. Thus, a standalone system is employed for this purpose that cannot be shared with any other applications, resulting in an overall management system for the entire network. With the introduction of sensor networks, processing and shared network systems are shared between sensors. Today, wireless sensor networks (WSNs) are replacing many of the data acquisition systems and instrumentations. The ability that each sensor can perform data collection or decision making and reporting wide range of physical conditions such as temperature, pressure, light, humidity, noise level, presence, object characteristics, soil composition, and viscosity enabled the development of wireless sensor nodes in many applications. Due to this wide range of characteristics, WSN have been employed in many areas and wide range of applications. The later section will explain the network behavior of wireless sensor networks.

Wireless Sensor Networks (WSN) has become an attractive technology to many applications in the last decade due to its low cost, low power consumption, and its multitasking functionality. A good description of wireless sensor network is the ability to detect phenomena, collect data, and transmit information accordingly (Haenggi, 2005). It is not surprising the growing research and interest in this technology to form many worldwide workshops and conferences. The most current ones are listed as follows:

- The 9th ACM Conference on Embedded Networked Sensor Systems at Seattle, WA, USA 2011
- Second International Workshop on Interconnections of Wireless Sensor Networks at Barcelona, Spain 2011
- The 8th IEEE International Conference on Mobile Ad-hoc and Sensor Systems at Valencia, Spain 2011
- Track of Cyber Physical Society with SOA, BPM and Sensor Networks at Paris, France 2011

- First International Workshop on Advanced Communication Technologies and Applications to Intelligent transportation systems, Cognitive radios and Sensor networks 2011 at Seoul, Korea 2011
- Workshop on Architectures, Services and Applications for the Next Generation Internet: Global Sensing at Kiel, Germany 2011
- 3rd International Workshop on Sensor Networks and Ambient Intelligence at Hong Kong SAR, China 2010
- The fifth international workshop on Middleware Tools, Services and Run-Time Support for Sensor Networks at Bangalore, India 2010
- The Fourth Workshop on Real-World Wireless Sensor Networks at Colombo, Siri Lanka 2010
- Sixth International Conference on Intelligent Sensors, Sensor Networks and Information Processing at Brisbane, Australia 2010
- ACM International Symposium on Performance Evaluation of Wireless Ad Hoc, Sensor, and Ubiquitous Networks at Bodrum, Turkey 2010
- 7th International Workshop on Data Management for Sensor Networks, at Singapore 2010
- First International Workshop on Advances in Sensor Technologies, Systems and Applications at Fukoka, Japan 2010
- The 8th ACM Conference on Embedded Networked Sensor Systems at Zürich, Switzerland 2010

- The 2010 International Workshop on Intelligent Sensor and Wireless Networks at Bradford, UK 2010
- The Third International Workshop on Sensor Networks at Genoa, Italy 2010
- The 9th ACM/IEEE International Conference on Information Processing in Sensor Networks at Stockholm, Sweden 2010
- 1st International Conference on Sensor Networks Applications, Experimentation and Logistics at Athens, Greece 2009
- 1st International Workshop on Sensor Networks and Ambient Intelligence at Dunedin, New Zealand 2008
- 2nd International Workshop on Sensor Webs, Databases and Mining in Networked Sensing Systems at Turku, Finland 2008

Application of Wireless Sensor Networks

WSNs are classified into two categories (Shen, Jaikeo, & Srisathapornphat, 2005). The first is for querying applications in which the user is interested in collecting data based on specific criteria. For example, in monitoring weather conditions, temperature, humidity, light, and pressure are all parameters of interest. In this category, some intelligent data collection might be employed to filter out data rather than getting "raw data." In the second category, sensor networks are used in tasking applications that involve programming sensor nodes to execute actions depending on certain events. Events are numerous, simplest type of events can be interrupting requests that interrupt the sensor function if detecting unusual behaviors. Complicated events can be involving number of sensor networks to cooperate together to achieve more accurate data. The rapid developments of radio frequency architecture have enabled the integration with sensor nodes to form (WSN) that are also divided in two similar categories as mentioned by Sohraby, Minoli, and Znati, 2007:

1. Category 1 WSNs (C1WSNs): this type of WSNs is mainly mesh-based systems, but can operate as point-to-point or star-based, multi-hop radio connectivity between sensor nodes (end devices) as seen in Figure 3. In this category a forwarding node has the mechanism to find the best route to the destination node thus, allowing it to have "more than one radio hop from routing or forwarding node." The main characteristics of this network are that (1) sensor nodes can act as repeaters (i.e. sensor nodes can send and receive on behalf of other sensor nodes) this type of behavior is known as "cooperative" (2) dynamic routing is supported by forwarding nodes thus providing physical and logical presence of more than one physical link (3) forwarding nodes can perform data processing to reduce the length of routing (4) distance of communication can be up to thousands of meters.

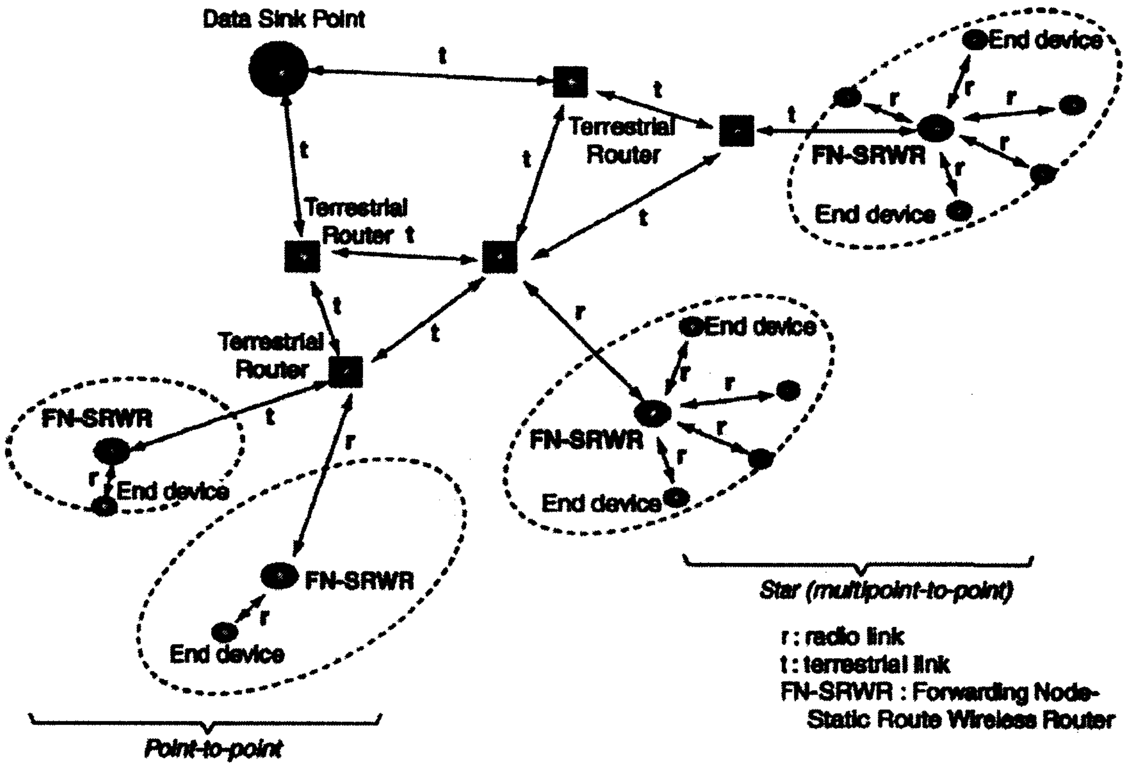

Figure 3: Category 1 WSN
(Modified by Sohraby et al., 2007)

2. Category 2 WSNs (C2WSNs): this type of WSNs can only perform as point-to-point networks or star-based network and only has one single-hop radio connection to sensor nodes, thus there is only one route from sensor nodes (end device) to the forwarding node or terrestrial network as seen in Figure 4. Therefore, C2WSNs have the following limitations (1) only one radio hop connection to sensor nodes, (2) static routing instead of dynamic routing and

one physical connection available to the terrestrial link (3) forward node does not perform any data processing on behalf on other sensor nodes and (4) radio frequency measured is only in hundred meters.

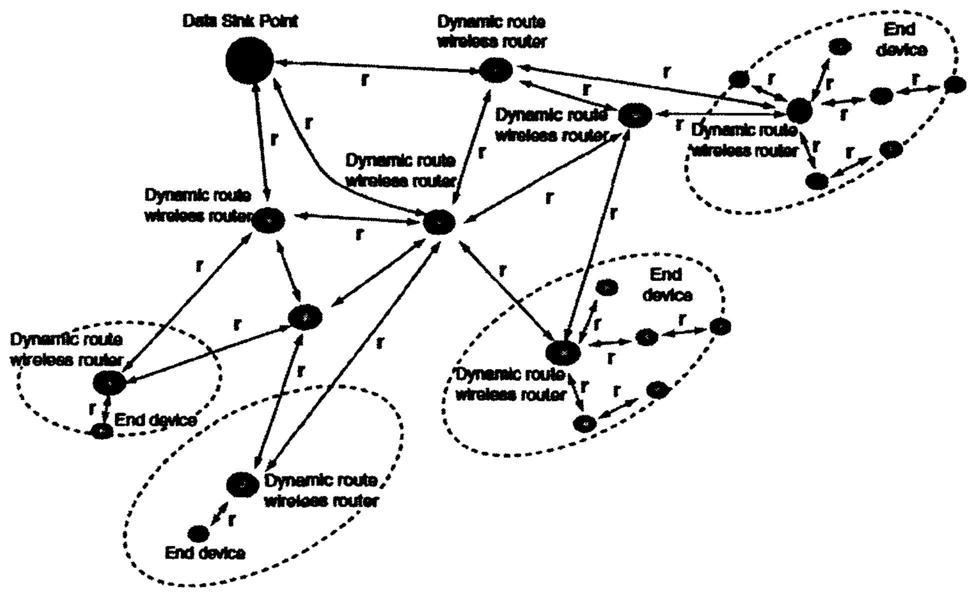

Figure 4: Category 2 WSN
(Modified by Sohraby et al., 2007)

Due to the categories provided by Shen et al. and Sohraby et al., WSNs can support wide range of applications. Thus applications are divided into two groups: one is supported by C1WSNs and the second is supported by C2WSNs.

Military Applications

WSN can be used by military for many applications that functions as detection tools such as surveillance, targeting systems, identification of enemy movements or as decision making tools such as command, control, communications, analysis of movements, and intelligence. The flexibility in WSN is much desired in military applications. Winkler, Tuchs, Hcughes, and Barclay (2008) identified ten assumptions that military expects from WSN technology:

1. Physical attributes of sensors: The WSN ability to be unattended by human, ease of deployment by robotic vehicles. Each wireless sensor node can be smaller than the palm of the hand and have the size of a matchbox.
2. Self-configuring after deployment: Even when certain node fails, wireless sensor nodes can reconfigure themselves to adapt the loss.
3. Network size: for major military applications, the average area covered by the network can range between 5-20 km^2. Knowing that the distance between each node can be in the average of 375m, less than 100 nodes can be used.
4. Information flow can be in both ways although in some application one-communications are sufficient. But for applications that require controlling techniques such as directing surveillance cameras, two-way communications are beneficial.
5. Durations of usage: Some networks are only used for several days. For longer term applications, WSNs are characterized by low power consumption and require an exchange of batteries to extend the lifetime. Moreover, each sensor node can be equipped with sleep mode when it is not used.

6. Physical and electronically inconspicuous operation: It is very desired that network can be covered with small electromagnetic emission pattern to remain hidden.
7. Data type: The data type used in WSNs is very limited (<30 bytes) but it still useful to identify incidents and provide detailed reports. Moreover, a node can be connected to Programmable Logic Control (PLC) that can analyze the data received.
8. Data reliability: It is necessary to ensure the accuracy received by the end user and implement the techniques to verify data delivery.
9. Denial of service: For military applications, it is very important that WSN is capable of reporting the incident of any jamming attempt.
10. Tamper-proof: Security of data in military applications is very important, and therefore the data held on the node are not to be shared by any third party and have built-in anti-tamper mechanisms.
11. Costs: The cost of wireless sensor nodes is less expensive than the "civil Bluetooth-focused market."

Applications of the WSN in the military field are numerous. Actually, the WSN development was motivated by military applications such as battlefield surveillance; (Bokareva et al., 2006) developed a distributed tracking and detection system based on hybrid WSN architecture that can track military targets such as tanks and vehicles based on the signal strength of the sensor nodes detecting the target. The system consisted of sensor nodes capable of capturing magnetic and acoustic measurements as seen in Figure 5. Due to the false alarms generated using noise detection, sensor nodes were time-synchronized by the Flooding Time Synchronization Protocol (FTSP). The function of the FTSP is to "utilize a radio broadcast to synchronize the possible multiple receivers to the time provided by the sender of the radio message" (Maróti, Kusy, Simon, & Lédeczi, 2004). With the utilization of the FTSP protocol, the receiver node synchronizes itself to the frequency of the carrier signal to prevent reduce false detection of targets. Similar studies in tracking mobile targets were demonstrated by Yang and Sikdar (2003) and Maróti, Simon, Ledeczi, and Sztipanovits (2004). The first one used a robust architecture for managing and coordinating a large scale sensor networks. Their interest was in power conservation and using only "the most appropriate sensors" for the target. In order to perform the task, the system uses the following information: (1) target identity, (2) target's present location, (3) target's next predicted location, and (4) target time occurrence or time stamp. The second study was an acoustic-based system consisted of predetermined or randomly deployment of sensor nodes that perform self-localization and establish a common time based. The system communicates with a base station to propagate the information through routing service. Another recent study on vehicle tracking using the WSN was done by Padmavathi, Shanmugapriya, and Kalaivani (2010). The results of the study were:

1. Run algorithm in short time over the network and thus enabling sleep time for nodes that save large amount of energy.

2. Elimination or collection of the same particle data to decrease amount of memory and energy.
3. The use of several central localization calculating points reduced vulnerability of the system to an attacker, eliminated the point failure problem, and enabled energy distribution.

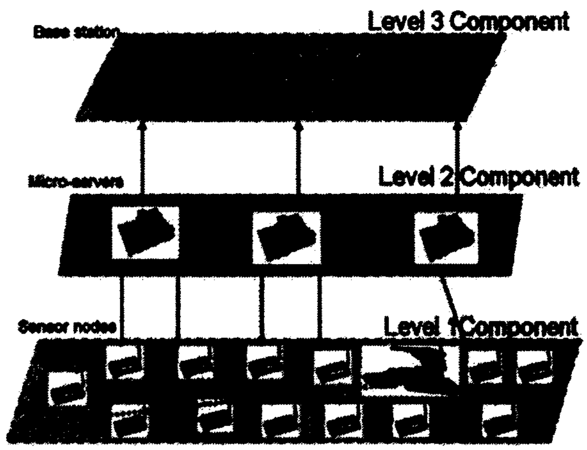

Figure 5: Magnetic and acoustic measurements using the WSN
(Modified by Bokareva et al., 2006)

Industrial Applications

In industrial environments, wiring data cables could be a major issue. The cable wiring cost depends on the location of machines, the type of plants, and the labor work needed for installation and maintenance. By using wireless sensor networks, cables are replaced with a reliable wireless network that can provide a robust data communication, avoid extreme costs and enhance the workforce productivity. Each WSN can hold up to thousands of wireless nodes deployed in an industrial plant. WSN systems are used effectively in machine controlling and condition monitoring. The key advantages of Zigbee wireless networks are the flexible network topology and the low power consumption.

In industrial applications, it is very important to have a robust WSN due to the electromagnetic power sources such as welding machines, motors, and so on. Such disturbances can reduce the communication quality between nodes. "Performance is one of the most important issues: the ability of sensors to transfer information within a small, fixed, and known time is crucial point." (Flammini, Ferrari, Marioli, Emilano, & Taroni, 2008). Localization of the nodes is very crucial in industrial applications. In order to predict performance of the WSN based on locations, the Radio Signal Strength Index (RSSI) is calculated in the following formula (Flammini et al., 2008):

$$RSSI(d) = PT - PL(do) - 10\eta Log(d/do) + X\sigma \quad (4)$$

where PT is the transmitted power, PL(do) is the path loss for a reference distance, and η is the path loss exponent.

The above formula does not take into consideration other disturbances such as walls or obstacles. Radio links are highly affected with these disturbances and particularly for large distances. Another method of measuring performance provided by

Flammini et al. (2008) was a histogram showing the frequency distribution of lost packets as shown in Figure 6.

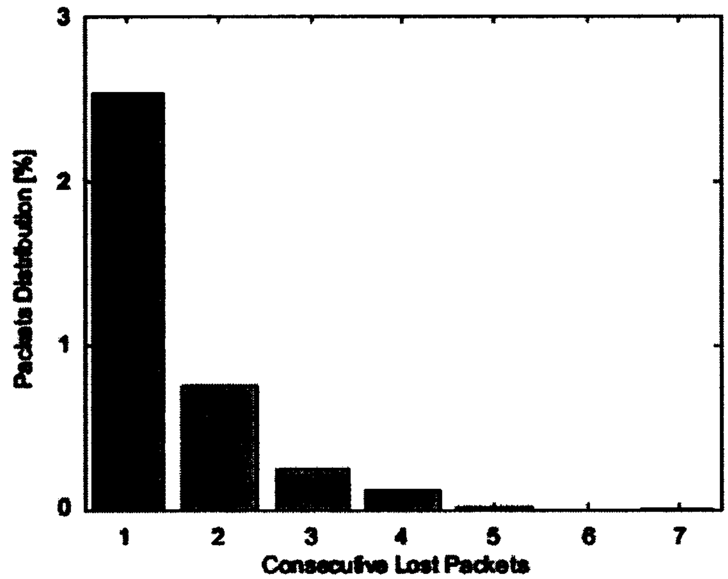

Figure 6: WSN lost packet distribution using histogram
(Modified by Flamminin et al., 2008)

The benefits of introduction of wireless devices as oppose to using wired solutions to monitor or control industrial applications were identified by Egea-Lopez, Martinez-Sala, Vales-Alonso, Garcia-Haro, and Sanahuja (2005) as:

1. Lower installation and maintenance costs
2. Solution for physical barrier problems inherent in wiring
3. Providing two way communications with field device
4. Improving the accuracy of information

5. Providing remote access to measurement data
6. Real time response.

Many researchers are currently engaged in developing the WSN solution in industry for different areas. Shen, Srisathapornphat, and Jaikaeo (2001) provided sensor information network architecture that facilitates monitoring and tasking of sensor nodes useful in factory process control and automation. Tavares, Velez, and Ferro (2008) designed and implemented a WSN process to supply the user with diverse types of information such as temperature, fuel consumption, and tire pressure in automobile. Kohlstrand, Danowski, Schmadel, and Arms (2003) presented an application consisting of ten or more sensors to measure gaps where rubber seals are to be placed thus replacing a cumbersome wire. Safety applications have its share in WSN for example, WSN can be employed to detect hazardous materials to send early detection signals of leaks or spills before serious damage can happen (Edgar & Callaway, 2004). In monitoring applications, the WSN are very practical to monitor temperature, vibration, lubrication flow, etc. of the parameters of machines. These parameters may use to predict machine sudden downtime or to control damaging events. In manufacturing applications, WSN have been developed to provide fault detection tool and monitoring of machine conditions. Tan, Huang, Zhang, and Lee (2009) deployed wireless sensor nodes on several milling machines that handled signal processing and identified the system errors. The WSN system is connected to a host computer to monitor the overall system. The purpose of this research was to provide a real time process to detect tool wear of machines and generate alarm signals when faults occur as seen in Figure 7. An algorithm flow chart showing the fault detection technique is provided in Figure 8.

