EVALUATION OF ZIGBEE RECEIVED SIGNAL STRENGTH INDICATOR PERFORMANCE IN INDOOR ENVIRONMENT

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A PROJECT SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF THE DEGREE OF BACHELOR OF ENGINEERING (B.ENG) IN ELECTRICAL / ELECTRONIC ENGINEERING, UNIVERSITY OF BENIN, EDO STATE, NIGERIA.

OCTOBER 2025

CERTIFICATION

We hereby declare that all works, done and ideas implemented in the project *Evaluation of ZigBee Received Signal Strength Indicator Performance in an indoor environment* were carried out by Adigwe Victor (ENG2002196), Akpan Israel (ENG2002209), Calotta Onome Obus (ENG2002278), Ehiagwina Eramhahiemhen Olumese (ENG2002229), Ehigiator Emmanuel, Osemudiame (ENG2002230), students of the Department of Electrical/Electronic Engineering, Faculty of Engineering, University of Benin, Benin City. This project was undertaken in partial fulfillment of the requirements for the award of the Bachelor of Engineering (B.Eng.) degree in Electrical/Electronic Engineering, under the supervision of Engr. O. N. Enehizena

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Date	Date

ACKNOWLEDGEMENT

We would like to express our heartfelt gratitude to all those who have supported us throughout the course of this project. First and foremost, we give thanks to God for His grace and guidance throughout this endeavor. We are grateful for the strength and wisdom He has bestowed upon us, enabling us to overcome challenges and achieve our goals.

Secondly, we extend our deepest thanks to our parents, whose unwavering love and encouragement have been our greatest source of strength. Their sacrifices and belief in our potential have inspired us to strive for excellence.

We would also like to thank the University of Benin for providing a conducive environment for learning and research. The resources and opportunities offered by the institution have been invaluable in shaping our academic journey.

A special acknowledgment goes to our project supervisor; Engr. Osatohanmwen N. Enehizena Your guidance, insightful feedback, and constant support have been instrumental in the successful completion of this report. We are truly grateful for your mentorship and encouragement.

Lastly, we would also like to appreciate our friends and classmates for their companionship and collaborative spirit. The discussions and shared experiences has enriched our learning experience and made this journey enjoyable. Thank you all for being a part of this journey.

ABSTRACT

This study examines the performance of the ZigBee Received Signal Strength Indicator (RSSI) in indoor environments, with a focus on understanding how distance and environmental obstacles influence wireless signal propagation. The research was conducted at the Faculty of Engineering, University of Benin, utilizing two ZigBee Pro S2B modules configured through XCTU software. Measurements were taken at distances ranging from 10 feet to 50 feet, under various conditions involving obstacles such as furniture, walls, and human presence.

The findings indicate that RSSI values exhibit a progressive decline with increased distance and greater obstacle density. Specifically, the signal strength diminished by approximately 4 to 6 dB for every 10-foot increment, with an additional decrease of 3 to 5 dB for every two additional obstacles encountered. It was determined that walls and human presence are the most significant factors contributing to signal attenuation, due to effects related to reflection, absorption, and scattering.

These results are consistent with theoretical path loss models and corroborate prior empirical studies, reinforcing the notion that the performance of ZigBee technology is significantly influenced by environmental conditions. The study concludes that ZigBee is well-suited for short-range, low-power Internet of Things (IoT) and sensor applications; however, optimal node placement and the implementation of mesh networking are critical for ensuring reliable communication in complex indoor environments. The insights derived from this research hold valuable implications for enhancing the design and deployment of wireless sensor networks in academic and smart-building contexts.

Contents

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

The demand for low-power, short-range, and energy-efficient wireless communication systems has experienced substantial growth, particularly within academic and research environments that significantly rely on real-time data exchange, digital learning, and laboratory automation (Alam et al., 2021). Institutions such as the University of Benin necessitate a dependable and stable wireless communication infrastructure to support both academic and research functions. Nevertheless, challenges such as Radio Frequency Interference (RFI), network congestion, and environmental obstructions frequently disrupt connectivity and compromise data reliability (Hameed et al., 2020).