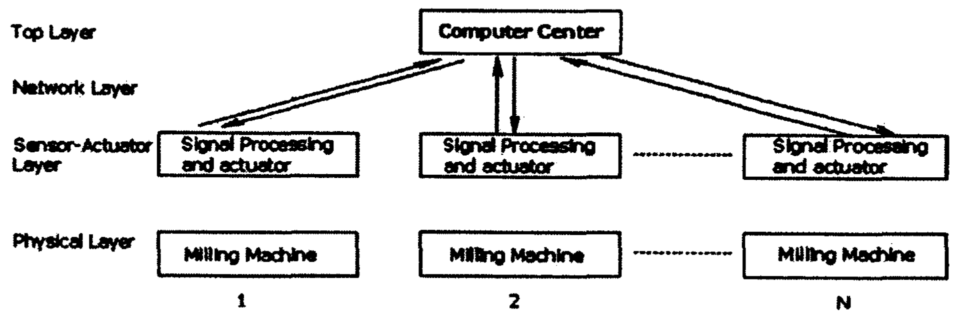

Figure 7: WSN tool wear detector algorithm
(Modified by Tan et al., 2009)

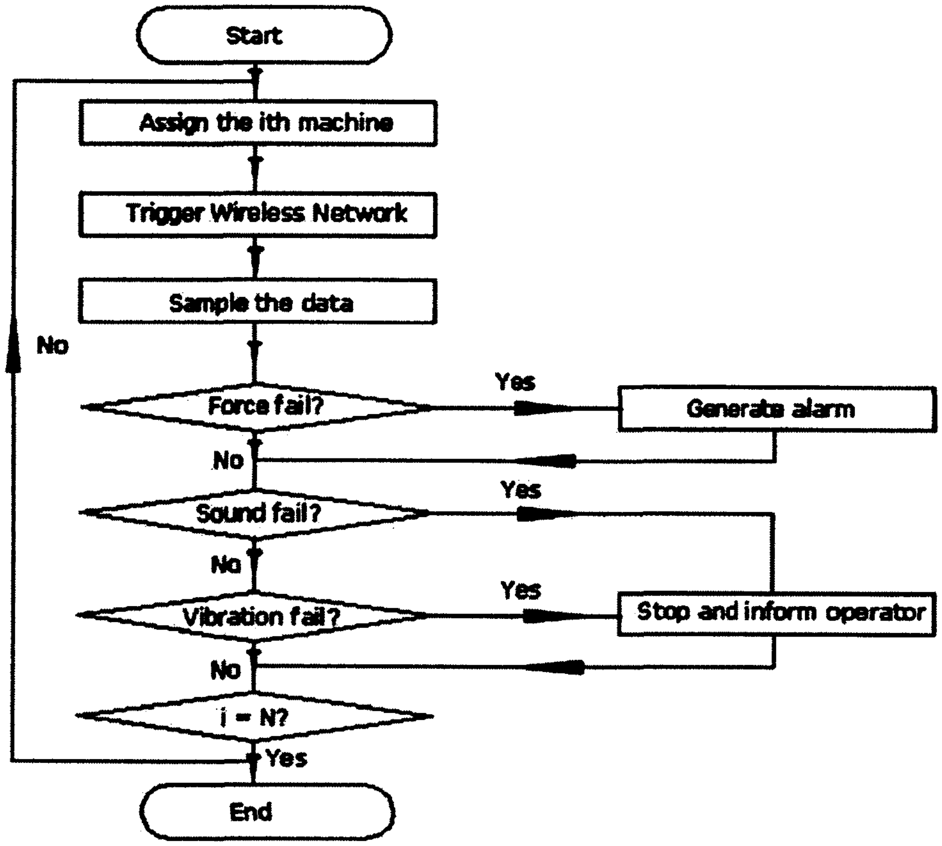

Figure 8: Fault detection technique flow chart
(Modified by Tan et al., 2009)

Similarly, to monitor three-phase induction motors, Xue, Sundararajan, and Brithinee (2006) used wireless sensor networks (WSNs) to measure temperature and vibration signals of three-phase inducting motor as shown in Figure 9. Bayindir and Cetinceviz (2010) established water pumping control system utilizing the WSN and replacing cables due to the harsh environment in which chemicals, vibrations or moving parts could potentially damage the cabling and the wires. The system was not only designed to monitor the tank level of the water pump, but also to send ON/OFF signals to the water pump using pressure transmitters. It was a convenient solution that utilizes the WSN technology and reduces cables installation and maintenance.

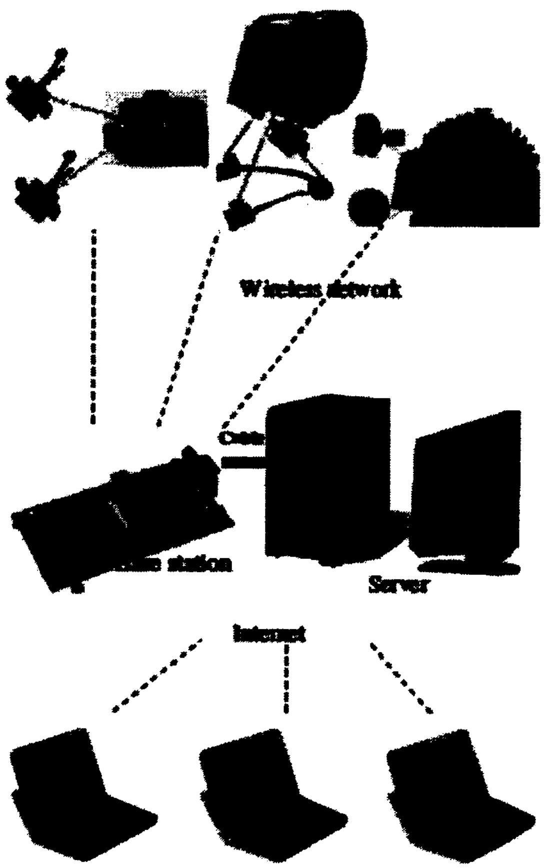

Figure 9: WSN for measuring three-phase induction motor
(Modified by Bayindir and Cetinceviz, 2010)

Environmental and Civil Engineering Applications

The WSN environmental applications are numerous and include tracking movements of animals, weather conditions, forest fire detection, flood detection, agriculture development, civil and environmental engineering monitoring.

Forest fire not only cost millions of dollars but can result many human lives, animals, infrastructure, and environmental damages such nature. Early detection of forest fire is very important to avoid and lower the damages. There have been many researches in this field. For example, Hefeeda (2007) analyzed the Fire Weather Index (FWI) System in a wireless sensor network to provide an efficient fire detection system, as seen in Figure 10, and Sahin (2007) who equipped native animals living in forests with wireless sensors that measure the temperature and transmit location information as seen in Figure 11.

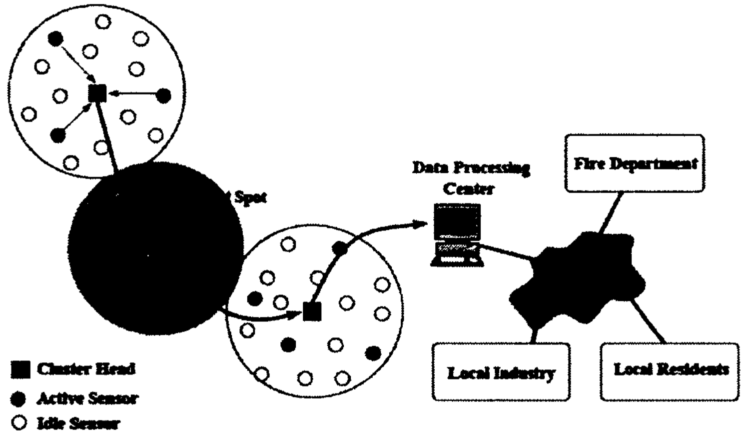

Figure 10: Fire weather index system (FWIS)
(Modified by Hafeeda, 2010)

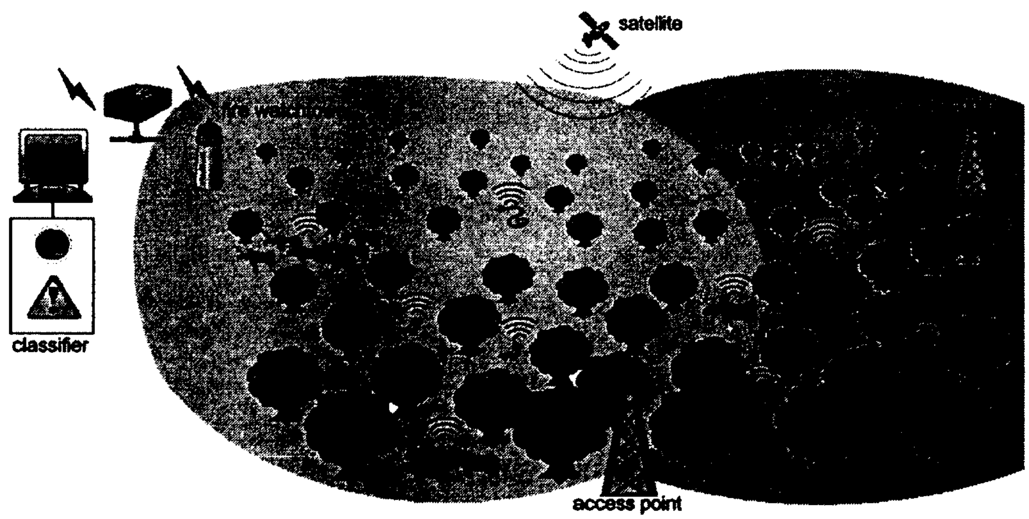

Figure 11: WSN with native animals
(Modified by Sahin, 2007)

In environmental engineering, there are many studies related with the environmental protection such as air pollution and control using nano-scale WSN. Mahfuz and Ahmed (2005) provided a comparative study between using Zigbee networks over Bluetooth and WiFi. The advantages of Zigbee were that a Zigbee network is a form wireless sensor network of low data rate and power that are proper to be used in applications that require sending and receiving small packets from sensors and switches to regulate and turn devices on and off. Early flood detection is also a serious problem because it includes threats on human lives, infrastructures, and animals; therefore, many experiments and demonstrations were carried out by researchers to improve support for flood warning (Hughes et al., 2007) and (Rus & Basha, 2008). Another example on civil engineering using the WSN is the bridge monitoring system by Lee et al. (2007) to gather related environmental parameters specifically, vibrations and transmits data to a backup database for monitoring staffs to analyze and study. The WSNs are also involved in measuring soil water content and temperature such as the farm-based WSN developed by Sikka et al. (2006) using gypsum block sensors to one meter soil depth.

Medical Applications

The healthcare market indicates an increasing growth for deploying wireless sensor nodes in healthcare applications as can be noted in Figure 12. The main purpose of the WSN healthcare applications is to monitor health conditions and facilitate the information sharing that can be used to track and identify the progress of a disease or recover in non-critical monitoring cases or to send alarm signals based on critical health conditions (Zigbee Alliance, 2009). Examples of the WSN in healthcare system are represented by the integration of Zigbee technology in glucose meter, pulse oximeter, electrocardiograph, weigh scale, thermometer, blood pressure monitor, and respirometer.

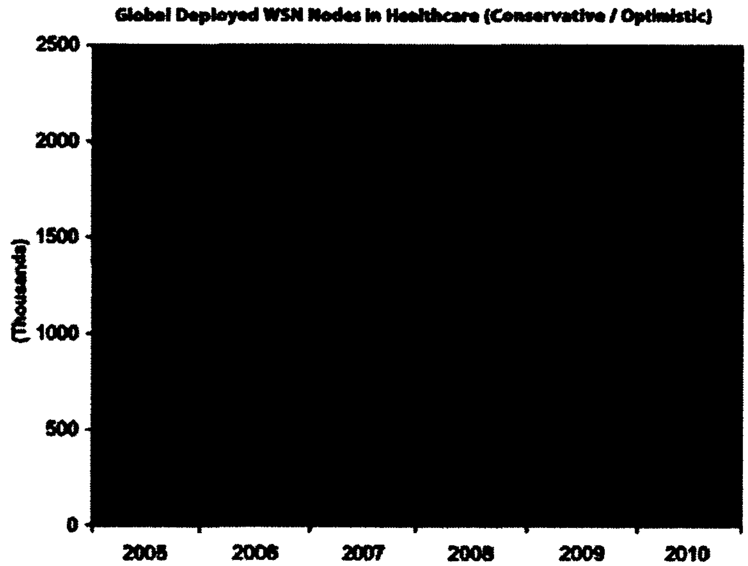

Figure 12: ON world WSN deployment in healthcare
(Modified by Zigbee Alliance, 2009)

Moreover, advances in healthcare WSN technology are numerous. For example Lubrin, Lawrence, and Navarro (2005) reported the building of a remote monitoring prototype taking advantage of the MICA2 ZigBee device to monitor body temperature, heart rate, pulse rate and other parameters. The system was interfaced with an HP iPAQ H5450 PDA to provide real-time remote monitoring and a bridge between the WSN and a web server. A similar study was completed by Malan, Fulford-Jones, Welsh, and Moulton (2004) interfacing a Berkeley MICA ZigBee module with an iPAQ pocket PC to develop a pulse oximetry mote. Gao, Greenspan, and Welsh, (2005) designed a developed a patient monitoring system that integrates alarming and locations sensors with electronic patient database records to facilitate collaboration between providers at disaster locations, hospitals, or distant facilities. Therefore, Zigbee WSNs have been very attractive technology for healthcare applications because of its focus on monitoring conditions and its telecommunication capabilities as oppose to other wireless technologies such as the Bluetooth and the RFID. Lee et al. (2009) provided in Table 1 comparison of Zigbee technology to other technologies used to argue the promises of Zigbee in healthcare applications.

Table 1

Comparison of Zigbee technology with other technologies. (Modified by Lee et al., 2009)

Wireless technology	Zigbee	Bluetooth	RFID
Standard	802.15.4	802.15.1	433-900 MHz
Application focus	Monitoring and control	Cable replacement	Multi-barcode replacement
System resources	4-32 KB	Over 250 KB	-
Battery (days)	100-1000	1-7	-
Bandwidth(KB/s)	20-250	720	<1
Transmission range (m)	1-100	1-10	0-5
Success metrices	Reliability, power, cost	Cost, convenience	Cost, convenience

Home Control Applications

Home automation is defined as "the introduction of technology within home to enhance the quality of life of its occupants, through the provision of different services such as telehealth, multimedia entertainment and energy conservation" (Gill, Yang, Yao, & Lu, 2009).The key benefit of going wireless in home automation is the elimination of cables cost and adding mobility. Previous studies in home automation have faced many difficulties. For example, the use of Java based technology by Al-Ali and Al-Rousan (2004) to incorporate built-in security required an expensive wired solution, and the Bluetooth based home automation system containing a local sub-controller have been identified by Gill et al. of being an expensive solution and have issues related to network access delay. Therefore, a low-cost and flexible ZigBee based home automation system architecture was designed that eliminated the use of expensive devices such as personal computer. The system was designed in a way that can be monitored and controlled locally via any Java enabled WiFi device or remotely using an internet enabled device which supports Java. An internal evaluation was performed and the Zigbee access delay was 670 milliseconds compared with 1337 milliseconds using the WiFi controller. Thus, Zigbee devices have the lowest network access delay.

WSN Structure

Wireless sensor networks as seen in the applications scenarios consist of a bridge between the physical world and the computational world. Therefore, WSNs have been proven as an effective solution to many challenging situations that requires flexibility and robustness. To deploy WSNs, these networks need to be designed and implemented in a way to provide a flexible and convenient use. In order to do this, this section will provide a brief introduction on the WSN architecture. First, wireless sensor networks have been defined as "systems consisting of a large number of nodes, each equipped with a certain amount of computational, communication, storage, sensing, and actuation resources" (Feng, Koushanfar, & Potkonjak, Sensor Network Architecture, 2005). Generally, a sensor node consists of five components: Processor, Storage, Sensors, and Radio. Figure 13 shows a basic structure of a single WSN.

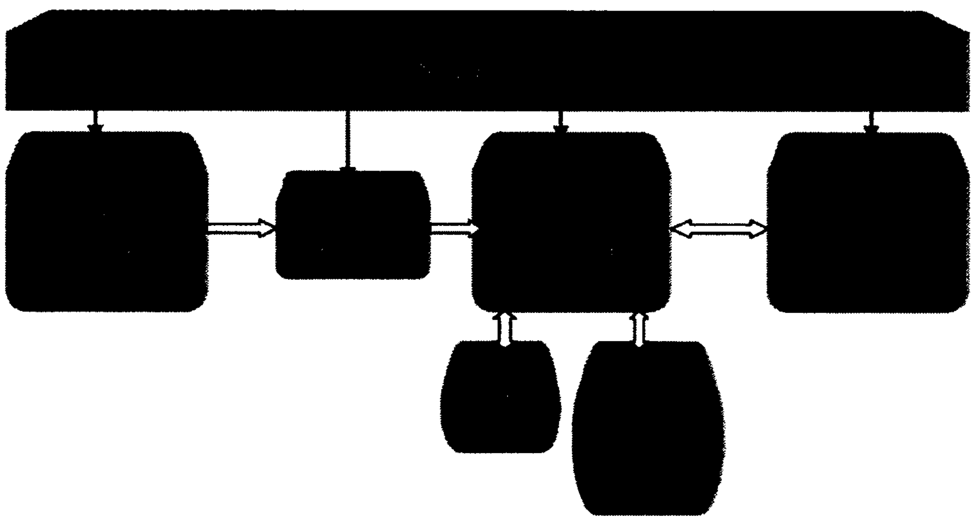

Figure 13: Architecture of a sensor node

Processor

Each WSN node has a microcontroller acting as the Central Processing Unit (CPU). The main function of the microcontroller is to collect and process data. The microcontroller decides when and where to send or receive data to or from other sensor nodes. The purpose of using microcontrollers is flexibility in connecting with sensors, perform time-critical signal processing, low power consumptions, and contain built-in memory. Thus, microcontrollers are programmable and very flexible. Today, most microcontrollers are equipped with flash memory RAM, analog-digital convertors, and digital I/O ports allowing for wider range of applications. It has been reported that a single integrated circuit costs between $1 and $5 (Lester, 2003). It is very important to consider the peripheral connections required for the application when selecting a microcontroller. For example the Atmega 1281V microcontroller can be interfaced through several ports using the AT-Command, IRQ lines, USART, or ADC lines (ATMEL, 2009). The XBee-PRO XSC is interfaced by the UART, AT-Commend, but has no ADC input lines (Digi International Inc., 2008).

Power

Power consumption between one WSN node and another varies because of the different microcontrollers used between one family and another. For example, the ATmega32 is an 8bit microcontroller with 32 Kbytes flash memory has a power consumption of 1.1 mA when active, 0.35 mA in sleep mode. The power requirement for the XBee-PRO XSC is 265 mA for transmission mode, 65 mA for receiving mode, and 45μA for sleep mode.

Storage

The Random Access memory is widely used in wireless sensor nodes to store instantaneous messages and packets sent or received. Because random Access memory loses its content when the power is off, WSN's are integrated with flash memory or Electrically Erasable Programmable Read-Only (EEPROM) flash memory allowing data to be stored, erased, or written. The size of flash memory in WSN is application dependent.

Sensors

Sensor networks as explained earlier can be integrated in thousands of wireless applications. Additionally, many wireless nodes have the capability to be connected to external sensors such as vibration, pressure, temperature. Therefore, the function of sensors is to sense. The function of sensors is straightforward and is not flexible as the processing or communication part. Moreover, some WSNs are integrated with multiple sensors and can be hooked to additional sensors. For example, Zigbit modules contain temperature and light sensors integrated in the same board and can operate simultaneously.

Radio

In any wireless module, the radio is the most important part that enables the unit to communicate wirelessly. It also determines the range of frequency and the physical layer characteristics such as the RSSI. The radio module can be controlled to operate as a receiver, sender, or both. The radio frequency RF is part of the physical layer responsible to establish communication between one transceiver and one or more transceivers. Its main tasks are signal modulation and encoding of data in presence of channel noise and interferences (Feng, Koushanfar, & Potkonjak, Sensor Architecture, 2005). As a result, the design of radio architecture is a major part of the WSN architecture to maintain security and reliable network and it is the most expensive part as to energy consumption of transmission and reception. To solve the issues of RF performance such as reliability, security, and power consumption, the medium access control (MAC) policies can help in reducing the radio interferences and power consumption. For example, the MAC protocols can force a certain node to go to sleep mode while maintaining the connection. Jung and Vaidya (2002) developed a scheme that use the maximum power for RTS-CTS handshake packets responsible for determining the channel and power level to use for data transmission, and the minimum power for data and acknowledgement packets (DATA and ACK).

WSN Topologies

There are several modes of WSN communication called topologies. Each topology defines the protocols of communication and provides the overall structure of the network.

Star Network

A star topology is a communication where a host is called the base station can send/receive to a number of wireless nodes. Each wireless node can only communicate (send/receive) with the base station as represented in Figure 14.

In star topology, the base station is usually a fixed node connected to a host computer to monitor the overall traffic of the network. Whereas the remote wireless nodes are most likely battery powered. The advantages of star topology is in the remote nodes which they don't communicate with each other and thus require less maintenance because of its simplicity, and therefore less power consumption because they do not reply to other incoming traffic or noise. Each star network chooses a PAN identifier not used by any other network within the range of application. Each star network operates independently by definition. The main disadvantage of the star topology is tha the host station must be located in within the radio transmission of all the remote nodes having the same PAN identifier. In star topology, if the base station fails, the whole network is down and thus, star topology is not a robust as other topologies.

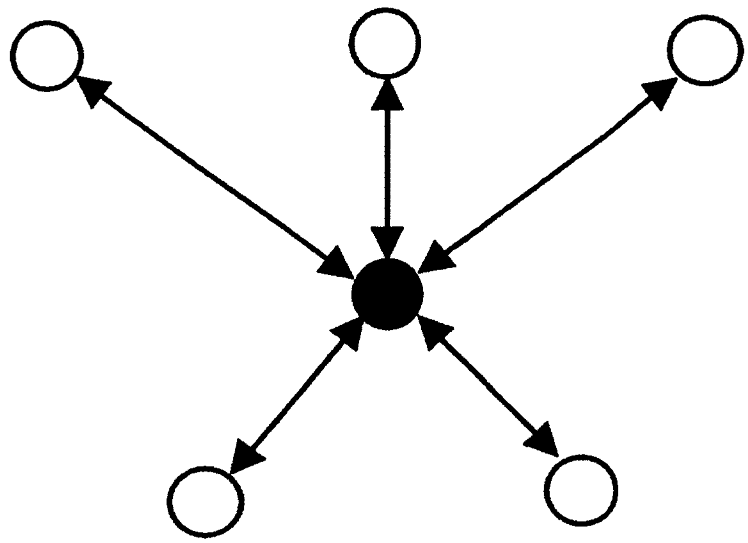

Figure 14: Star Topology

Mesh Network

In a mesh network, a node can transmit to any other node within its radio transmission. In mesh networks, nodes can use the mutihop communication allowing a node to send a message to another node outside its radio transmission via an intermediate node.