ZigBee, which is based on the IEEE 802.15.4 standard, is specifically designed to address these challenges by providing a robust, low-power, and self-healing mesh network that is well-suited for Internet of Things (IoT) applications (Farahani, 2011; Kamal & Nor, 2022). This technology is widely adopted in various applications, including home automation, smart metering, environmental monitoring, and industrial control, due to its capacity to support a substantial number of nodes with minimal energy consumption (Zhang et al., 2023).

Despite its inherent advantages, the performance of ZigBee in indoor environments is considerably affected by variations in the Received Signal Strength Indicator (RSSI), which can result from physical obstacles, multipath propagation, and interference from coexisting wireless systems such as Wi-Fi and Bluetooth (Raza et al., 2022). Therefore, evaluating the RSSI performance of ZigBee under realistic indoor conditions is essential for optimizing network reliability, determining optimal node placement, and enhancing communication quality in IoT deployments (Gupta et al., 2020).

This study aims to evaluate the RSSI performance of ZigBee networks within the Faculty of Engineering at the University of Benin. The findings are anticipated to provide valuable insights into the behavior of ZigBee in complex indoor environments, assist in formulating optimal deployment strategies, and promote the adoption of energy-efficient wireless communication technologies in Nigerian institutions.

1.2 Problem Statement

Reliable wireless communication continues to pose significant challenges in indoor environments, particularly within institutions where Internet of Things (IoT) systems rely on stable data transmission. At the University of Benin’s Faculty of Engineering, communication disruptions resulting from interference, signal attenuation, and physical obstacles impede the continuity of learning and research activities.

While ZigBee is acknowledged for its low-power operation and mesh-network resilience, a number of technical challenges hinder its effectiveness. These challenges include diminished Received Signal Strength Indicator (RSSI) due to environmental obstructions, signal degradation stemming from electromagnetic interference, and uneven network coverage due to suboptimal node placement (Kamal & Nor, 2022). Furthermore, the absence of localized empirical data regarding ZigBee performance in Nigerian academic settings limits the potential for its optimized deployment.

As a result, there is a pressing need to systematically assess ZigBee RSSI behavior within indoor environments. This assessment will aid in identifying the factors that influence signal reliability and will facilitate the development of evidence-based recommendations for effective wireless network design in educational and research contexts.

1.3 Aim of the Study

The aim of this study is to evaluate the performance of ZigBee Received Signal Strength Indicator (RSSI) in indoor environments, with a focus on optimizing communication reliability and energy efficiency within the Faculty of Engineering, University of Benin.

1.4 Objectives of the Study

To achieve this aim, the study will pursue the following objectives:

To measure and analyze the RSSI values of ZigBee nodes under varying indoor environmental conditions.

To investigate the impact of physical obstacles, distance, and interference on ZigBee signal performance.

To model and interpret RSSI variation patterns to assess signal reliability and coverage stability.

To propose optimized deployment guidelines for improving ZigBee network performance in indoor IoT applications.

1.5 Research Methodology

This study employs a comprehensive experimental and analytical methodology that systematically aligns each research objective with its corresponding method:

1. Measurement and Analysis of ZigBee RSSI Values: The primary objective is to gauge and analyze the Received Signal Strength Indicator (RSSI) values of ZigBee technology under varying indoor conditions.

For this purpose, ZigBee Pro S2B modules will be strategically deployed at various locations within selected rooms and corridors of the Faculty of Engineering. RSSI data will be captured utilizing XBee USB adapters and XCTU software, exploring a range of environments, including open spaces, obstructed areas, and multi-floor layouts.

2. Investigation of Signal Performance Influencers: The second objective seeks to investigate the influence of obstacles, distance, and interference on ZigBee signal performance. This will involve conducting controlled experiments in which physical barriers, such as walls and furniture, are introduced to assess their impact on RSSI attenuation.

3. Modeling and Interpretation of RSSI Variation Patterns: The third objective aims to model and interpret the variation patterns of RSSI values. Statistical and graphical analyses—including the calculation of mean RSSI, variance evaluation, and signal loss modeling—will be executed using MATLAB and Python tools. These analyses will facilitate the understanding of relationships among distance, obstacles, and signal stability within the experimental framework.

4. Development of Optimized Deployment Guidelines: The final objective is to propose optimized deployment guidelines informed by the empirical findings. These recommendations will encompass effective strategies for the placement of ZigBee nodes, appropriate settings for transmission power, and configurations of network topology suitable for indoor environments, particularly those within academic institutions.

This systematic approach ensures that each objective is attained through a structured and quantifiable process, thereby establishing a direct linkage between experimental results and actionable design insights.

1.6 Significance of the Study

This study is of considerable significance as it offers empirical insights into the Received Signal Strength Indicator (RSSI) performance of ZigBee technology in indoor environments, thereby contributing both theoretical and practical value. Theoretically, it enhances the understanding of signal propagation behaviors and the environmental factors that impact low-power wireless communication. Practically, the findings will inform the development of optimal deployment strategies for Internet of Things (IoT) systems, particularly in academic and laboratory contexts where energy efficiency and communication reliability are of paramount importance.

Moreover, this research will:

- Assist in reducing signal interference and packet loss within indoor ZigBee networks.
- Facilitate the design of cost-effective, energy-efficient wireless infrastructure in Nigerian universities.
- Serve as a reference for engineers and researchers engaged in the development of IoT applications reliant on ZigBee technology.
- Promote local capacity building in the field of wireless communication research and performance evaluation.

1.7 Scope of the Study

This study is intended to evaluate the performance of the Received Signal Strength Indicator (RSSI) for ZigBee Pro S2B modules within the indoor environments of the Faculty of Engineering at the University of Benin. The scope of the research includes:

- The installation and configuration of ZigBee nodes and coordinators.

- The measurement of RSSI at various locations and distances, considering different environmental conditions.

- The analysis of signal attenuation, interference, and propagation characteristics.

- The formulation of recommendations aimed at enhancing ZigBee deployment in comparable institutional indoor settings.

It is important to note that this study does not encompass the evaluation of outdoor RSSI performance, the assessment of other wireless technologies (such as Wi-Fi and Bluetooth), or any advanced protocol-level modifications beyond the standard configurations of ZigBee.

CHAPTER TWO: LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Overview of Wireless Sensor Networks (WSNs)

Wireless Sensor Networks (WSNs) are comprised of spatially distributed sensor nodes that communicate wirelessly to monitor various environmental or physical conditions, such as temperature, motion, and signal strength (Akyildiz et al., 2020). Each node within a WSN is typically equipped with a sensing unit, a microcontroller, a transceiver, and a power source. This integration facilitates autonomous sensing, data processing, and transmission across the network (Yick, Mukherjee, & Ghosal, 2021).

WSNs represent a fundamental element of the Internet of Things (IoT) ecosystem, supporting a diverse array of applications, including smart homes, healthcare, industrial monitoring, and environmental surveillance (Kumar & Patel, 2022). In these systems, the effectiveness and reliability of wireless communication are crucial for ensuring accurate and timely data exchange. Among the various wireless standards available, ZigBee has emerged as a leading solution for low-power, low-data-rate sensor applications, primarily due to its energy efficiency and scalability (Sadowski & Spachos, 2018).

2.2 ZigBee Technology and Applications

ZigBee is a wireless communication protocol grounded in the IEEE 802.15.4 standard. It is tailored for short-range, low-power, and cost-effective communication, making it particularly suitable for Internet of Things (IoT) and Wireless Sensor Network (WSN) applications (Farahani, 2011). The protocol primarily operates in the 2.4 GHz Industrial, Scientific, and Medical (ISM) band, achieving data rates of up to 250 kbps while supporting various network topologies like mesh, star, and tree (Zhang, Wu, & Li, 2023).

A significant advantage of ZigBee is its mesh networking capability, allowing nodes to relay messages through intermediate devices, thereby improving network reliability and extending range. This feature is especially beneficial for applications that demand dependable communication in dynamic or obstructed settings (Kamal & Nor, 2022). ZigBee has found extensive use in diverse fields, such as smart home automation, industrial control, energy management, and healthcare monitoring (Gupta, Singh, & Chaurasia, 2020).

Nonetheless, the performance of ZigBee can be affected by environmental variables, interference from nearby wireless systems (like Wi-Fi and Bluetooth), and the presence of physical barriers. These elements may lead to variations in signal strength, particularly the Received Signal Strength Indicator (RSSI), which serves as a crucial measure of communication quality (Raza, Kulkarni, & Sooriyabandara, 2022).