Townsend and Arms (2004) described mesh networks as having two advantages and two disadvantages. A mesh network is characterized by redundancy and scalability: If a single node fails, a remote node can communicate with another node in its range to deliver the message to the desired destination. The range of the network is not limited to the range between nodes, adding more nodes to the network can extend the range of the network. The trade off in this case will be the power consumption for the nodes to implement multihope communications to deliver messages to final destinations. Furthermore, as destinations become more extended, the delivery time increases especially for low power operation.

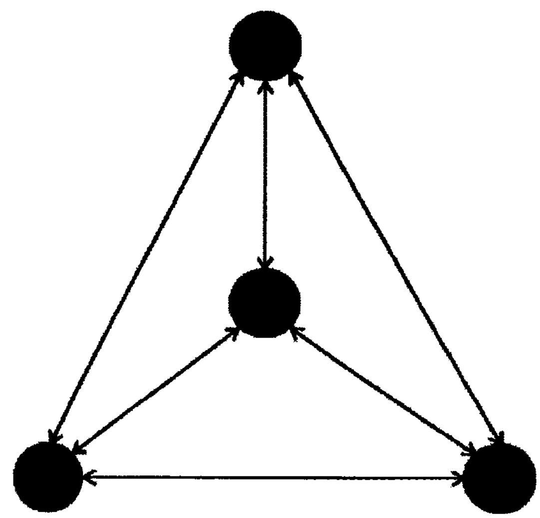

Figure 15: Mesh network

Hybrid Network

To overcome the issues of power consumption resulted by mesh networks and provide a robustness solution, the low powered nodes do not have the capability to forward messages. Forwarding messages from low power nodes to other nodes on the network or multihop communications is maintained by other nodes, usually higher power (Townsend & Arms, 2004). This type of networks is widely used in ZigBee standard that will be explained later.

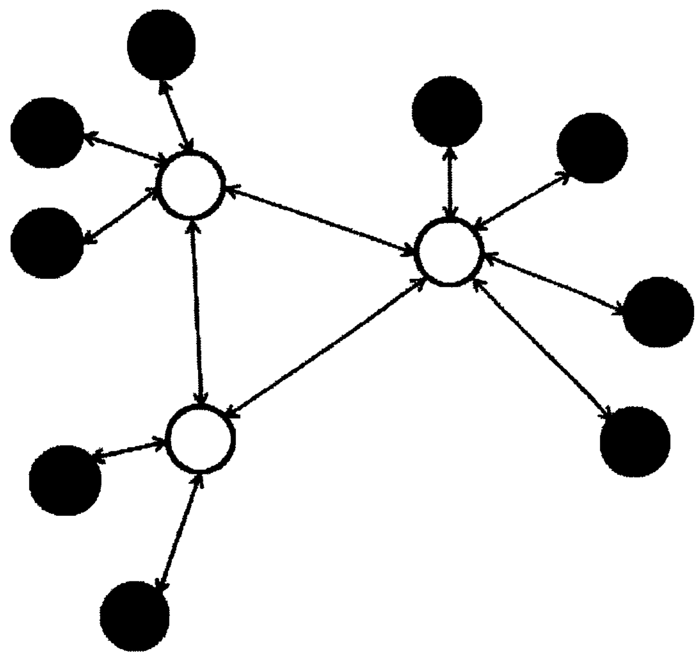

Figure 16: Hybrid star-mesh network topology

Zigbee Overview

Zigbee is an intelligent solution that helps in adding more control to wide range of applications by improving safety, security, efficiency, and reliability. Zigbee is an industrial standard for ultra-low power low-cost wireless sensor networks applications.

The Zigbee standard is based on the physical link layer operating at IEEE 802.15.4. The IEEE 802.5.4 standard includes transmission bands at 2.4GHz (global), 915 MHz (Americas) and 868 MHz (Europe) of low data rate ranging from 20 Kbps to 250 Kbps.

On the top of the physical layer, ZigBee consists of two additional layers, the application layer and the network layer respectively. Each layer executes specific services for the layer above (Severino, 2008) .

Zigbee Alliance

ZigBee alliance was established in 2002. It is an open organization to wide variety of members from different background. The main mission of ZigBee alliance is to provide and develop standards for more sustainability by utilizing the ZigBee technology. The fact that Zigbee is characterized by being low power, open wireless networking standards, easiness of installation, and offering variety of applications or environments, have characterized the mission of the alliance with a green solution replacing many complicated network architecture (Zigbee Alliance, 2009).

Zigbee is energy efficient and cost effective solution to many applications. One achievement of the Zigbee technology in the green market is the reduction in cables' manufacturing and installation, where one or two tiny chips can replace hundreds of feet of materials processing.

Zigbee Architecture

The basic Zigbee architecture consists of three layers: The application layer, the Network layer, the Medium Access Control layer (MAC), and the physical layer.

Application Layer

The application layer can have multiple functions. For example temperature, humidity, and light sensors can be handled by separate applications. Therefore, the role of the application is to describe the function of the ZigBee device. The application layer consists of the APS Sub-layer, Zigbee Device Object (ZDO). The function of the APS sub-layer is to match between devices depending on their needs and services. The ZDO layer has discovery responsibility such as responding to binding requests and defining the roles of devices (Kinney, 2003).

Network Layer

The Zigbee network layer (NWK) is responsible to monitor and secure the network for each node within the range of the network. The security provided by the network layer is summarized in the following:

- Establishing a new network is started by the NWK

- NWK is responsible to give or prevent access to the network and that includes joining and leaving a network, configuring new node or devices by assigning addresses.
- Synchronization and routing techniques through the ability to track and synchronize wireless frames with other devices and direct them to the intended destination.
- Provides security by setting up keys to determine the security level to use by MAC.

Medium Access Control

The MAC provides Data Service such as exchanging packets between with PHY layer, and Management Service such as network association, device synchronization, communication status, and communication control. It is designed to handle multiple topologies. ZigBee provides security processing to both single and multi-hop messaging. The MAC layer retrieves the security key associated by a transmitted or received frame to process the frame as necessary (Kinney, 2003).

Physical (PHY) Layer

The physical layer (PHY) determines the frequency, the modulation, and has the control over the radio transceiver. The PHY layer can activate and deactivate the radio transceiver. The transceiver is concerned with the modulation and demodulation of the digital signal. The process of modulation is to map groups of symbols in one finite waveform before sending the packet. Thus modulation is carried out by the transmitter. The demodulation process is used by the receiver to recover the modulated digital signal. Due to noise and interference, some symbols might get interpreted with certain error. This error is called the bit error rate (BER;Karl & Willig, 2007).

Wireless Sensor Network Performance

The applications of WSN are of different types depending on the sensors such as light, thermal, acoustic, and are able to monitor conditions such as temperature, humidity, movement, vibration, pressure. The process of measuring these conditions in wireless environments has promised many application areas such as military, environment, health, and industry (Raghavendra, 2006). WSN's are also known to be as powerful because of their flexibility and are known as "challenging research and engineering problem" because there is no enough identified set of requirements that can classify them (Karl & Willig, 2007). This explains the wide research that has been employed to explore the potential and the issues surrounding the WSN's or ZigBee networks. For example, ZigBee networks operating on the 2.4GHz have been examined by many researchers due to the effect of WLAN on its performance (Shuaib et al., 2006). Shaib et al. studied the coexistence between the two wireless technologies sharing the same unlicensed frequency due to the RF channels overlap. They explained this phenomenon in the graph provided in Figure 17.

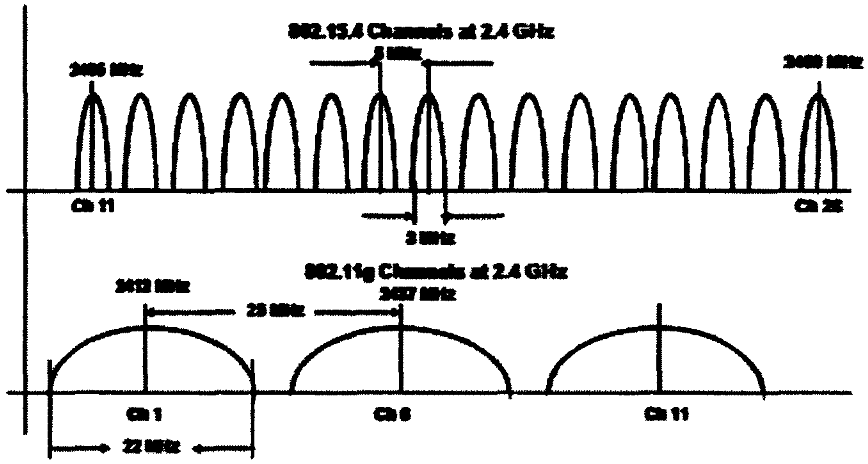

Figure 17: RF spectrum for ZigBee and WiFi
(Modified from Shuaib et al., 2006)

The results of this study showed that the effect of the ZigBee interference has more effect in the uplink than the downlink of the WLAN and that the ZigBee performance is affected when the spectrum of both channels co-inside. In a similar study, Zeghdoud, Cordier, and Terre (2006) evaluated the impact of WiFi interference on ZigBee performance by simulation and the calculations were based on the signal-to-noise ratio (C/I+N). Their focus was also on the 2.4 GHz frequency band that utilizes sixteen channels as shown in Figure 18.

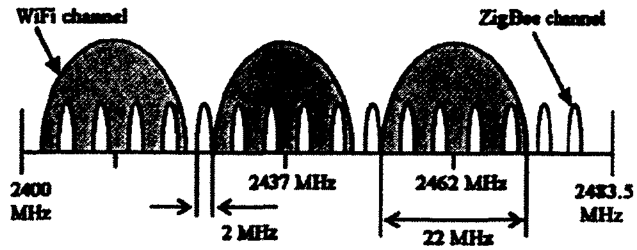

Figure 18: Zigbee and WiFi channels
(Modified from Zeghdoud et al., 2006))

Kim and Kwon (2009) proposed a novel topology control algorithm to reduce interference effects on ZigBee devices based on the formulas shown in equations below. Whereas Shin et al. (2007) obtained the frame error rate (FER) from the bit error rate for the ZigBee network and concluded that WLAN and Bluetooth are considered as band and partial band jammer for ZigBee.

$$P_{TX}^{MIN}(dBm) = PL(dB) + P_{RX}^{TH}(dBm) \tag{5}$$

$$SINR(dB) = 10\log\frac{10^{P_{RX}/10}}{10^{P_I/10} + 10^{P_N/10}} \tag{6}$$

Where PL is the path loss

P_{RX}^{TH} is the received power threshold

SINR is the power ration in dB for the strength of the desired signal to the strength of the undesired signals.

P_{RX}, P_I, and P_N denote the received power, the interference power, and the noise power respectively.

Evaluating ZigBee in Harsh Environments

Because ZigBee is a new technology, only recently several studies have been conducted to evaluate the performance of ZigBee in industrial applications. Ferens, Woo, and Kinser (2009) identified the following requirement to choose a suitable wireless technology for the application of sensor networks:

1. Standard based-protocol that has greatest chance to be compatible with other products.
2. Low data rate network.
3. Minimal power and low cost network.
4. Self-forming and self- healing network ability.

Such description provided by Ferens et al. is typically the standardized form of WSN or ZigBee network. ZigBee are characterized by having "self-healing protocol will automatically reroute the data or messages to an alternate, clear path so that they will still reach the intended destination. Furthermore, nodes will have to be removed or added to the system at some point in the future. Therefore, the system should be capable of discovering and allocating resources in an unmanaged way (self-forming)." Based on Ferens et al. study, in the peer-peer network, the frame error rate (FER) increases as signal-to-noise (SNR) decreases. This means the noise causes higher FER values.

Tsai et al. (2007) studied the deployment of WSN within a car and reported the results of both received signal strength index (RSSI) and the link quality indicator (LQI). The research also measured the attenuation of signal strength experienced as the signal propagates from the transmitter antenna to the receiver antenna as follows:

$$CL(dB) = P_{transmitted} - P_{Received} \tag{7}$$

Where CL denotes attenuation of signal strength in dB.

The authors indicated that the channel loss depends on the distance between transmitter – receiver and the type of medium along the path between both the transmitter and the receiver. They measured the transmitted power and recorded the channel loss of each node.

The Evaluation of the Zigbee performance is defined by two categories. The first can be called as the signal power evaluation and the second is the packet loss study. The two studies are represented in the literature review and will be explained in details in the next section.

Signal Power Evaluation

The wireless signal power evaluation is determined by the received signal strength indicator (RSSI). In general, the received power is dependent on the distance between the sender antenna and the received antenna, and the transmitted power as described by Friis free-space equation:

$$P_{received}(d) = \frac{P_{tx}.G_t.G_r.\lambda^2}{(4\pi)^2.d^2.L} \quad (8)$$

Where $P_{received}$ (d) is the received power at a distance d, d is the distance between the sender antenna and the received antenna, P_{tx} is the transmitted power, G_t is the transmitter antenna gain, G_r is the received antenna gain, λ is the wavelength, L represents the losses through the receive/transmitter circuitry.

Tsai et al. (2007) developed a detection algorithm based on RSSI to overcome the link performance of Zigbee networks operating in vehicle. The detection algorithm was executed at the base station that will send out one of the action commands to the corresponding node once a problem is detected:

1. Increase transmitting power to observe if it can overcome channel loss due to fading.
2. Retransmit signal to overcome interferences issues.
3. Increase transmitting power to overcome low received signal strength.

Tsai et al. found that the RSSI signal is a reliable indicator of the wireless packet rate sensitivity and the interferences that decrease the goodput performance.

Since the RSSI signal is dependent on the distance, Petrova, Riihijarvi, M¨ah¨onen, and Labella (2006) also monitored the change of the RSSI with respect to the distance between transmitter and receiver, and they concluded that the RSSI values behave differently from one environment to another. For example, in an outdoor environment the

RSSI values were less stable than in an indoor environment due to multi-path fading the wireless link.

The research done by Ferrari, Medagliani, Di Piazza, and Martal `o (2007) was similar to Tsai et al. (2007), by considering three constant transmitted power and measured the RSSI experimentally and compared the resulting values to interpolating data. It was expected that the experimental data to be close to the interpolated ones and the increased transmitted power lead to increased RSSI since the environment did not change.

The conclusion that can be drawn from Tsai et al. (2007), Petrova et al. (2006), and Ferrari et al. (2007) is that the RSSI signal is a key role in wireless sensor network since it can be used to measure the distance, the transmitted power, and even describe the environment such as indoor, outdoor, or an environment with many reflection phenomena such as furniture, walls, or people crossing.

Packet Loss Study

There are few studies that focused on the packet loss in Zigbee networks. For example, Armholt, Junnila, and Defee (2007) found that the channel access failure as a result of large packets causes lost packets. The study by Cao, Liang, Balasingham, and Leung (2010) suggested optimizations before applying Zigbee applications based on the findings that performance can varies with different distances and mobility can increase number of packets lost. Matlab was used by Ruiz-Garcia, Barreiro, and Robla (2008) to monitor the packets loss in real-time with respect to temperature changes. Ding, Sahinoglu, Orlik, Zhang, and Bhargava (2006) measured the duplicated and retransmitted packets to study the efficiency of Zigbee network.

CHAPTER III

METHODOLOGY

The study involved testing and implementing a model to verify the performance of WSN in industrial environments. Two wireless nodes were used to conduct the experiment and collect data. In order to test the development kit in real industrial environments, three industrial locations were selected to complete the study.

The research was carried out to examine the reliability of the Zigbee performance in industrial environments. The analysis of the RSSI signals and the Frame Error Rate (FER) were tested with experimental implementation. In addition, each industrial location has its characteristics for wireless signal propagation. This will be calculated based on the collected data. The Zigbee performance was examined in three different methods. Two of these methods relied on the saved data collecting. The third method was an instantaneous real time method to verify the collected data.

Industrial Locations Selection

This study is limited to the industrial locations available in the area. Essentially, the industrial locations must be generally characterized by being equipped with heavy manufacturing equipment and industrial activities.

Three industrial locations were selected to collect data to evaluate the ZigBee wireless network. The first was selected in a manufacturing laboratory at the University of Northern Iowa where human presence and blocks such as metallic objects or walls are minimal as in Figure 19. The second location was at a manufacturing facility of a local Midwestern manufacturing company where human presence is higher, more metallic objects exist and higher traffic or moving objects are detected as in Figure 20. Finally, the third location was selected at the assembly line of the manufacturing company characterized by the presence of highest human activity and large moving vehicles, and issues of wireless infrastructure reported.

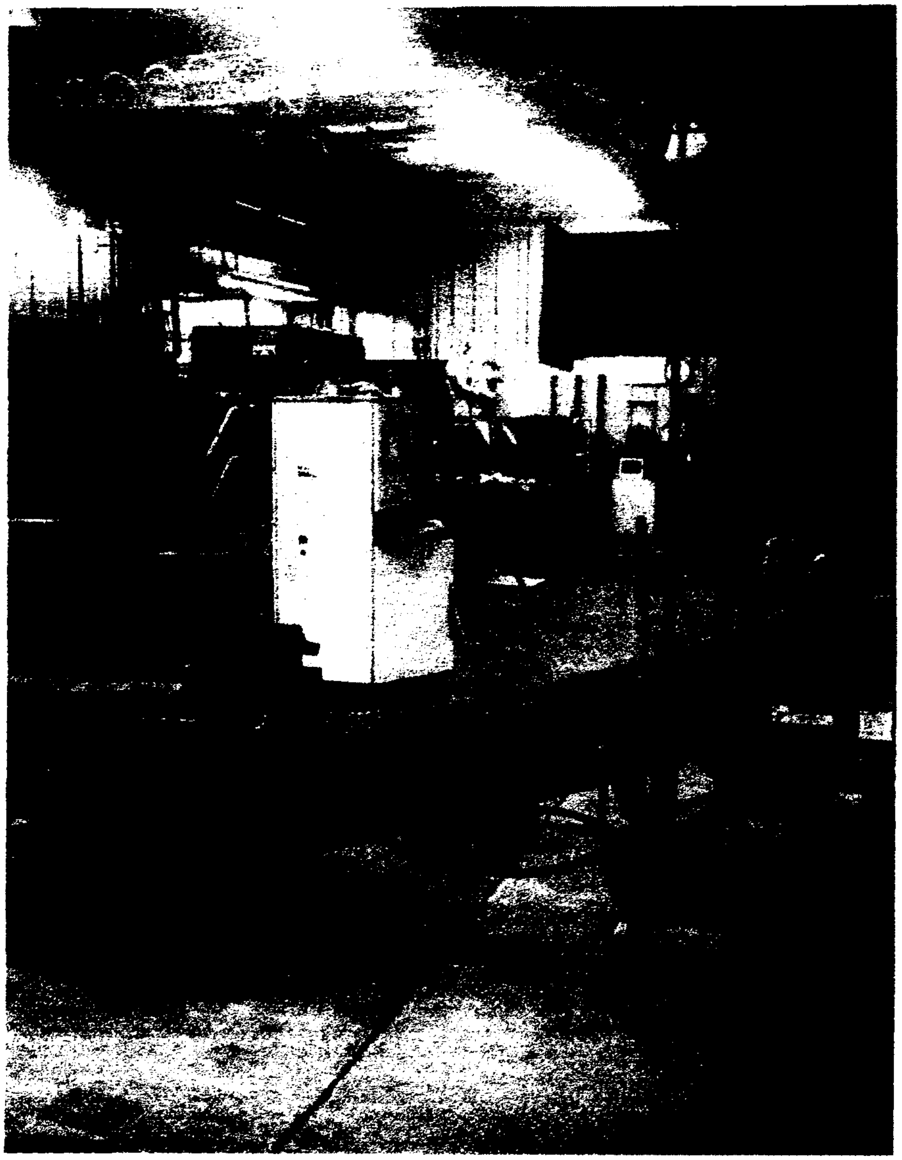

Figure19: Metal casting activity at the manufacturing laboratory at the University of Northern Iowa

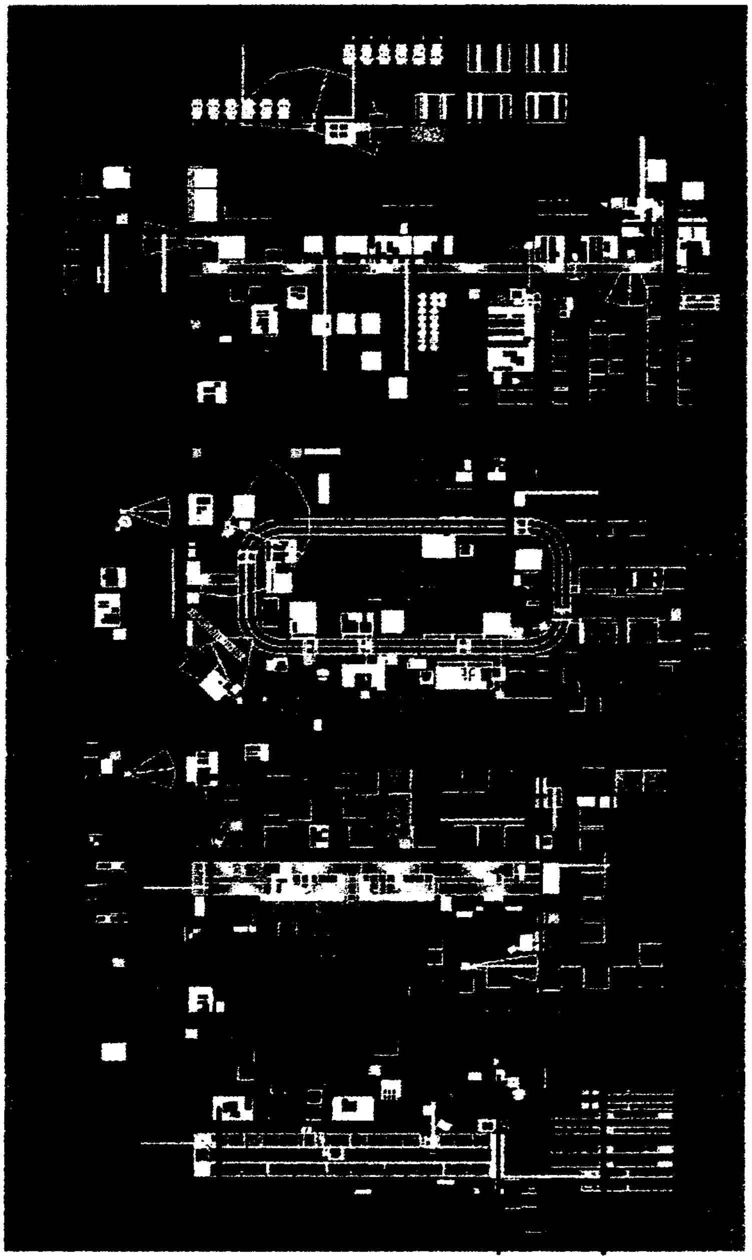

Figure 20: CAD drawing showing industrial equipment at the Manufacturing Midwestern Company.