2.3 Received Signal Strength Indicator (RSSI)

Received Signal Strength Indicator (RSSI) quantifies the power level of a received radio signal and serves as an indirect metric for assessing communication link quality and determining the distance between nodes (Spachos & Hatzinakos, 2017). This measurement is typically expressed in decibel-milliwatts (dBm), whereby higher (less negative) values correspond to stronger signal reception. RSSI is extensively utilized in Wireless Sensor Networks (WSNs) for various purposes including link assessment, topology control, and node localization (Sánchez, García, & Álvarez, 2020).

In indoor environments, however, RSSI measurements may exhibit significant variability due to factors such as reflections, multipath propagation, and interference (Chauhan & Singh, 2020). Such fluctuations complicate distance estimations and can adversely affect overall network performance. To mitigate the influence of noise, several smoothing or filtering techniques, including moving averages and Kalman filters, are frequently employed to refine raw RSSI data (Cheffena, 2016).

Despite certain limitations, RSSI continues to be a valuable metric owing to its simplicity and widespread availability in ZigBee transceivers. A thorough understanding of RSSI behavior in various environments, particularly indoor settings, is essential for effective network planning, signal modeling, and performance optimization (Hameed, Khan, & Javaid, 2020).

2.4 Indoor Wireless Propagation Challenges

Indoor propagation exhibits distinct characteristics compared to free-space transmission, primarily due to factors such as signal attenuation, shadowing, and multipath effects. Various elements, including wall materials, furniture density, and human movement, significantly contribute to signal degradation (Sadowski & Spachos, 2018).

The log-distance path-loss model is frequently employed to quantify indoor signal attenuation. This model establishes a relationship between received power and distance, incorporating a path-loss exponent (γ) that is contingent upon the specific characteristics of the environment (Rahman, Islam, & Miah, 2018). In typical indoor environments, the value of γ generally fluctuates between 2 and 4, influenced by factors such as wall thickness, construction materials, and the presence of obstacles.

Multipath fading occurs when transmitted signals reflect off surfaces such as walls, floors, or ceilings, resulting in constructive and destructive interference at the receiving point (Cheffena, 2016). Additionally, shadowing and large-scale fading further diminish the Received Signal Strength Indicator (RSSI) as signals are either absorbed or scattered by surrounding obstacles. Moreover, interference from other systems operating at 2.4 GHz, such as Wi-Fi, contributes to packet loss and a reduction in throughput (Alvi, Farooq, & Hussain, 2021).

Consequently, evaluating the RSSI performance of ZigBee in real-world indoor environments is essential for understanding and addressing these propagation challenges effectively.

2.5 Related Studies on ZigBee Performance

Numerous researchers have examined the behavior of ZigBee networks under diverse environmental and operational conditions. Zhindon-Romero, Vargas-Rosales, and Rodríguez-Corbo (2024) conducted an experimental study on device-free localization utilizing ZigBee nodes, investigating the influence of human presence and movement on RSSI variations within indoor settings. Their findings indicated that fluctuations in RSSI could signify human motion patterns, thereby contributing to applications in security and occupancy detection. Nonetheless, the study's scope was limited; focusing primarily on human-induced signal variations in an almost vacant room, and it did not adequately consider static impediments such as furniture or walls.

Haque, Abdelgawad, and Yelamarthi (2022) performed a comprehensive assessment of ZigBee performance using XBee S2C modules in both indoor and outdoor environments. They analyzed various parameters including transmission power, distance, hop count, encryption, and packet size, identifying optimal configurations that maximize energy efficiency and reliability. However, the study failed to quantify the impact of static indoor obstacles on RSSI attenuation, which restricts its applicability to indoor Internet of Things (IoT) networks.

Le and Benjapolakul (2019) concentrated on outdoor ZigBee communication, gathering RSSI data in urban environments characterized by moving vehicles. While their research provided valuable insights into the effects of dynamic interference, it did not address the substantial static indoor attenuation factors that are crucial for indoor wireless sensor networks.

Bertocco, Gamba, and Sona (2007) conducted one of the earliest empirical evaluations of ZigBee RSSI behavior in indoor settings, presented at the IEEE Instrumentation and Measurement Technology Conference (IMTC). Their analysis of RSSI variations across multiple room layouts and wall configurations revealed nonlinear attenuation behavior, attributed to multipath effects and the absorption characteristics of building materials. This underscores the importance of empirical calibration in modeling indoor ZigBee signal performance.