Development Kit Configuration

The Zigbit 900 Development kit is a simple solution that provides WSN prototyping and development. It contains meshbean2 development boards that include the ATmega1281 Microcontroller. The ATmega12821 is a low power 8-bit microcontroller with 128 Kbyte flash program memory and 8-Kbyte SRAM. This microcontroller can be programmed with the provided "Range Test" tool to develop customized wireless solutions based on BitCloud Software. The advantage of the flash program memory is to provide a storage location for the application. The "Range test" application was downloaded to the microcontroller using provided software called Bootloader. The meshbean2 board is supported with the 800/900MHz-band AT86RF212 RF implementing the IEEE802.15.4. The communication between the microcontroller and the RF transceiver is fully implemented inside the meshbean2 board as represented in Figure 21.

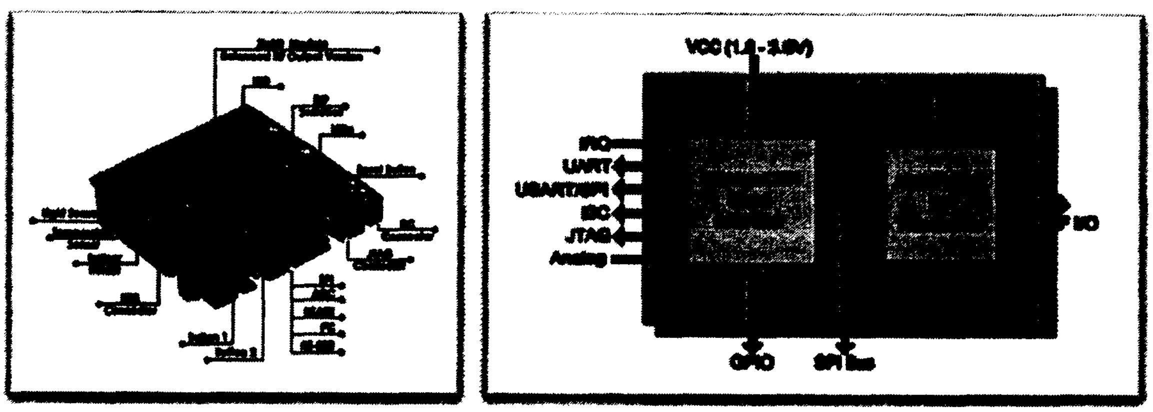

Figure 21: MeshBean Amp componenets (left). Meshbean I/O block diagram (right). (Modified from Meshnetics, 2008)

In order to use the development kit, the following hardware components are required:

1- Two Meshbean2 board and two external antennas

2- Two USB 2.0A/mini-B cable

3- External interface cable

4- A computer with Windows XP loaded

5- Bootloader software from Atmel Website.

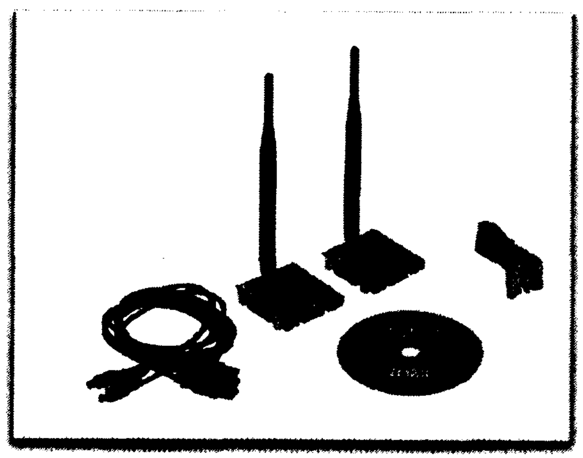

Figure 22: ZigBit 900 development kit
(Modified from Meshnetics, 2008)

BitCloud Environment

The BitCloud is an embedded software stack that describes the architecture of the ZigBee network plus additional services that are specific to the development kit. As shown in Figure 23, the topmost layer is the application layer visible to the user and that can be modified. Common services are also available to the user such as Task Manager, Power Manager and can be utilized by lower layers. Core stack layer consists of the ZDO, APS, NWK, and MAC.

Table 2

Zigbee Software Stack Architecture

Application layer (APL)	
ZigBee Device Object (ZDO)	[illegible]
HWD (hardware)	[illegible]

Setting up the Development Environment

To setup the WSN network, each node was connected the computer using the Universal Serial Bus (USB) mini cable to download the output of the compiler to the ATmega1281 microcontroller. Each meshbean2 board can be set up as transmitter or receiver by programming the DIP switches shown in Figure 21. To configure the node as a transmitter, the switch SW4:3 was set to ON. The same switch was set to OFF to configure the node as a transmitter.

Table 3

Node role functionality

SW4:3 switch	Node role
OFF	Transmitter
ON	Receiver

The transmitter node can be placed at the desired location while the receiver node must be connected to a computer to read and store the network status using the following port settings:

1. Data Rate 38400bps
2. Data Bits 8 bits
3. Parity: none
4. Stop Bits: 1
5. Flow Control: none

Once the wireless connection across the sender and the receiver of the WSN was established, the sender node will start transmitting performance measurement information about the network established between the two wireless nodes. The receiver node connected to the computer will store the wireless connection status information and save them in a log file.

Frame Error Rate

The frame error rate was measured based on the counts each repeated frame. The repetition of each frame is a result of the frame that was not received in the first time due to (1) sender node is not active; (2) the wireless messages are being blocked by the environment characteristics that can be either due to structure such as concrete walls, metals, moving objects, human activity or due to harsh environment such as activities of industrial and manufacturing operations as a result of electromagnetic interference, temperature, and other related factors. Errors due to loss of connection related to power issues or permanent blocking such as out of range or sender/receiver failure will be eliminated because it is beyond the intention of this study.

Frame error rate was also measured using the development kit XB24-DKS. The sender node was programmed to send a frame every one second. At the receiver node, frames were monitored and compared to the ones at the sender node to test the performance of the WSN.

Digital and Analog Line Passing

The XB24-DKS was programmed to transmit digital and analog data. Digital data was simulated with an external power supply connected to the input of the sender node.

Analog data was simulated by connecting a signal generator to the input of the sender node.

Received Power

The power received at the receiver node contains most of the information to evaluate the performance of the WSN network in this study. The power received is the power at the receiving antenna. It is directly proportional to the gain of the receiver and transmitter antennas, the frequency, and inversely proportional to the distance between the receiver antenna and the transmitter antenna as described in the formula below:

$$P_{received}(d) = \frac{P_{tx}.G_t.G_r.\lambda^2}{(4\pi)^2.d^2.L}$$

where

P_t = transmitted power in Watts;

G_t = transmitter gain;

G_r = receiver gain;

Λ = wavelength in meters;

d = distance between transmitter and receiver in meters;

L = losses due to circuitry;

The received signal strength indicator is defined as the ratio of the received power to the reference power that usually has an absolute value of 1mW. Thus, the received power can be deduced from the received signal strength indicator (RSSI) based on this formula:

$$RSSI(dBm) = 10.\log\frac{P_{RX}}{P_{\mathrm{Re}f}} \quad (9)$$

where

P_{RX} = power at the receiver in Watts;

P_{Ref} = absolute received power value (W) approximately 1mW;

<u>Environmental Conditions</u>

Any environment has its own signal propagation conditions. These conditions can be measured by the path-lost factor that depends on both the received power reference and the distance between transmitter antenna and the receiver antenna:

$$P_{received}(d) = P_{received}(d_0).\left(\frac{d_0}{d}\right)^{\gamma} \quad (10)$$

Where

$P_{received}(d_0)$ = power received at reference in Watts;

d_0 = reference distance equal to 1m for short range systems in meters;

γ = path-lost exponent;

d = distance between transmitter and receiver in meters;

Data Collection

There are two methods of collecting data: the first was based on visual real time charts of RSSI signals followed by analysis part to calculate the received power and the path-lost exponent. This method was limited to only one industrial location at the manufacturing laboratory at the University of Northern Iowa. The second method consisted of the frame error rate captured in a log file by the received node and stored in the host computer. This method was conducted at each selected industrial location selected.

The visual data contained the RSSI charts. Each RSSI chart show the changes of the RSSI value with respect to time at the desired location. The position of the transmitter node was changed, and another set of RSSI values were captured. At each location, the average RSSI was used to calculate the path-lost exponent.

The frame error rate along with the RSSI signal was captured in a log file. Since it was difficult to read the log file, a script was developed to extract the information of the frame error rate and represent the data in a chart at each industrial location. In order to determine the environmental conditions of the wireless signal propagation, the numbers of errors were classified according to the number of occurrences. For example, the duplicated frames are considered of having a frequency two, the frame counters that have been repeated three times are considered of having a frequency of three, and so on.

Each log file captured contained millions of data that are imported for the statistical analysis. Therefore, a Visual Basic script was written to extract the FC values and RSSI values to a single file for statistical observation. Appendix A and Appendix B show the script written for this purpose.

A functional block diagram of the wireless system including the internal circuit of the wireless nodes is shown in Figure 23 and a functional block diagram including the environmental condition testing is shown in Figure 24.

Figure 24 shows that wireless sender and receiver nodes were deployed at each location. Location 1 represents the manufacturing laboratory at the University of Northern Iowa. Locations 2 and 3 represent industrial environment at a Midwestern Manufacturing Company.

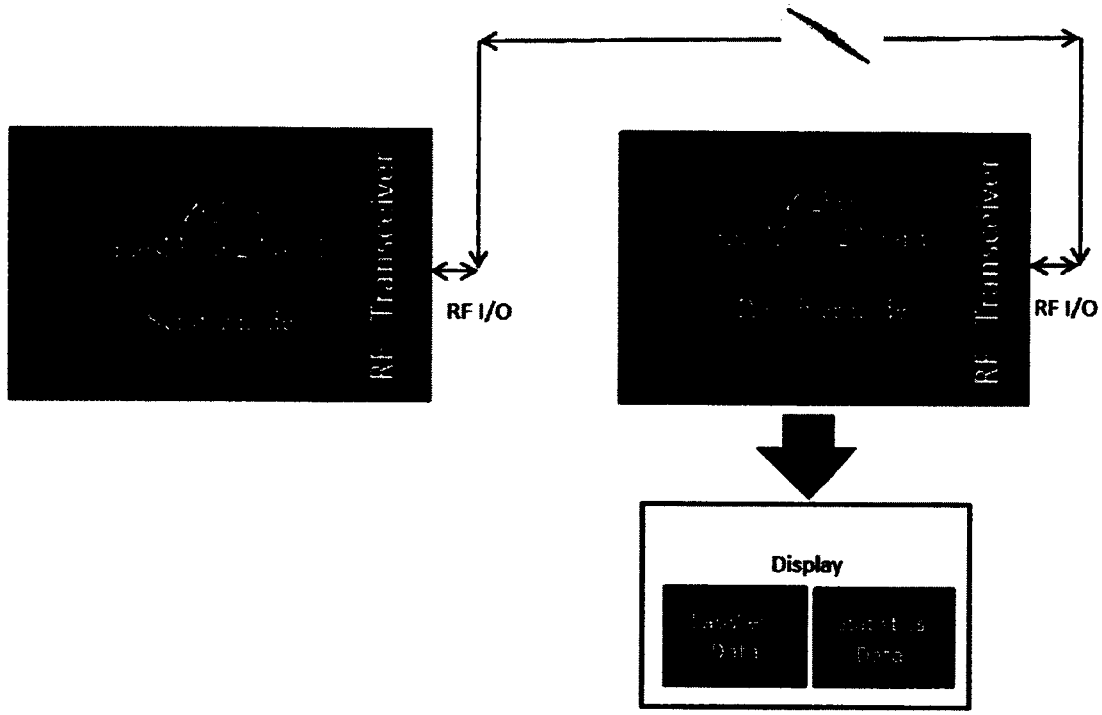

Figure 23: Functional block diagram of the wireless setup

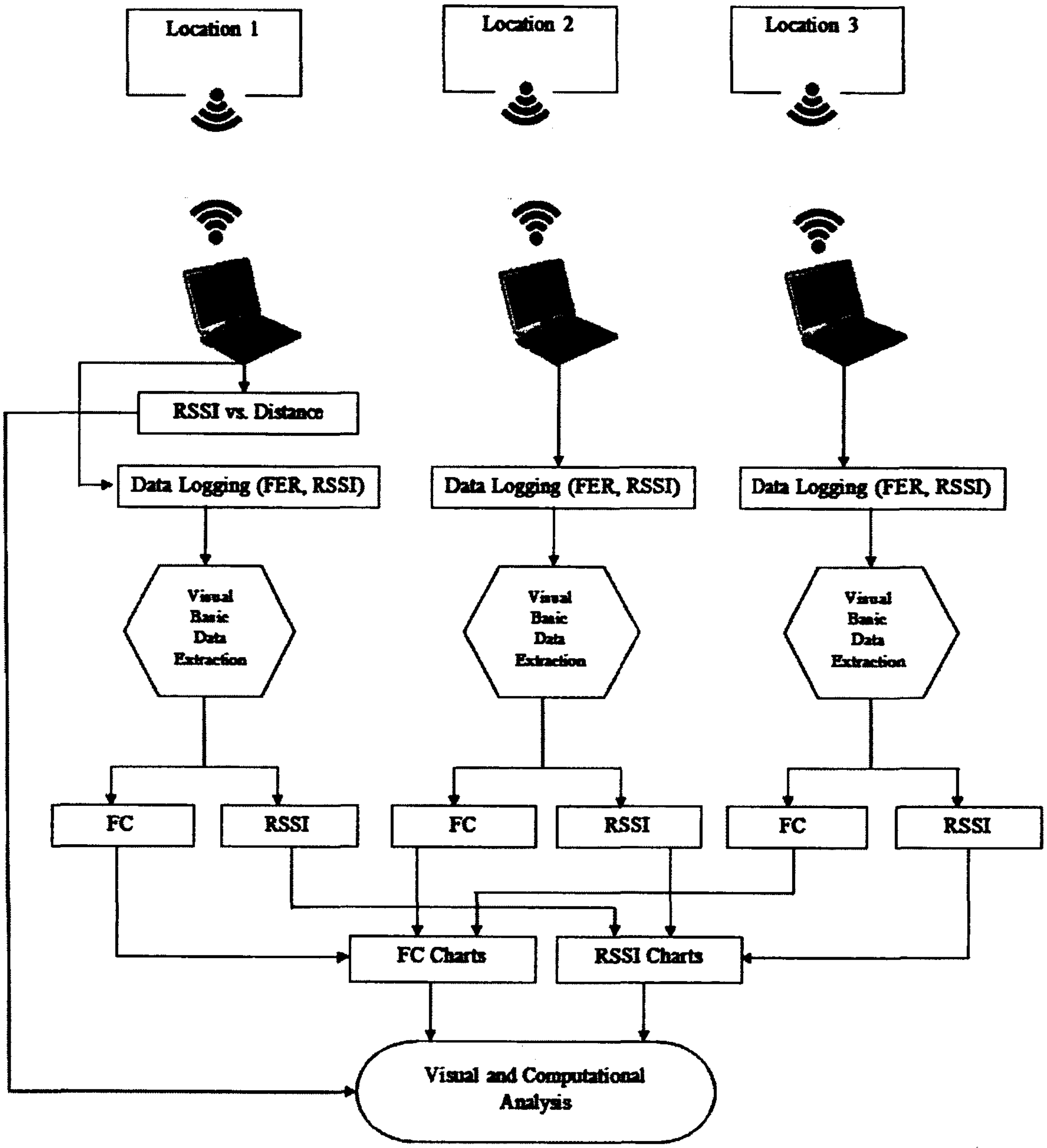

Figure 24: Functional block diagram showing the overall wireless system scheme used in this research

CHAPTER IV

RESULTS

Getting the received signal strength index (RSSI) values was the first attempt to check the RSSI signal at each manufacturing environment. For the purpose of this experiment, the setup of the wireless nodes was established as described in Chapter III. A host station was determined to be a fixed station, where a wireless node was connected to a computer with LabView™ to capture the RSSI data. The LabView™ was designed to record the frame rate per second. One end node device was planted at a desired distance from the host node. The distance was then increased and the RSSI value was recorded at the receiver node.

One of the main objectives of this proposed project was to complete a visual and computational analysis on the captured data. The analysis included transmitted power, received power, signal losses, the RSSI value, and the change in frame rate.

Each RSSI signal was captured and recorded as in Figures 25 through 36 at a distance ranging from 3 meters to 42 meters respectively. Using the graphical user interface (GUI) to measure the RSSI was only limited to the manufacturing laboratory at the University of Northern Iowa. The log file method was used in the other industrial locations to perform the same analysis at the real industrial locations.

Path-Lost Exponent Study

Path-Lost Exponent Study of First Scenario

A manufacturing laboratory was the first source of industrial environment selected for this study. For the purpose of this experimental study, two wireless nodes were configured to form a star topology network and placed at the production laboratory of the University of Northern Iowa. One wireless node was connected to a station computer and the other node was configured to be the mobile node. Each node was loaded with a script that will allow the two nodes to communicate securely and exchange performance parameters by sending and receiving test messages. The stationary node was configured to receive messages. Each message contains the signal quality parameters such as the RSSI, and the frame error rate. The received signal strength of each message was visually measured with respect to time. Because the sender node had the capability to be relocated, the RSSI values were measured with respect to time and distance. The values were recorded visually using the LabView™ data acquisition software. There are two phases of this case: the first phase is a visual, real time simulation that provides the user with the ability to monitor RSSI signals and detect any variations due to any processes that might occur in the manufacturing laboratory. The processes can be summarized as manufacturing or production activities such as welding, CNC operations, metal casting. Metal casting was one of the processes that characterize the industrial locations as harsh environment due to the emissions of gases, mold, heat, and melted metals as shown in Figure 19. The figure gives an example of the type of the manufacturing applications that occurred during the experiment. This application is called metal casting and it involves producing high temperatures, molds, and solid particles in the air that will affect the propagation of signals. The electromagnetic fields produced by the machining processes might interfere with other frequencies such as wireless connections of the WSN operating on 916 MHz.

The distance variation between the transmitter and the receiver can cause significant variation in the received signal strength. Another significant change might be due to the stationary or movable obstacles characterized by a parameter called the "path lost". Because the signals in this experiment is not transmitted in vacuum but in air and in addition to the existence of objects, humans, and other activities, this type of interference introduces additional challenges to the to the frequency signal attenuation that can be included in the path lost exponent.

The received signal power is inversely proportional to the frequency and distance between the receiver and the transmitter. It is directly proportional to the transmitted power according to this equation:

Received Power: $P_{received}(d) = \frac{P_{tx}.G_t.G_r.\lambda^2}{(4\pi)^2.d^2.L}$

Where P_t is the transmitted power in mW, G_t is the transmitter gain, G_r is the receiver gain, λ is the wavelength, d is the distance between transmitter and receiver, L is the losses due to circuitry. The received power can also be measured with respect to a reference received power according to this formula:

Power Received: $P_{received}(d) = P_{received}(d_0) . \left(\frac{d_0}{d}\right)^{\gamma}$

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)} \right)}{\ln\left({d_0}/{d}\right)} \tag{11}$$

Where d_0 is the reference distance such that d≥d0. For cellular systems (frequencies in GHz) d_0 is selected to be 1km, but for short range frequencies such as WLAN's d_0 is in the range of 1m. γ is the path lost exponent.

RSSI can be calculated using a reference value according to this equation:

$$\text{RSSI} = -(10\text{n}\log_{10}\text{d} + \text{A}) \tag{12}$$

Where n is the signal propagation constant, and A is the received signal strength at 1 m.

The manufacturer transmitted power was given as:

$P_t(\text{dBm}) = +8\text{dBm}$

Converting from dBm to mill watts is given in this equation:

$$P_t(mWatts) = 10^{P_{dBm}/10} = 10^{+8/10} = 6.309\, mW$$

The wavelength at 916 MHz can be determined by:

$$\lambda = \frac{velocity}{frequency} = \frac{3 * 10^8 m/s}{916 * 10^2/s} = \frac{1}{3.0533} m$$

Assuming that there are no losses, then:

G_t=G_r=1 and L=1, then the theoretical value of the received power can be simplified to:

$$P_{received}(d) = \frac{6.309 * 1 * 1 * (\frac{1}{3.0533})^2}{(4 * \pi)^2 * d^2 * 1} = \frac{0.004285}{d^2} mW$$

The reference power at 1 m can be deduced to be:

$$P_{received}(d_0) = P_{received}(1m) = 0.004285\, mW$$

$$P_r(dBm) = 10 \times \log(0.004285) = -23.68\, dBm$$

The RSSI values shown in Figure 25 are in the form of straight line with some positive spike values that are equal to 0.005mW due to the sensitivity of the RF antenna.

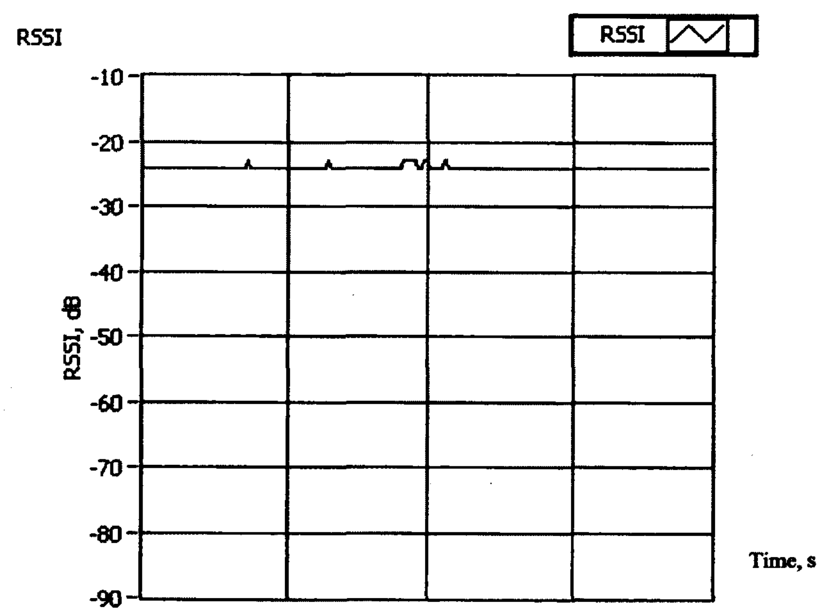

Figure 25: RSSI signal at distance of 2.1 meters

The observed values at distance of 2.1m are:

Measured received power:

$$P_r(dBm) = -24\ dBm$$

$$P_r(mW) = 10^{P_{dBm}/10} = 10^{-24/10} = 0.00398\ mW$$

Expected Path Lost Exponent can be calculated using the formula (13):

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(\frac{0.005}{0.004285}\right)}{\ln\left(\frac{1}{2.1}\right)} = 0.099$$

The expected received power and the path-lost exponent are calculated by applying the equations (11) and (12):

Expected received power:

$$P_{received}(2.1) = \frac{0.004285}{d^2} == 0.00097\ mW$$

$$P_{received}(2.1) = 10 \times \log(0.00097) = -30.12dBm$$

Therefore, the expected path-lost exponent is found as follows:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)} \right)}{\ln\left({d_0}/{d} \right)} = \frac{\ln\left({0.00097}/{0.004285} \right)}{\ln\left({1}/{2.1} \right)} = 1.99$$

Results at 5.1meters in Figure 26 reflected some fluctuation in the RSSI signal due to an increase in the distance between the transmitter node and the sender node and therefore, more interference was found in the data link between the sender node and the receiver node.

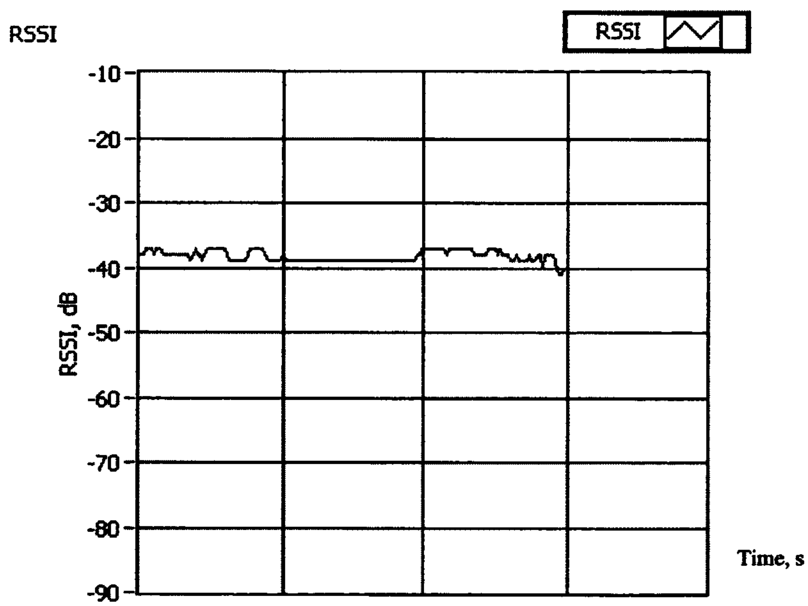

Figure 26: RSSI signal at distance of 5.1 meters

The observed values at distance of 5.1m are:

Observed received power:

$$P_r(dBm) = -39\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-39/10} = 0.000126\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)} \right)}{\ln\left({d_0}/{d} \right)} = \frac{\ln\left({0.000126}/{0.004285} \right)}{\ln\left({1}/{5.1} \right)} = 2.1$$

The expected values at distance of 5.1 m are:

Expected received power:

$$P_{received}(5.1) = \frac{0.0042851}{d^2} = \frac{0.004285}{5.1^2} = 0.000165\ mW$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)} \right)}{\ln\left({d_0}/{d} \right)} = \frac{\ln\left({0.000165}/{0.004285} \right)}{\ln\left({1}/{5.1} \right)} = 1.99$$

The results at the distance of 8.2 m became more stable and they are depicted in Figure 27.

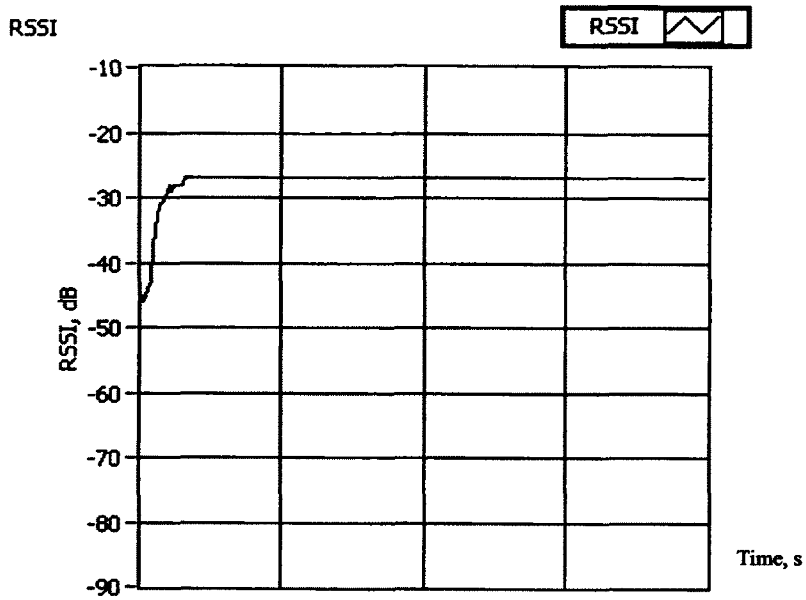

Figure 27: RSSI signal at distance of 8.2

The observed values at distance of 8.2 m are:

Observed received power:

$$P_r(dBm) = -28\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-28/10} = 0.00158\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(\frac{0.001586}{0.004285}\right)}{\ln\left(\frac{1}{8.2}\right)} = 0.4727$$

The expected values at distance of 8.2 m are:

Expected received power:

$$P_{received}(5.1) = \frac{0.004285}{d^2} = \frac{0.004285}{5.1^2} = 6.38 \times 10^{-5}\, mW$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)} \right)}{\ln\left({d_0}/{d} \right)} = \frac{\ln\left({6.38 \times 10^{-5}}/{0.004285} \right)}{\ln({1}/{8.2})} = 1.99$$

Results in Figure 28 at distance of 11.5 were constant and stable. At this distance, the sender location was deployed at a higher elevation which made the two wireless nodes, the sender and the receiver, communicating with no obstacles. However, the RSSI signal was decreased as the distance increased.

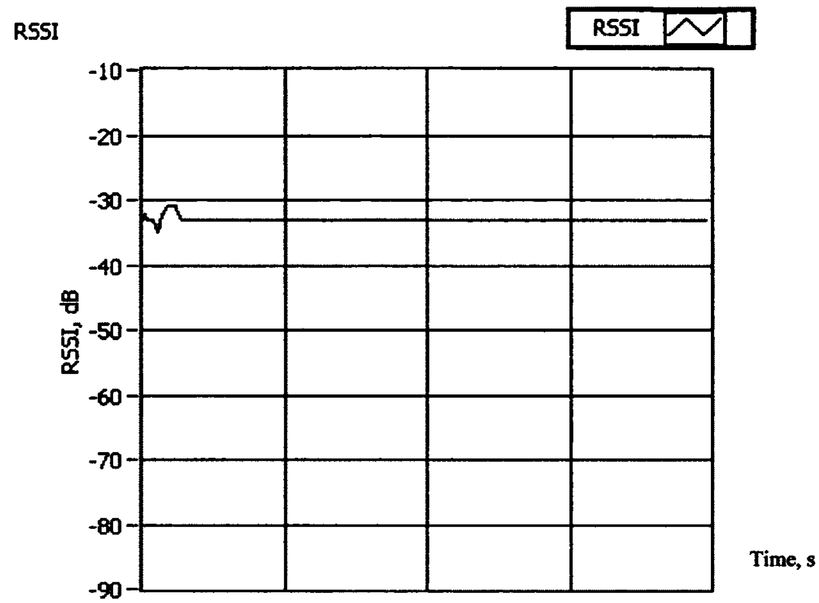

Figure 28: RSSI signal at distance of 11.5 meters

The observed values at distance of 11.5 m are:

Observed received power:

$$P_r(dBm) = -34\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-34/10} = 0.000398\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(0.000398/0.004285\right)}{\ln\left(1/11.5\right)} = 0.973$$

The expected values at distance of 11.5 m are calculated as follows:

Expected received power:

$$P_{received}(11.5) = \frac{0.004285}{d^2} = \frac{0.004285}{11.5^2} = 3.244 \times 10^{-4}\, mWatts$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)} \right)}{\ln\left({d_0}/{d} \right)} = \frac{\ln\left({3.244 \times 10^{-4}}/{0.004285} \right)}{\ln\left({1}/{11.5} \right)} = 1.99$$

Results at the distance of 14.6 meters in Figure 29 also indicated constant value of RSSI relative to the distance.

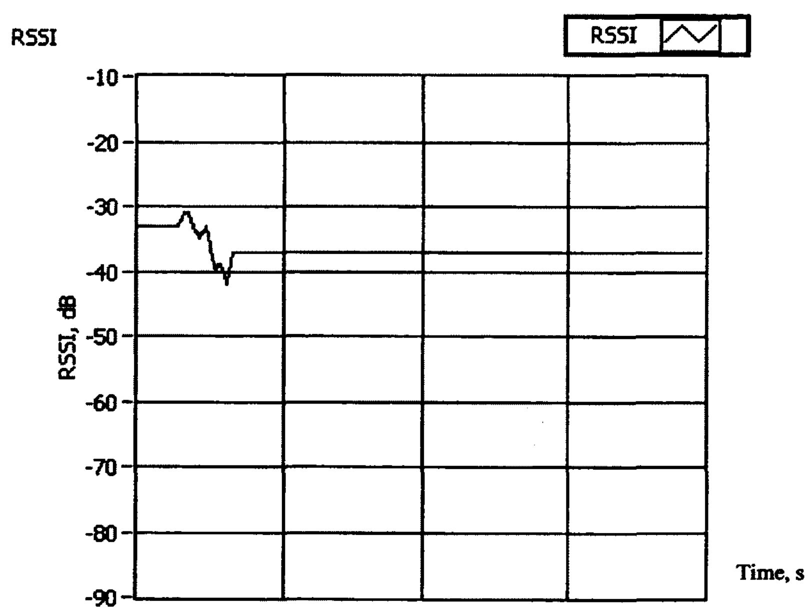

Figure 29: RSSI signal at distance of 14.6 meters

The observed values at distance of 14.6 m are:

Observed received power:

$$P_r(dBm) = -37\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-37/10} = 0.000199\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(\frac{0.000199}{0.004285}\right)}{\ln\left(\frac{1}{14.6}\right)} = 1.143$$

The expected values at distance of 14.6 m are calculated as follows:

Expected received power:

$$P_{received}(14.6) = \frac{0.004285}{d^2} = \frac{0.004285}{14.6^2} = 2.01 \times 10^{-5}\ mW$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(\frac{2.01 \times 10^{-5}}{0.004285}\right)}{\ln\left(\frac{1}{14.6}\right)} = 1.99$$

At a distance 26.8 meters, RSSI had more variation versus time because the sender node was surrounded by machines and obstacles. The variation in the RSSI values was due to both the obstacles found between the sender node and the receiver node, and the EMI produced by machines.

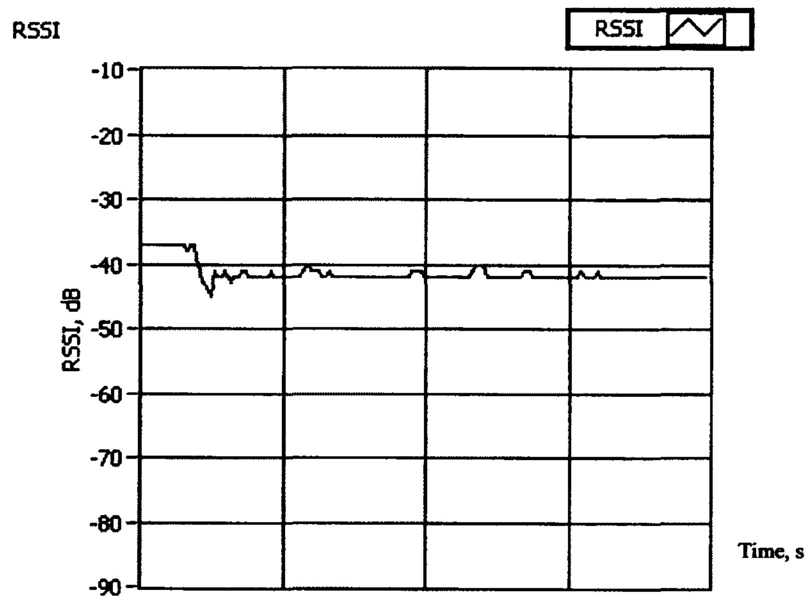

Figure 30: RSSI signal at distance of 26.8 meters

The observed values at distance of 26.8 m are:

Observed received power:

$$P_r(dBm) = -42\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-42/10} = 0.0000631\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)} \right)}{\ln\left({d_0}/{d} \right)} = \frac{\ln\left({0.0000631}/{0.004285} \right)}{\ln\left({1}/{26.8} \right)} = 1.283$$

The expected values at distance of 26.8 m are calculated as follows:

Expected received power:

$$P_{received}(26.8) = \frac{0.004285}{d^2} = \frac{0.004285}{26.8^2} = 5.97 \times 10^{-6}\ mW$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)} \right)}{\ln\left({d_0}/{d} \right)} = \frac{\ln\left({5.97 \times 10^{-6}}/{0.004285} \right)}{\ln\left({1}/{26.8} \right)} = 1.99$$

Results at distance of 28.3 meters are found to be fluctuating due to the surrounding disturbance such as machinery and other interference as depicted in Figure 31.

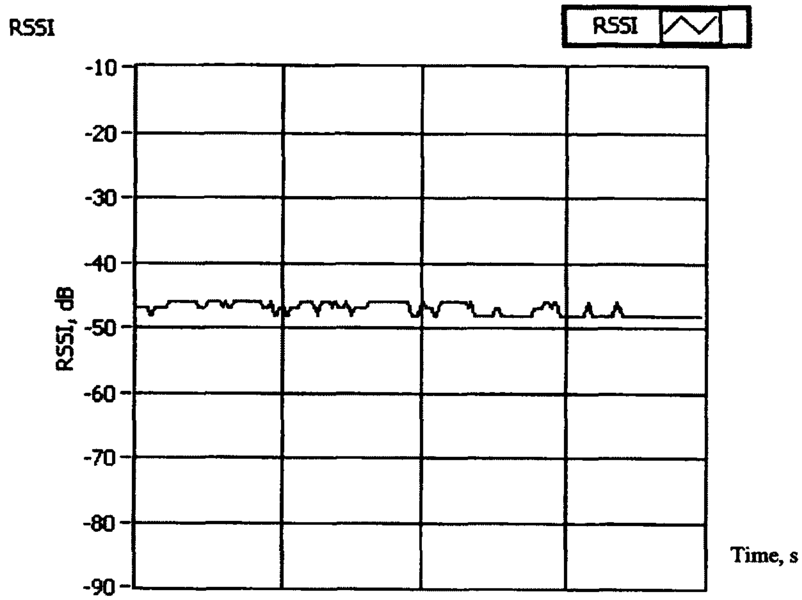

Figure 31: RSSI signal at distance of 28.3 meters

The observed values at distance of 28.3 m:

Observed received power:

$$P_r(dBm) = -48\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-48/10} = 0.0000158\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left(P_r(d)/P_r(d_0)\right)}{\ln\left(d_0/d\right)} = \frac{\ln\left(0.0000158/0.004285\right)}{\ln\left(1/28.3\right)} = 1.675$$

The expected values at distance of 28.3m are:

Expected received power:

$$P_{received}(28.3) = \frac{0.004285}{d^2} = \frac{0.004285}{28.3^2} = 5.36 \times 10^{-6}\, mW$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(\frac{5.36 \times 10^{-6}}{0.004285}\right)}{\ln\left(\frac{1}{28.3}\right)} = 1.99$$

Results at distance of 31.7 meters are shown in Figure 32.

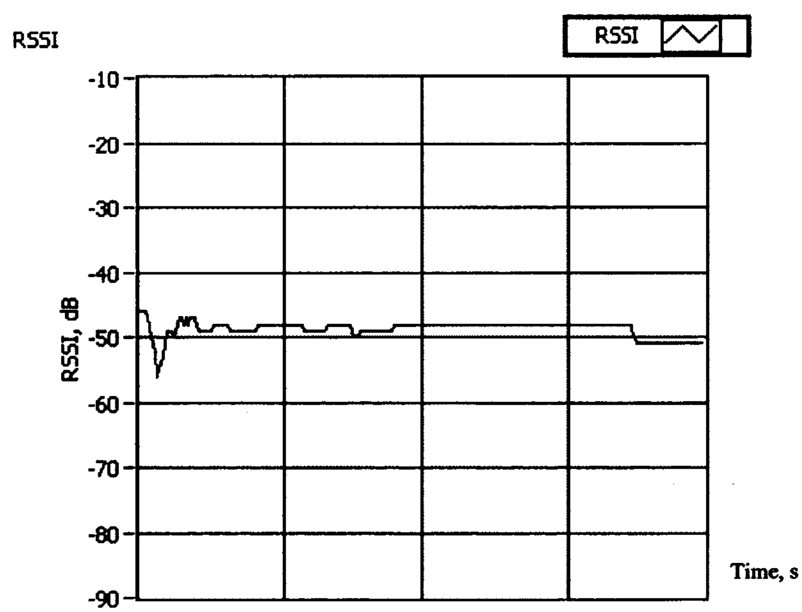

Figure 32: RSSI signal at distance of 31.7 meters

The observed values at distance of 31.7 m are:

Observed received power:

$$P_r(dBm) = -49\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-49/10} = 0.0000126\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)}\right)}{\ln\left({d_0}/{d}\right)} = \frac{\ln\left({0.0000126}/{0.004285}\right)}{\ln\left({1}/{31.7}\right)} = 1.69$$

The expected values at distance of 31.7 m are calculated as follows:

Expected received power:

$$P_{received}(31.7) = \frac{0.004285}{d^2} = \frac{0.004285}{31.7^2} = 4.267 \times 10^{-6}\ mW$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)}\right)}{\ln\left({d_0}/{d}\right)} = \frac{\ln\left({4.267 \times 10^{-6}}/{0.004285}\right)}{\ln\left({1}/{31.7}\right)} = 1.99$$

Results at distance of 33.2 meters are represented in Figure 33:

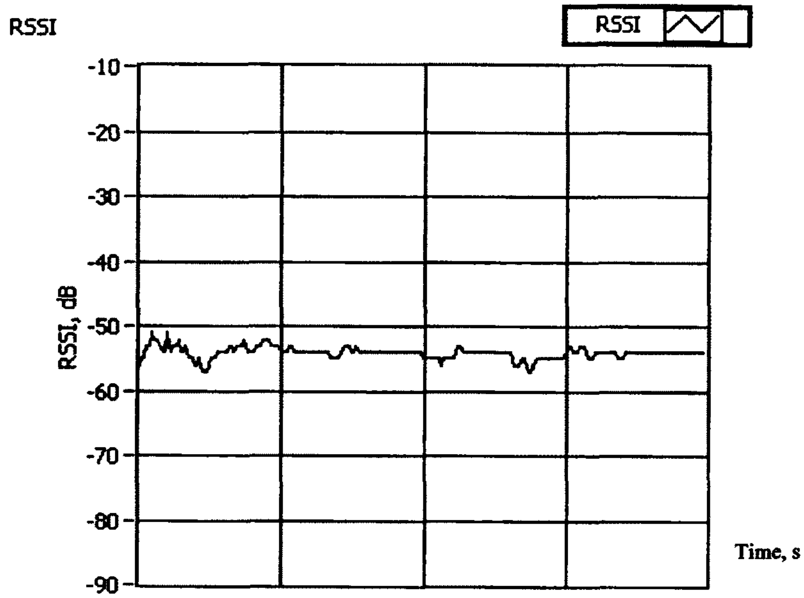

Figure 33: RSSI signal at distance of 33.2 meters

The observed values at distance of 33.2 m are:

Observed received power:

$$P_r(dBm) = -54\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-54/10} = 3.98 \times 10^{-6}\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(\frac{0.00000398}{0.004285}\right)}{\ln\left(\frac{1}{33.2}\right)} = 1.99$$

The expected values at distance of 33.2 m are calculated as follows:

Expected received power:

$$P_{received}(33.2) = \frac{0.004285}{d^2} = \frac{0.004285}{33.2^2} = 3.893 \times 10^{-6}\, mW$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)} \right)}{\ln\left({d_0}/{d} \right)} = \frac{\ln\left(3.893 \times 10^{-6}/{0.04285} \right)}{\ln(1/{33.2})} = 1.99$$

Results at distance of 34.7 meters are shown in Figure 34 and have very changing RSSI values but within a moderate range.

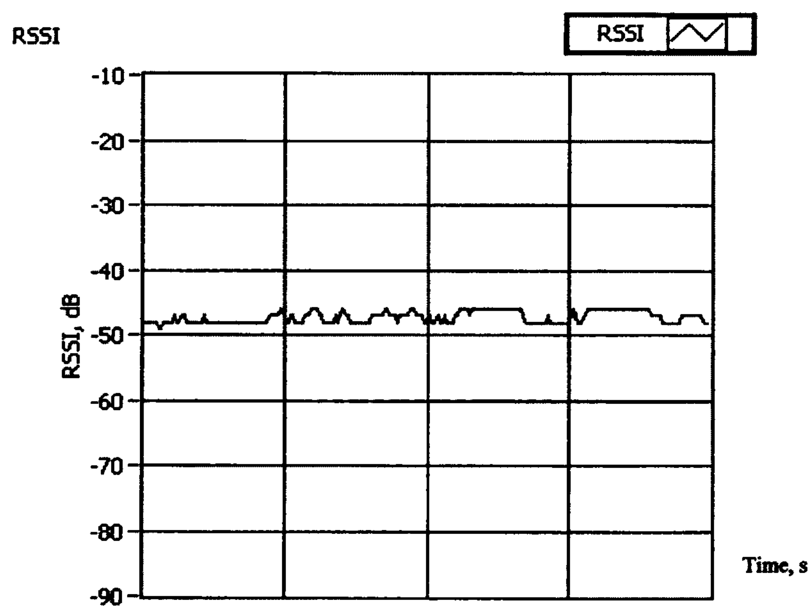

Figure 34: RSSI Signal at Distance 34.7 meters

The observed values at distance of 34.7m are:

Observed received power:

$$P_r(dBm) = -48\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-48/10} = 0.0000158\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(\frac{0.0000158}{0.004285}\right)}{\ln\left(\frac{1}{34.7}\right)} = 1.58$$

The expected values at distance of 34.7 m are calculated as follows:

Expected received power:

$$P_{received}(34.7) = \frac{0.004285}{d^2} = \frac{0.004285}{34.7^2} = 3.56 \times 10^{-6}\ mW$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(\frac{3.56 \times 10^{-6}}{0.004285}\right)}{\ln\left(\frac{1}{34.7}\right)} = 1.99$$

Results at distance of 38.4 meters are found to be with some negative spikes as shown in Figure 35.

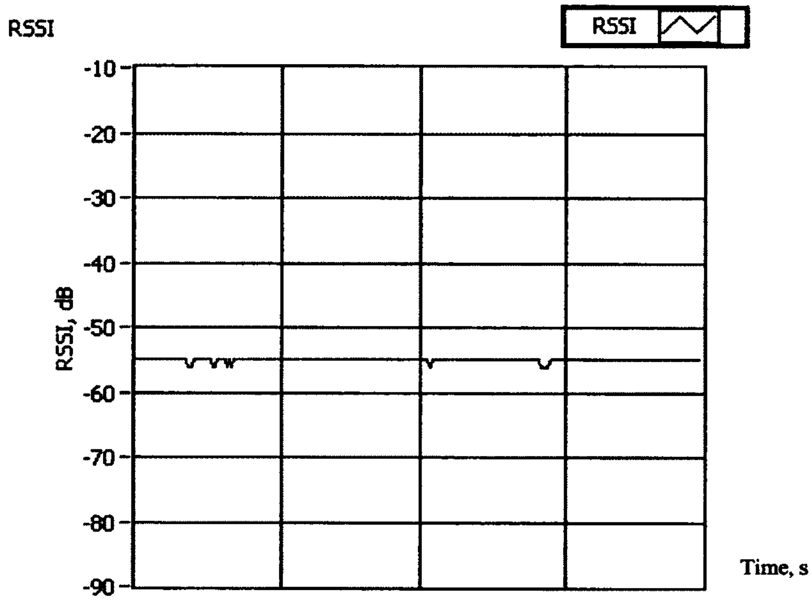

Figure 35: RSSI signal at distance 38.4 meters

The observed values at distance of 38.4 m are calculated as follows:

Observed received power:

$$P_r(dBm) = -55\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-55/10} = 0.00000316\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(\frac{0.00000316}{0.004285}\right)}{\ln\left(\frac{1}{38.4}\right)} = 1.98$$

The expected values at distance of 38.4 m are calculated as follows:

Expected received power:

$$P_{received}(38.4) = \frac{0.004285}{d^2} = \frac{0.004285}{38.4^2} = 2.9 \times 10^{-6}\ mW$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left(\frac{P_r(d)}{P_r(d_0)}\right)}{\ln\left(\frac{d_0}{d}\right)} = \frac{\ln\left(\frac{2.9 \times 10^{-6}}{0.004285}\right)}{\ln\left(\frac{1}{38.4}\right)} = 1.99$$

Results at distance of 41.5 meters were determined to be smooth as shown in Figure 36.

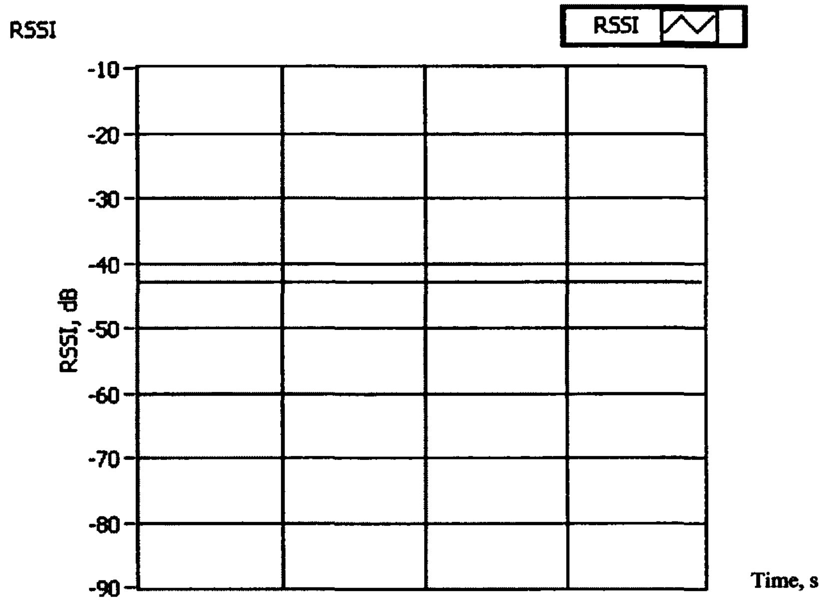

Figure 36: RSSI signal at distance of 41.5 meters

The observed values at distance of 41.5 m are:

Observed received power:

$$P_r(dBm) = -43\ dBm$$

$$P_r(mWatts) = 10^{P_{dBm}/10} = 10^{-43/10} = 0.0000501\ mW$$

Observed path-lost exponent:

$$\gamma = \frac{\ln\left(P_r(d)/P_r(d_0)\right)}{\ln\left(d_0/d\right)} = \frac{\ln\left(0.0000501/0.004285\right)}{\ln\left(1/41.5\right)} = 1.19$$

The expected values at distance of 41.5 m are calculated as follows:

Expected received power:

$$P_{received}(41.5) = \frac{0.0131}{d^2} = \frac{0.0131}{41.5^2} = 2.49 \times 10^{-6}\ mW$$

Expected path-lost exponent:

$$\gamma = \frac{\ln\left({P_r(d)}/{P_r(d_0)}\right)}{\ln\left({d_0}/{d}\right)} = \frac{\ln\left({2.49 \times 10^{-6}}/{0.004285}\right)}{\ln\left({1}/{41.5}\right)} = 1.99$$

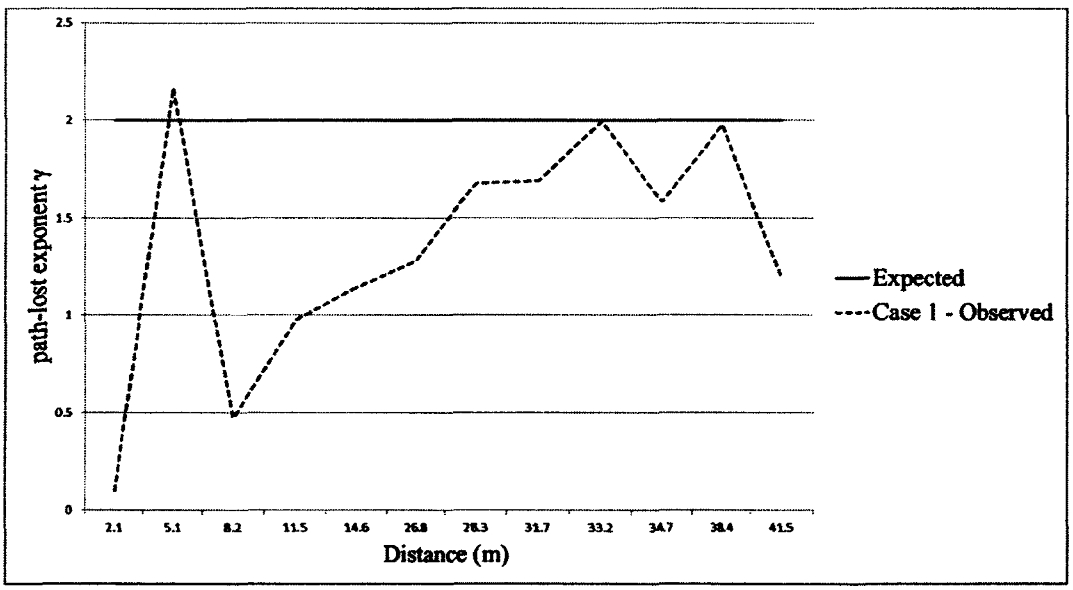

Figure 37: Path-lost exponent γ observed in the manufacturing laboratory at the University of Northern Iowa compared to expected values

Table 4

First scenario of observed path-lost exponent compared to expected

Distance (m)	Expected γ	Observed γ – Case1
2.1336	1.998	0.099
5.1816	1.999	2.165
8.2296	1.999	0.472
11.5824	1.999	0.973
14.6304	1.999	1.144
26.8224	1.999	1.283
28.3464	1.999	1.675
31.6992	1.999	1.687
33.2232	1.999	1.993
34.7472	1.999	1.579
38.4048	1.999	1.977
41.4528	1.999	1.194

Summary of the manufacturing laboratory scenario in calculating the path-lost exponent is shown in Figure 37 and Table 4. The path-lost exponent (γ) was noticed to be less than the expected values at smaller distances. At distance of 28m, the value of the path-lost exponent started to get closer to the expected values and matched at distances 33.2m and 38.4m. It should be noted that at a distance of 5.1 m, the measured path-lost exponent was about 3 which is more than expected due to the calibration of the wireless sensor nodes at the beginning of the experiment.

Path-Lost Exponent Study of Second Scenario

In the previous section, a detailed description of the path-lost calculation was reported in the manufacturing laboratory at the University of Northern Iowa. The results were captured in real time graphs and the user was able to modify the desired locations easily due to the flexibility of that environment. However, in the practical industrial environment, the real-time method was not supported by a Midwestern Manufacturing Company, and obtaining the results was more problematic due to the restrictions of the environment and safety limitations. An overall study of the location was planned and certain locations were selected to match the ones in the previous test as shown in Figure 38.

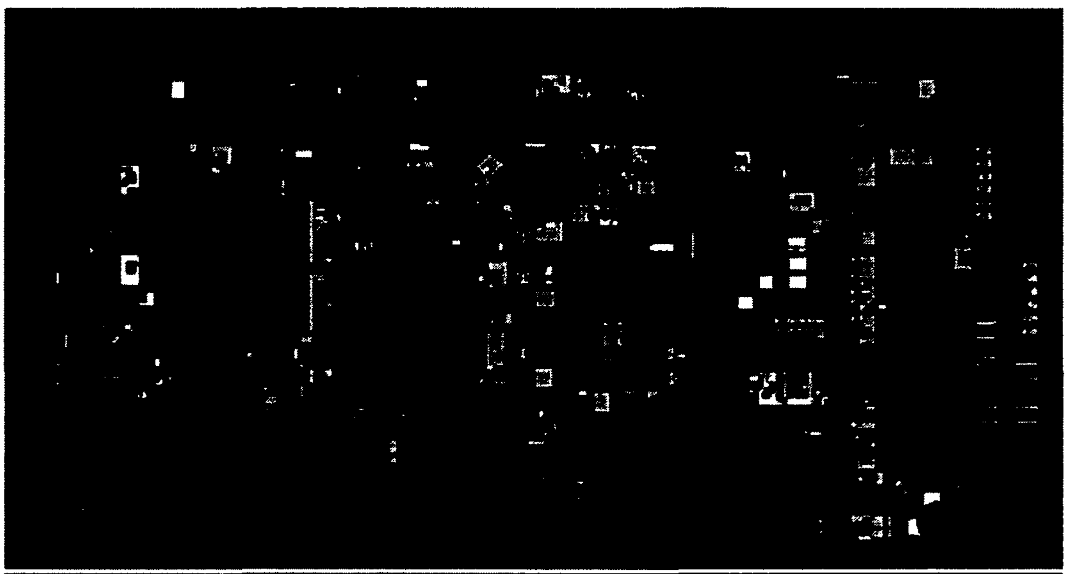

Figure 38: CAD factory layout showing the locations of ZigBee nodes deployed

In Figure 38, the receiving node is shown in the black rectangle, and all the black circles represent the positions of the sending node. The outcome of the data collected was a log file that stored all the information about the network status including the RSSI values and the Frame Error rate. The graph shown in Figure 39 was obtained using the data collected.

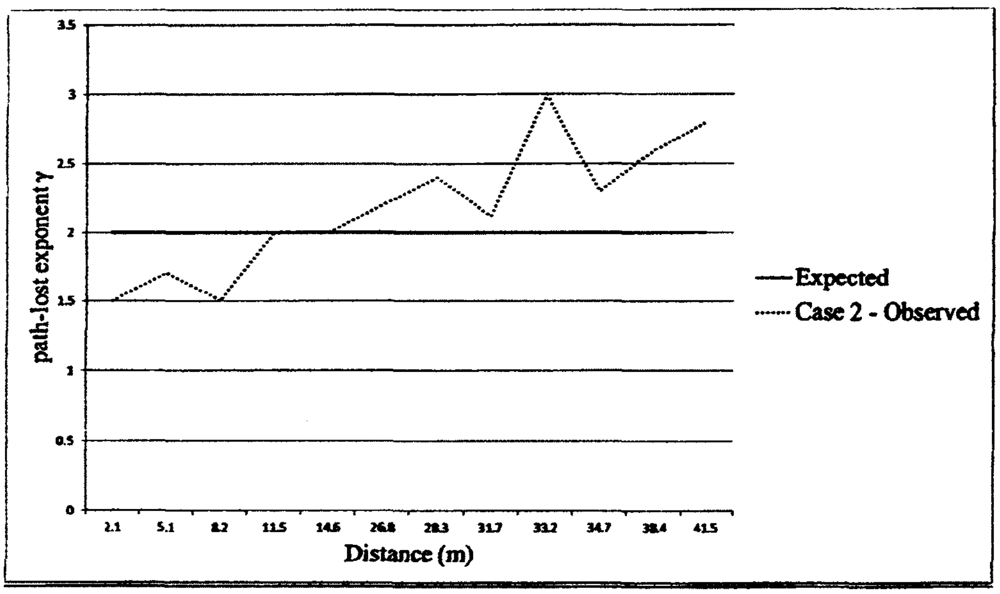

Figure 39: Path-lost exponent observed in the first real industrial environment compared to expected values

Table 5

Second scenario of observed path-lost exponent compared to expected

Distance (m)	Expected γ	Observed γ – Case2
[redacted]		
5.1816	1.99	1.7
[redacted]		
11.5824	1.99	2
[redacted]		
26.8224	1.99	2.2
[redacted]		
31.6992	1.99	2.12
[redacted]		
34.7472	1.99	2.3
[redacted]		
41.4528	1.99	2.8

Figure 39 indicates that the values at close distances between the sender node and the receiver node are lower than the expected values. At a distance close to 14 m, the path-lost exponent starts to increase indicating that this industrial environment has more obstacles that disturb the WSN wireless signal. In addition, in the industrial location, the wireless signal was propagating with a path-lost exponent that reached the value of 3.0 which is larger than the expected and even larger than the path-lost signal in the first scenario.

Path-Lost Exponent Study of Third Scenario

In this scenario, the path-lost signal reached a maximum value of 3.5 which is higher than the first and second scenario. Compared to the expected values, the path-lost exponent was generally higher. It was noticed in Figure 40, that the path-lost exponent was higher than the expected values except at two locations where it matched the expected vales at distances 11.5m and 33.2m. This concludes that when industrial environments can be more complicated for the path-lost exponent which may cause its value to increase.

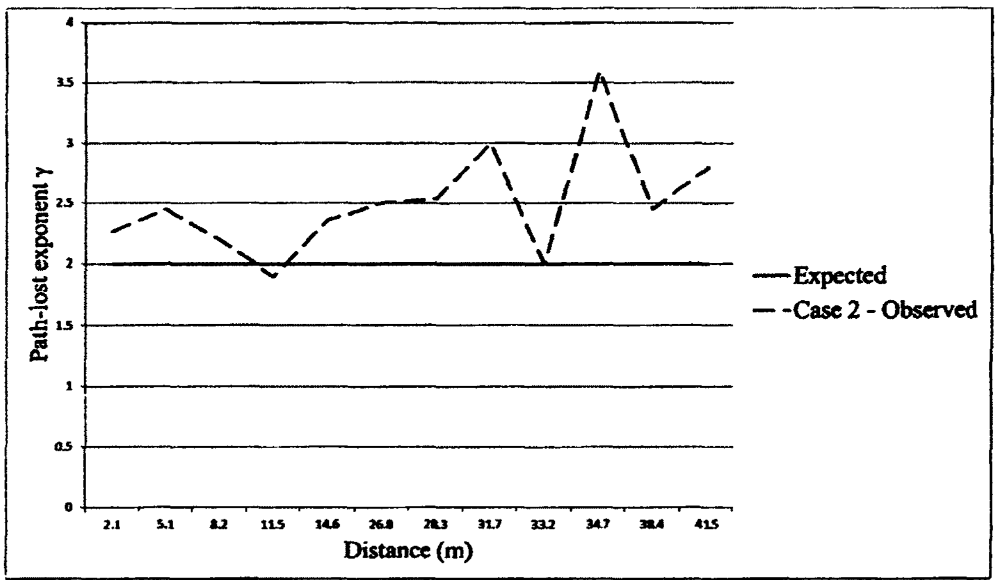

Figure 40: Path-lost exponent observed in the second real industrial environment compared to expected values

Table 6

Third scenario of observed path-lost exponent compared to expected

Distance (m)	Expected γ	Observed γ – Case3
[redacted]		
5.1816	1.99	2.45
[redacted]		
11.5824	1.99	1.9
[redacted]		
26.8224	1.99	2.5
[redacted]		
31.6992	1.99	3.02
[redacted]		
34.7472	2.05	3.62
[redacted]		
41.4528	2.05	2.8

Summary of Path-Lost Exponent Results

The path-lost exponent was verified to have an average value in certain environments such as educational and engineering buildings. But practically, this value can sometimes be less due to the constructive interference. This was proved by calculations based on the values provided by the manufacturer of the WSN module used in this experiment. Path-lost exponent indicates the obstacles and the interferences affecting the wireless signal. The proposed research project showed that the path-lost exponent can increase with the increase of the distance mainly because of the increased interference aroused by the obstacles. In educational buildings, the path-lost signal reached the expected value whereas in practical industrial buildings, the values were above the expected. Figure 41 summarized the results of the path-lost exponent acquired at each location. In case 2, the path-lost exponent maintained the expected values between the distances of 11.5 meters and 14.6 meters. It also started from a value that it is less than the expected and started to increase until it reached a value of 2.8. In case 3, the path-lost exponent started at a value larger than the expected by 0.3, and reached a maximum value of 3.6 which is larger than the expected by 1.6.

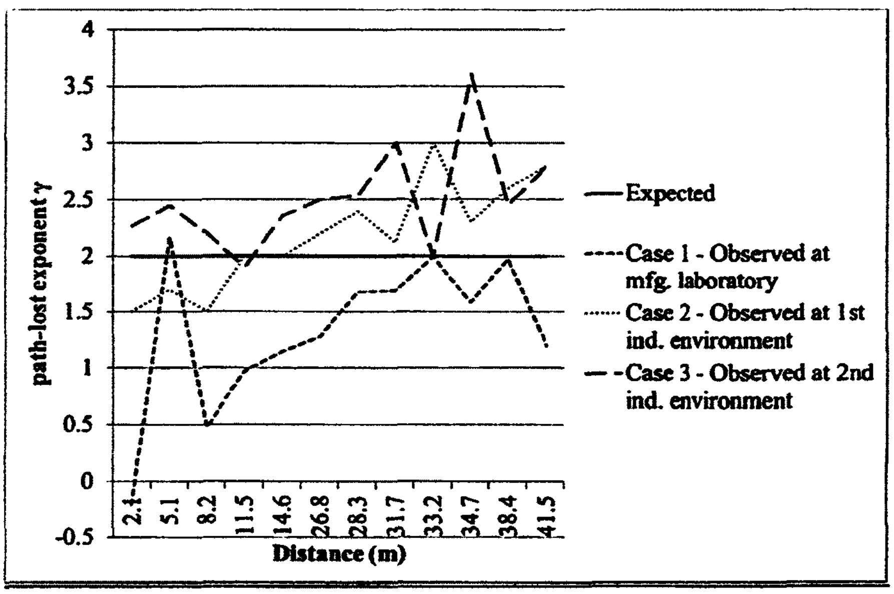

Figure 41: Path-lost exponent observed at three locations and compared to expected: (1) manufacturing laboratory, (2) first industrial environment, (3) second industrial environment

RSSI Study

RSSI Study of First Scenario

In this study, the RSSI values were collected from the stored log file. An average value was determined for each desired distance. The RSSI follows a principal that describes the relationship among the transmitted power, the received power of wireless signals, and the distances between the nodes. This principal was described in Equation (11) and applied in case 1 which was the expected values for this experiment.

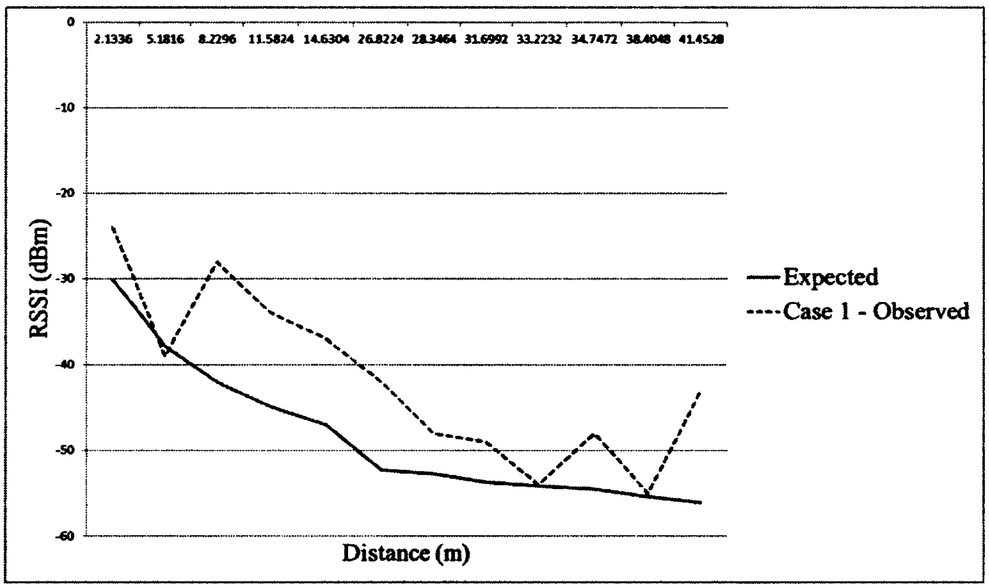

Figure 42: Average RSSI observed in the manufacturing laboratory at the University of Northern Iowa compared to expected values

The results of the RSSI values in the manufacturing laboratory were close to the expected values. The RSSI values were just above the expected values because it had less interference and obstacles that was already proved in the path-lost exponent. The values of the RSSI in case 1 were generally decreasing as the distance was increasing as shown in Figure 42.

Table 7

First scenario of observed RSSI values compared to expected

Distance (m)	Expected RSSI (dBm)	Observed RSSI (dBm)
[redacted]		
5.1816	-37.82	-39
[redacted]		
11.5824	-44.88	-34
[redacted]		
26.8224	-52.23	-42
[redacted]		
31.6992	-53.69	-49
[redacted]		
34.7472	-54.48	-48
[redacted]		
41.4528	-56.03	-43

Figure 42, shows the relationship between the distance and the RSSI values. One exception in this graph was at distance 5.1m, the RSSI showed a sudden decrease in its value due to the path-lost exponent value fond previously. Otherwise, the RSSI values behaved normally despite of being above the expected. Therefore, the RSSI in this scenario is in general close to the expected values especially at large distances. The distance range between 8.2m to 28.3m showed an increase in the RSSI values more than the expected but preserved its relation to the distance variation. This was explained by the relationship between the sender node and the receiver node such as having less interference, machinery operations, or in some cases constructive interference.

RSSI Study of Second Scenario

Similar to the first scenario, the RSSI values relative to the distance showed an expected decrease as distance increases. For distances ranging between 2.1m to 26m, the RSSI values were very close to the expected values. But at larger distance values, the RSSI values were impacted by the industrial environment conditions including busy location with metallic obstacles and noisy manufacturing operations. Therefore, the RSSI values showed the maximum variation at the distance of 33m when it dropped under -60dBm.

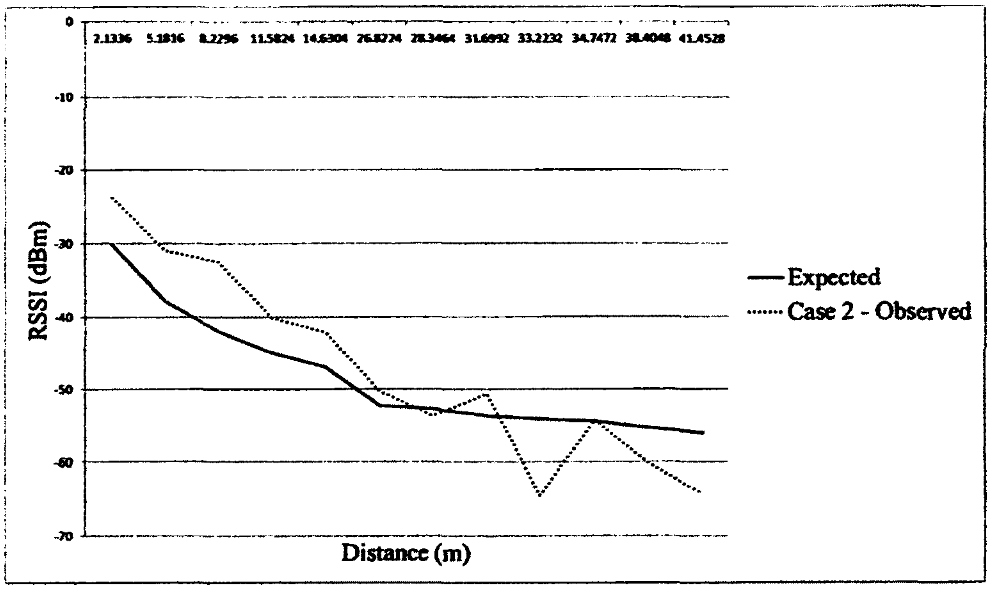

Figure 43: Average RSSI observed in the first real industrial environment and compared to expected values

Table 8

Second scenario of observed RSSI values compared to expected

Distance (m)	Expected RSSI (dBm)	Observed RSSI (dBm)
2.1336	-30.11	-23.76
5.1816	-37.82	-30.97
8.2296	-41.95	-32.55
11.5824	-44.88	-40.10
14.6304	-46.96	-42.13
26.8224	-52.23	-50.25
28.3464	-52.71	-53.68
31.6992	-53.69	-50.64
33.2232	-54.09	-64.47
34.7472	-54.48	-54.26
38.4048	-55.36	-60.02
41.4528	-56.035	-64.11

RSSI Study of Third Scenario

The second industrial location included more environmental conditions than the previous environments (manufacturing laboratory and first industrial location). Therefore, the values of the RSSI were expected to be less especially at larger distance values. Figure 44 demonstrates these findings. For example, or the distance ranging between 2.1m to 28m, the values of the RSSI were very close to the expected values (case1) but there were more variations noticed at larger distance especially at 34m where the RSSI value reached its minimum value of -73dBm. An exception in this range was at distance of 33.2m where the RSSI value was identical to the expected value. Such value can be explained by the position of the sender node in a location where it had less obstacles and direct line of view with the receiver node and therefore, less path-lost exponent value.

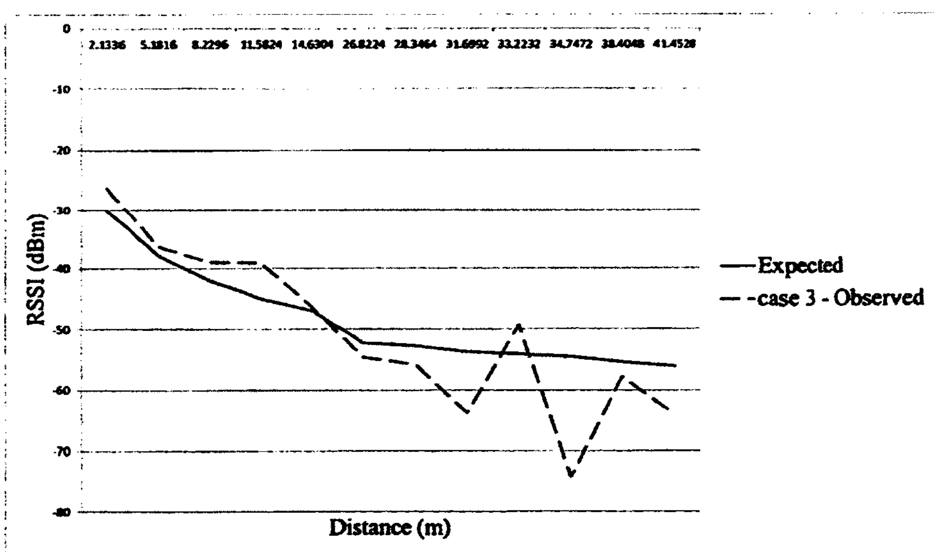

Figure 44: Average RSSI observed in the second real industrial environment and compared to expected values

Table 9

Third scenario of observed RSSI values compared to expected

Distance (m)	Expected RSSI (dBm)	Observed RSSI (dBm)
2.1336	-30.11	-26.30
5.1816	-37.82	-36.36
8.2296	-41.95	-38.96
11.5824	-44.88	-39.03
14.6304	-46.96	-46.36
26.8224	-52.23	-54.53
28.3464	-52.71	-55.79
31.6992	-53.69	-63.85
33.2232	-54.09	-49.25
34.7472	-54.48	-74.30
38.4048	-55.36	-57.71
41.4528	-56.03	-64.11

Summary of RSSI Results

The RSSI was verified to be indirectly proportional with distance between sender node and receiver node. Figure 45 shows how RSSI values change from one environment to another. Case 1 represents the RSSI values observed at the manufacturing laboratory at the University of Northern Iowa that are relatively close to the expected values. Case 2 represents the RSSI values at the first Industrial location showing more fluctuation than case. Case 3 representing the second industrial location had the maximum fluctuation. Case 1and 2 represented the best performance of RSSI at lower distances ranging between the distance of 2.1m to 28m.

For distance values higher than 28 m, case 2 included less fluctuation than the expected values. Therefore, at each industrial location, the RSSI signal varied depending on the environment conditions.

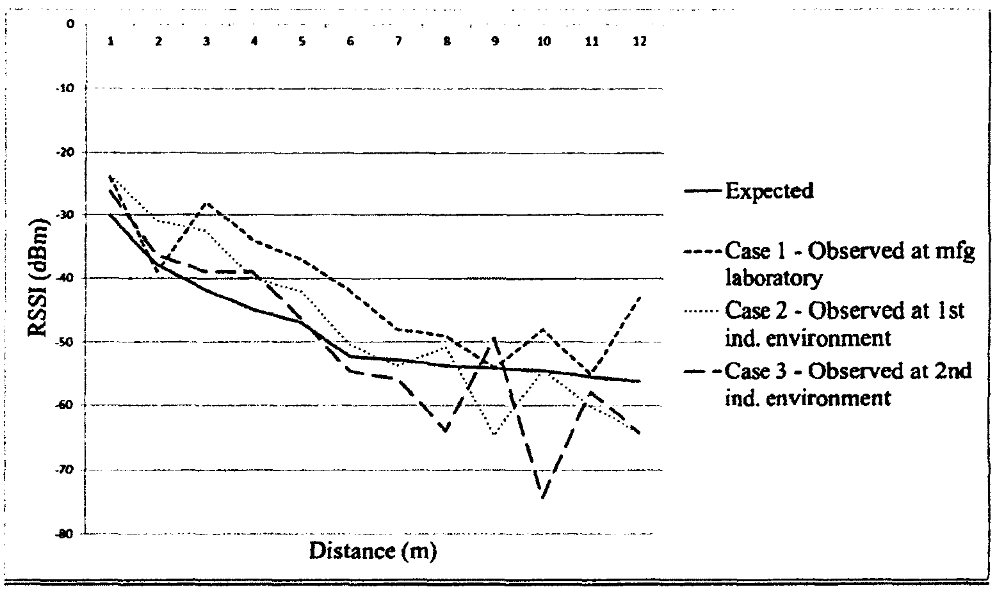

Figure 45: RSSI observed at three locations and compared to expected: (1) manufacturing laboratory, (2) first industrial environment, (3) second industrial environment

Table 10

Summary of RSSI at the manufacturing laboratory at University of Northern Iowa

Distance (meter)	Expected RSSI (dBm)	Observed RSSI (dBm)	Expected path-lost γ	Observed path-lost γ	% γ Difference
2.1336	-30.119	-24	1.998	-0.211	95.030
5.1816	-37.826	-39	1.999	2.165	-8.298
8.2296	-41.951	-28	1.999	0.473	76.356
11.5824	-44.889	-34	1.999	0.973	51.341
14.6304	-46.962	-37	1.999	1.144	42.788
26.8224	-52.237	-42	1.999	1.283	35.849
28.3464	-52.710	-48	1.999	1.675	16.226
31.6992	-53.696	-49	1.999	1.687	15.645
33.2232	-54.097	-54	1.999	1.993	0.320
34.7472	-54.481	-48	1.999	1.579	21.042
38.4048	-55.361	-55	1.999	1.977	1.140
41.4528	-56.036	-43	1.999	1.194	40.289

Frame Error Study

Frame Error Study of First Scenario

A log file similar to the one in Appendix C was generated for the manufacturing laboratory experiment that concluded zero frame error rates. This means that the frame counter that was used to count the repeated frames had a value of zero. The algorithm used in the ZigBee network was counting the repeating frames. Each frame that was failed to be received by the sender was sent again. Once a frame was resent, the frame counter was incremented by one and so forth.

Frame Error Study of Second Scenario

The manufacturing environment selected at a Midwestern Company was selected to be the second case of the study. This environment was characterized by a moderate level of human presence, but contained several machining processes including drilling, testing, cutting, assembling, and transportation using automatic guided vehicles as shown in Figure 38.

Figure 38 is a top view of the manufacturing area that was selected to collect the wireless information about the WSN Network performance. The area is characterized by multiple manufacturing processes that communicate with each other using "mistake proofing" to eliminate waste of materials and increase productivity. WSN devices can be integrated with these processes to eliminate the use of wires and increase mobility. Therefore, it is important to test measure the losses of the wireless messages between the sender node and the receiver node. The sender wireless node was deployed at several locations as indicated in the factory layout as shown in Figure 38. The receiver wireless node was connected to a fixed computer and was setup to track the Frame Counter (FC). The values were stored in a local log file that was analyzed after collecting the data. The function of the Visual Basic script was to:

1- Extract the frame counter and the RSSI values to an excel sheet.

2- Deduce the measure path lost γ associated with each distance.

3- Plot charts of the measured path lost against distance and compare the resulted to the calculated values.

4- Sort the repeated frames by their number of occurrences.

5- Create a histogram showing the frequencies of repeated frames and deduce the longest frame error.

Moreover, using the log file was a better method for the frame counter because it allowed storing larger database whereas the visual GUI can only be used for instant reading.

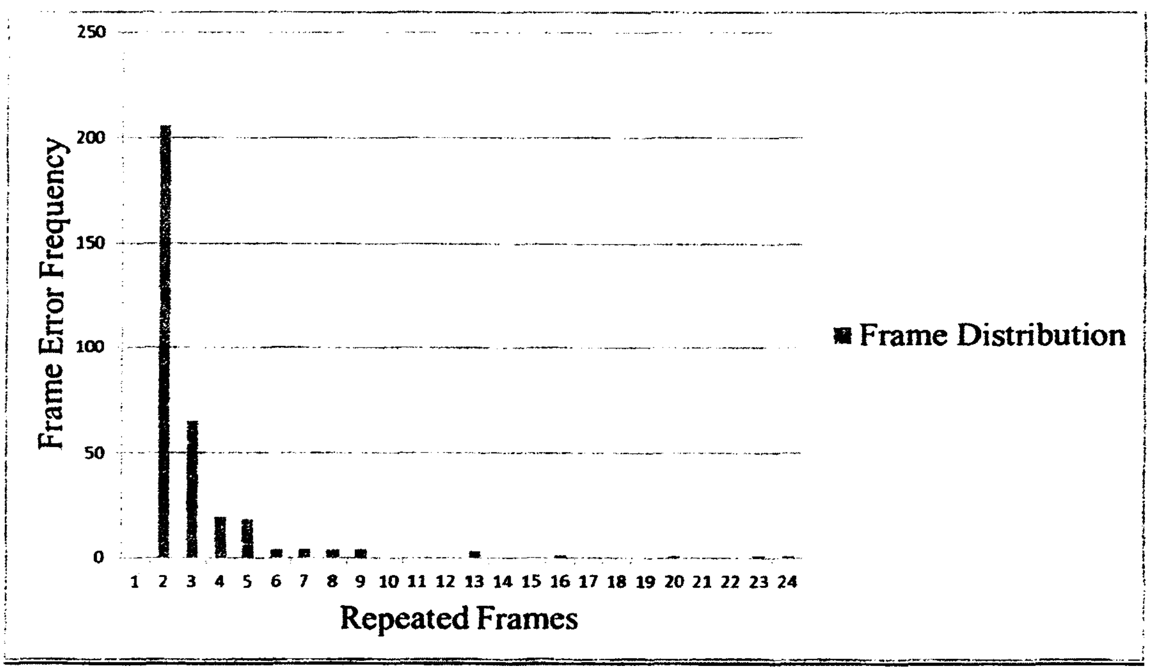

Figure 46: Frame error distribution of first industrial environment based on the values of the frame counter

Figure 46 shows that the maximum frame error rate occurred at a frequency of 24. However, at the frequency 2, there were more than 200 frames which were repeated two times. Although the repeated frames with frequency of 2 was the highest, but the frequency with 24 times was much more concern because it indicates that the same frame was repeated for many times resulting the wireless network connection to be disconnected during the repetition. Therefore, the longest repetition means the maximum disconnection time between the sender node and the receiver node referred to heavy interference caused by EMI and obstacles. Appendix D is a table showing the data collected for error frame of the second industrial environment.

Frame Error Study of Third Scenario

The frame error rate varied from the first location because the environmental conditions became harsher on the wireless signal transmission. However the maximum discontinue time stayed the same, about 24 seconds, but there was a significant increase in the frame distribution. For example, the discontinue time at 24 seconds had been noticed to repeat fifty times whereas as oppose to the first location, it only occurred one time. Comparing Figures 46 and 47, the error rate in the second was much higher which indicated that industrial environments with heavy metallic objects, machinery operations, and EMI behave harsh on WSN performance. Appendix E is a table showing the data collected for error frame of the third industrial environment.

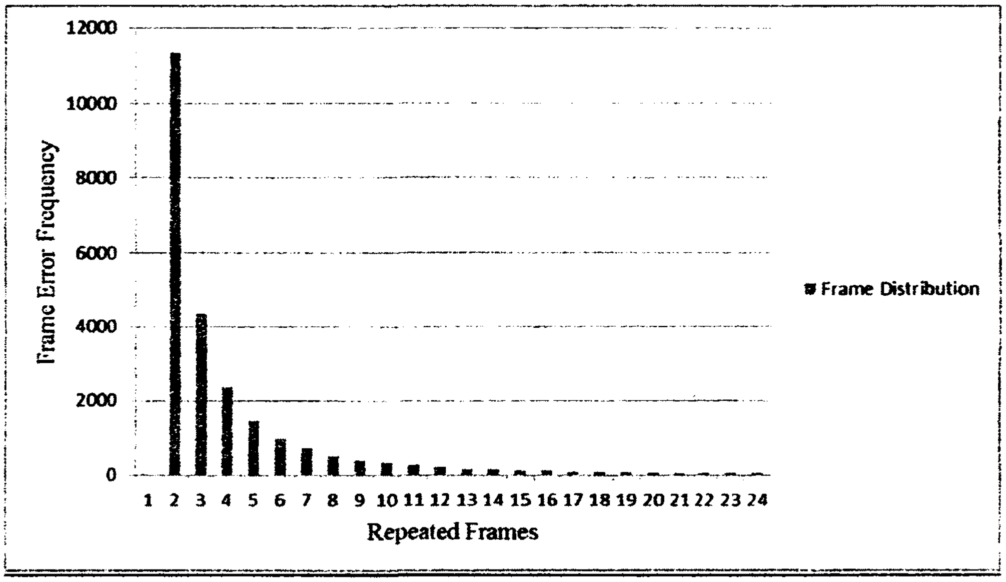

Figure 47: Frame error distribution of second industrial environment based on the values of the frame counter

Summary of Frame Error Results

The results of the frame error rate show that in real industrial environments the frame error rate do exist and vary by obstacles, environment, and distance. One evidence on that is by comparing the results between the two environments that shows a significant increase in the frame error rate.

Line Passing Experiment

The objective of line passing was to establish digital and analog input/output between two WSN modules without additional hardware and test the performance.

Digital Line Passing

Each XBee module has eight digital input/output. Only Two digital I/O selected for digital line passing. D0 and D1 were selected for digital input on the sender module and for digital output on the receiver module.

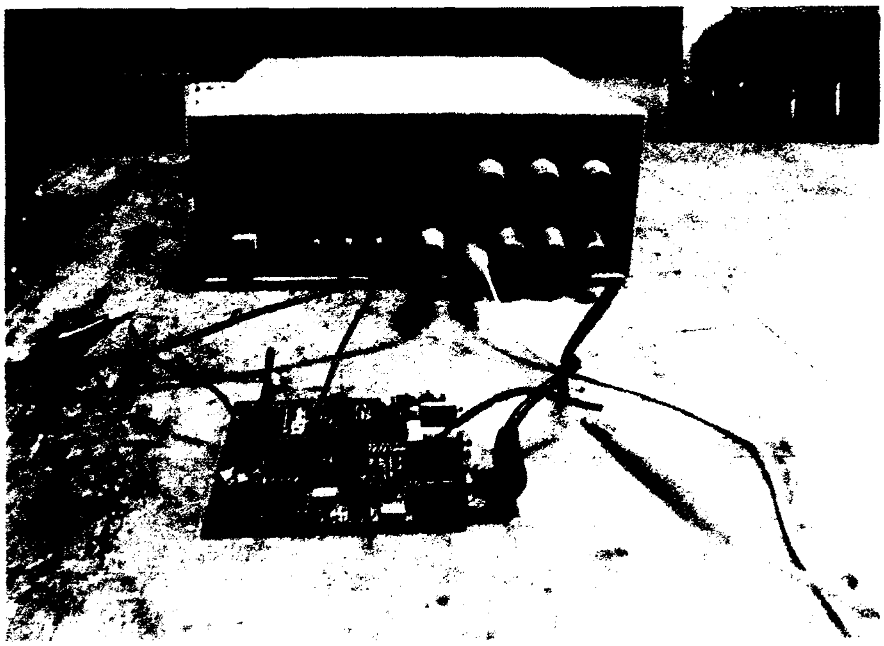

Figure 48: Sender module connected to power supply simulating digital line passing

The inputs on the sender module were connected to a power supply simulating the input digital data as shown in Figure 48. The receiver module was connected to a host computer that will receive a frame once the number of samples is reached. As shown in Figure 49, the sampling rate selected was 50 ms. Number of samples per wireless transmission was 44 samples. Since only D0 and D1 are selected as digital inputs, the output was expected to be one of the following in hexadecimal:

1. (00) if the inputs D0 and D1 are low
2. (01)if the inputs Do is high and D1 is low
3. (02) if the inputs Do is low and D1 is high
4. (03) if the inputs D0 and D1 are high

```
Base
DL=0x5678
MY=0x1234
D0=0x4
D1=0x4
D,2...7=0
T0=0x64
IA=0x5678
ATWR
ATCN

REMOTE
DL=0X1234
MY=0X567
D0=0X3
D1=0X3
D2...D7=0
IC=0X3
IT=0X44
IR=0X32
```

Figure 49: Configuration of XBee modules

```
Read data:
00000000: [illegible]
00000010: 03 00 03 00 03 00 03 00   03 00 03 00 03 00 03 00   [illegible]
00000020: 03 00 03 00 03 00 03 00   03 00 03 00 03 00 03 00   [illegible]
00000030: 03 00 03 00 03 00 03 00   03 00 03 00 03 00 03 00   ................
00000040: 03 00 03 00 03 00 03 00   03 00 03 00 03 00 03 00   ................
00000050: 03 00 03 00 03 00 03 00   03 00 03 00 03 00 03 00   ................
00000060: 03 00 03 [illegible] 7e 00 60 83   56 78 1c 00 2c 00 03 00   ...ß~. ƒVx......
00000070: 03 00 03 00 03 00 03 00   03 00 03 00 03 00 03 00   ................
00000080: 03 00 03 00 03 00 03 00   03 00 03 00 03 00 03 00   ................
00000090: 03 00 03 00 03 00 03 00   03 00 03 00 03 00 03 00   ................
```

Figure 50: Frames captured showing the output digital pins

The highlighted text in Figure 50 contains the value of the output D0 and D1 as (03) representing the number of samples. This frame was captured at the host computer connected to the receiver node.

Analog Line Passing

The analog line passing was simulated using a signal generator. Two Xbee modules were programmed. The sender module was connected to the signal generator as shown in Figure 51 with the settings:

- Destination address: 1234
- Source address: 5678
- D0 as analog input: 2
- Sample Rate: 20ms
- Number of samples: 5

Figure 51: Xbee sender module for analog line passing

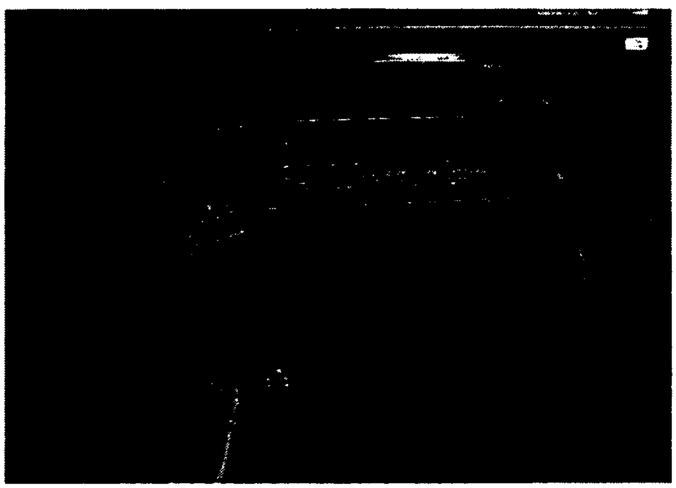

Figure 52: Xbee receiver module for analog line passing

The receiver module was connected to an oscilloscope to collect the analog data transmitted by the sender module. The receiver module is demonstrated in Figure 52.

The receiver module was programmed with the following settings to establish the connection between the input module and the output module:

- Destination address: 5678
- Source address: 1234
- Output as Pulse width modulation (P0): 2

The analog output at the receiver module is collected at the pulse width modulation (PWM) pin P0. The PWM allowed determining the amplitude of the analog input and the frequency monitored by the oscilloscope.

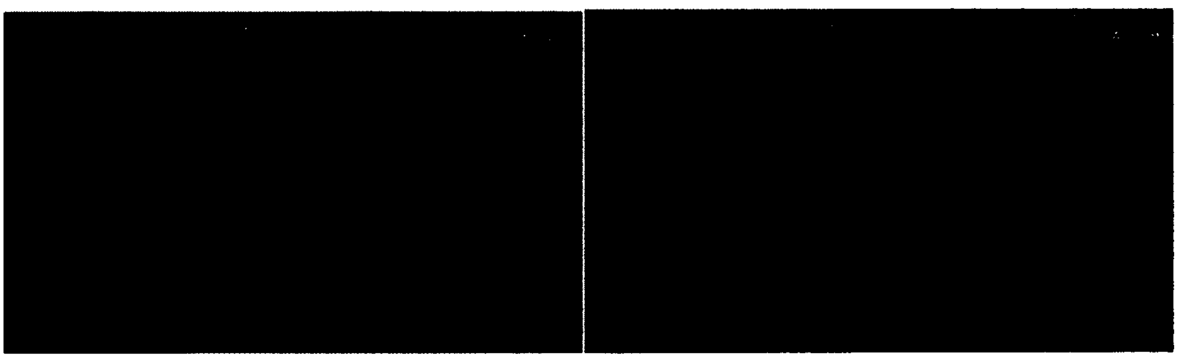

Figure 53: Oscilloscope readings for the input and output of XBee analog line passing

In Figure 53, the analog input to the sender module is shown to the left and the PWM output is shown to the right. The maximum width of the PWM represents the amplitude of the analog input.

Performance Test

The objective of the performance test is to find out the error rate of the WSN modules in industrial settings. This was done by comparing the number of packets transmitted and the number of packets received. Any lost packet detection was counted as an error.

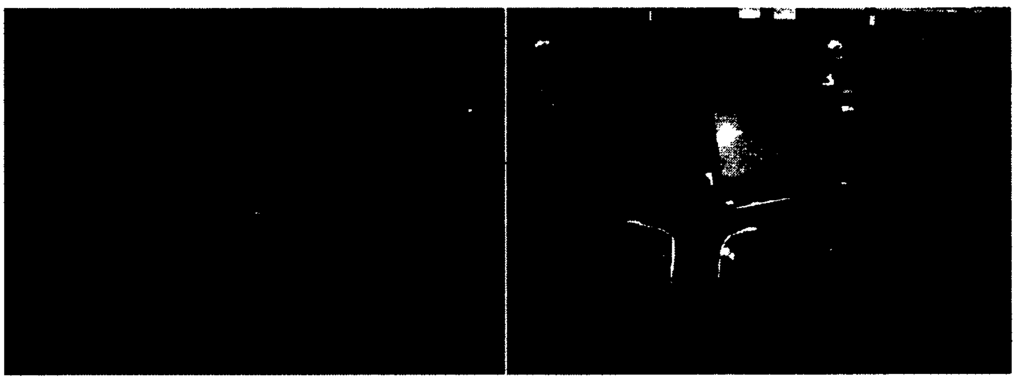

Figure 54: Performance test stations for packet error rate

In order to calculate the raw data, transmission retries were disabled when failed to receive acknowledgement of receiving a packet. This allowed calculating any error in the transmission due to interference in the environment.

Figure 54 shows the test stations in a manufacturing setting. The left is the sender module and the right is the receiver module. Both modules were connected to a computer to monitor the transmitted and received packets.

Two tests were administered to measure the performance of the WSN modules. The result of the first test was:

- Number of packets sent: 450
- Time delay between packets: 5 seconds
- Received packets: 436
- Error rate: 3.1%

The result of the second test was:

- Number of packets sent: 1007
- Time delay between packets: 1 seconds
- Received packets: 960
- Error rate: 4.1%

In conclusion, increasing number of packets caused increasing number of received packet error rate. However, when enabling the transmission retries a zero error rate was detected which therefore enhances the performance of WSNs in industrial settings especially with harsh environment.

CHAPTER V

CONCLUSIONS, SUMMARY, AND RECOMMENDATIONS

This dissertation focused on the study of the performance of WSNs operating at in three different industrial environments. The goal was to verify that the performance of such wireless signals can be widely used in industry and to measure its effectiveness. This study collected and evaluated three main parameters: received signal strength index (RSSI), path-lost exponent, and frame error rate. The test of the three parameters showed that with harsher industrial environment, the wireless signal quality can decrease Moreover, this study included a detailed description of simulating digital and analog data transmission in industrial setting accompanied with measuring the packet error rate.

The literature review in Chapter III provided remarkable points of the importance of the use of WSN's applications in many areas. The results and the data analysis compared in three industrial locations in Chapter IV presented the impact of the areas on the wireless signal performance and suggests for more testing. Therefore, this study was followed-up by analog and digital data transmission and the study of its performance by comparing the sent and received wireless packets. The study discussed the limitation issues of evaluating such commercial WSN's systems in industrial environments. Conclusions are drawn based on the specific research findings and outcomes. The study also provides recommendations for further studies and improvements that will be advised to evaluate and consider WSN's applications for industrial and manufacturing environments. Unlike other studies, where the focus was only on one parameter, this study provides the opportunity to analyze different multiple parameters that allows fair comparison among different levels of industrial environment and the integration of analog/digital data wireless transmission.

Study Overview and Conclusions

The evaluation of WSN's application in industrial environments was very challenging due to the availability of many commercial development kits with different protocol settings. An initial investigation was conducted to find the out the best development kit that have the characteristics to be interfaced with external applications to measure the parameters affecting the wireless signal performance. The study took place in three different locations and was selected based on the harsh environment level. The manufacturing laboratory was selected because it was known for its low level of manufacturing applications and it was limited for students' projects and classes. Therefore it was assumed that this environment would be a perfect baseline to other real industrial environments. The second industrial environment selected was known for its manufacturing processes and contained many areas of interests where wireless applications could be applicable and challenging. The third industrial location was similar to the second but contained larger equipment, and heavier manufacturing applications. In fact, it was an assembly line of a Midwestern Manufacturing Company. This study was developed based on an initial study that showed that RSSI might not be the only variable to test. The search recommended the use of more advanced hardware systems that are easier to communicate and they can store data for longer time periods. One of the challenges in this test was the battery lifetime. It is very important to take into consideration the battery lifetime. Because a wireless node was operating on battery, it was crucial to filter out the results that related to battery failure. Therefore, in WSN's applications, it is very important to choose wireless nodes that have long lifetime, and make sure that the node switches to the sleep mode when it is not in use.

In this study, each wireless node required enough power supply to transmit signals. The implemented study is mainly based on the transmission power conservation based on a parameter Receiving Signal Strength Index (RSSI), distance, and environment. The study verified that RSSI decreases as distance increases, but it also showed the practical facts concerning the RSSI measurements affected by reflections on metallic objects, electro-magnetic fields, and refraction by media with different propagation velocity. Thus, the RSSI measurements showed more variation from the expected in the real industrial environments.

Due to the fact that the RSSI does not directly represent the environment affecting the radio signals, the aim was to measure the path-lost exponent to show the characteristics of each environment. The path-lost exponent also changed for each time an RSSI value was generated. The path-lost signal was determined by the RSSI value generated. Therefore, if an RSSI value was different than the expected a new path-lost exponent was found. It was assumed the all the locations selected were engineering building which should have the same theoretical path-lost exponent. In this study the theoretical value was verified with the ZigBee characteristics. The results illustrated that at small distance values the path-lost exponent was not affected, but at large distances the path-lost exponent showed higher values than expected values. Also, at large distance values, the path-lost exponent showed higher values in the real industrial environment than the manufacturing laboratory. It also showed that the characteristics of the second industrial environment had more impact than the first industrial environment which was also true for the RSSI measurement.

This study was not limited to studying the radio power. It also included studying the frames lost for each wireless message exchanged by the sender node and the receiver node. Because the sender node resent the wireless messages that were not received by the receiver node, a record for each wireless message was saved and then the repeated frames were calculated in Figures 46 and 47. The manufacturing laboratory results did not indicate any issues with the frame error rate. However, both the first and second industrial locations showed repeated frames. It was noticed that the maximum repeated frames were the frames that had been resent twice by the sender node. Although, this value was the maximum, the study does not recognize this case as an issue compared to frames that were repeated twenty four times. This can be explained by the fact that a frame that was repeated twice took approximately a second, but the frames that were repeated twenty four times took about 24 seconds. Longer waiting time for the network might be very critical to the WSN's application performing certain operation. In manufacturing operations, there are some applications that may require zero waiting time while other applications may consider twenty four seconds as very large waiting time. This study focused on the waiting time that can be associated with WSN's applications.

Finally, this study required to implement a method for analog and digital data transmission in order to transmit and receive external data that was not generated by the system. Also the study was followed by a packet error rate to determine the packets lost in the air due to the environment. The latest test showed that the average packet rate was determined as 3.6%. It also showed that the number of error rate increased as number of sent packets was increased.

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APPENDIX A

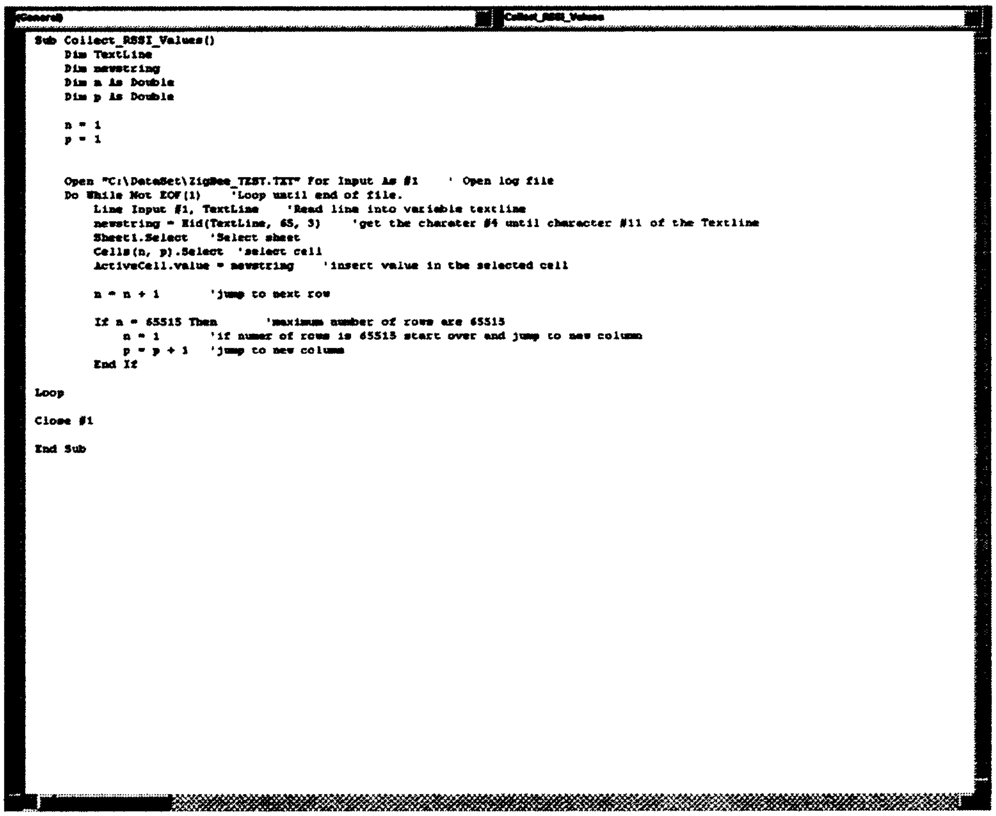
VB SCRIPT COLLECTING FC VALUES

(General) | Collect_FC_Values

```
Sub Collect_FC_Values()
    Dim TextLine
    Dim newstring
    Dim n As Double
    Dim p As Double

    n = 1
    p = 1


    Open "C:\DataSet\ZigBee_TEST.TXT" For Input As #1    ' Open log file
    Do While Not EOF(1)    'Loop until end of file.
        Line Input #1, TextLine    'Read line into variable textline
        newstring = Mid(TextLine, 4, 11)    'get the charater #4 until character #11 of the Textline
        Sheet1.Select   'Select sheet
        Cells(n, p).Select  'select cell
        ActiveCell.value = newstring    'insert value in the selected cell

        n = n + 1       'jump to next row

        If n = 65515 Then       'maximum number of rows are 65515
            n = 1       'if numer of rows is 65515 start over and jump to new column
            p = p + 1   'jump to new column
        End If

Loop

Close #1

End Sub
```

APPENDIX B

VB SCRIPT COLLECTING RSSI VALUES



```
(General)                                   Collect_RSSI_Values

Sub Collect_RSSI_Values()
    Dim TextLine
    Dim newstring
    Dim n As Double
    Dim p As Double

    n = 1
    p = 1


    Open "C:\DataSet\ZigBee_TEST.TXT" For Input As #1    ' Open log file
    Do While Not EOF(1)    'Loop until end of file.
        Line Input #1, TextLine    'Read line into variable textline
        newstring = Mid(TextLine, 65, 3)    'get the charater #4 until character #11 of the Textline
        Sheet1.Select   'Select sheet
        Cells(n, p).Select  'select cell
        ActiveCell.value = newstring    'insert value in the selected cell

        n = n + 1       'jump to next row

        If n = 65515 Then       'maximum number of rows are 65515
            n = 1       'if numer of rows is 65515 start over and jump to new column
            p = p + 1   'jump to new column
        End If

Loop

Close #1

End Sub
```

APPENDIX C

LOG DATA FOR MANUFACTURING LABORATORY

```
FC=14969587    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969596    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969606    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969615    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969624    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969634    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969643    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969652    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969662    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969671    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969680    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969690    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969699    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969708    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969718    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969727    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969736    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969746    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969755    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969764    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969774    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969783    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969792    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969802    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969811    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969820    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969830    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969839    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969848    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969858    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969867    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969876    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969886    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969895    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969904    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969914    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969923    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
FC=14969932    FEC=37792    BEC=12374417    LQI=255    RSSI=-46dBm(45)
```

APPENDIX D

FRAME ERROR FOR SECOND INDUSTRIAL ENVIRONMENT

Frame Frequency	Frame Error Repeated
[redacted]	
2	206
[redacted]	
4	19
[redacted]	
6	4
[redacted]	
8	4
[redacted]	
10	0
[redacted]	
12	0
[redacted]	
14	0
[redacted]	
16	1
[redacted]	
18	0
[redacted]	
20	1
[redacted]	
22	0
[redacted]	
24	1

APPENDIX E

FRAME ERROR FOR THIRD INDUSTRIAL ENVIRONMENT

Frame Frequency	Frame Error Repeated
2	11345
4	2372
6	974
8	512
10	333
12	207
14	153
16	120
18	92
20	60
22	57
24	50