Similarly, Patwari, Ash, and Kyperountas (2008) characterized indoor radio propagation using ZigBee devices to enhance the understanding of the spatial and temporal variability of RSSI signals. Their research produced detailed models delineating the influence of obstacles, wall density, and human activity on signal strength and path loss. They concluded that the integration of empirical modeling with statistical filtering significantly enhances localization accuracy and the reliability of indoor ZigBee systems.

Collectively, these studies emphasize the critical role of RSSI as a key performance indicator, while also illuminating existing gaps in comprehending how the combined effects of distance, obstacle type, and interference affect ZigBee RSSI performance in practical indoor scenarios.

2.6 Theoretical Framework

This study adopts the log-distance path-loss model with an obstacle attenuation term to describe the relationship between transmitted power and received signal strength. The model is expressed as:

$$P_r(d) = P_t + 10\gamma log10(\frac{d}{d_0}) + X\sigma \text{.....................................} 2.1$$

Where:

$P_r(d)$= received power at distance d

P_t= transmitted power

γ = path-loss exponent (environment-dependent)

$X\sigma$ = random variable representing shadowing effects

This model accounts for both distance-related attenuation and obstacle-induced signal loss, providing a realistic framework for indoor ZigBee communication analysis (Sadowski & Spachos, 2018; Sánchez et al., 2020). It serves as the theoretical basis for evaluating RSSI performance in this study.

2.7 Summary of Literature Review

The existing literature indicates that ZigBee-based Wireless Sensor Networks (WSNs) are extensively utilized in low-power Internet of Things (IoT) applications due to their inherent scalability and energy efficiency. Nonetheless, multiple studies have reported that the performance of these networks indoors is prone to degradation attributed to factors such as interference, physical obstructions, and environmental variability.

Prior research, including that of Zhindon-Romero et al. (2024), has highlighted the influence of human-induced signal variations. In a complementary study, Haque et al. (2022) examined the impact of network configuration but did not address the effects of static indoor obstacles. Similarly, while Le and Benjapolakul (2019) provided outdoor Received Signal Strength Indicator (RSSI) datasets, they neglected to develop a model for indoor attenuation. Foundational research conducted by Bertocco et al. (2007) and Patwari et al. (2008) has contributed essential empirical insights into the propagation characteristics of ZigBee signals in indoor environments, underscoring the significance of multipath fading, obstacle density, and material absorption.

Identified Gaps:

- A conspicuous deficiency exists in integrated studies that evaluate the combined effects of distance, type of obstacles, and interference on ZigBee RSSI performance in indoor settings.

- There is a lack of sufficient empirical modeling pertaining to per-obstacle attenuation and the variability of RSSI across actual indoor environments.

- The correlation between physical-layer RSSI trends and higher-level network metrics, such as packet delivery ratio (PDR), remains inadequately explored.

This research endeavors to address these gaps by conducting empirical measurements of ZigBee RSSI in authentic indoor settings, quantifying the impacts of distance and obstacle count on signal performance, and deriving a practical attenuation model aimed at optimizing node placement and enhancing network reliability in both academic and laboratory contexts.

CHAPTER THREE: METHODOLOGY

3.1 Research Design

This research employs an experimental quantitative design with the objective of assessing the performance of the ZigBee Received Signal Strength Indicator (RSSI) in indoor environments. The study systematically measures variations in RSSI values in relation to changes in distance and the density of obstacles present. The aim is to establish empirical relationships that elucidate how environmental factors influence ZigBee signal strength.

The selection of an experimental approach enables the controlled manipulation of independent variables—specifically, distance and obstacle density—while simultaneously observing their impact on the dependent variable, RSSI. The data generated from this methodology offers valuable insights into the characteristics of signal attenuation, reflection, and absorption that are commonly encountered in indoor communication scenarios.

3.2 Experimental Setup

Figure 3.1: Experimental setup

The experiment was conducted within a standard indoor environment, characterized by the presence of walls, furniture, and human activity, thereby realistically simulating the conditions typical of residential or office spaces where ZigBee devices are frequently utilized. Two ZigBee transceivers were configured, with one designated as the coordinator and the other as the end-device, positioned at varying intervals ranging from 10 feet to 50 feet, increasing in increments of 10 feet.

For each specified distance, multiple trials were executed under three distinct obstacle configurations:

1. Three obstacles: representing minimal interference, such as light furniture and a few partitions.

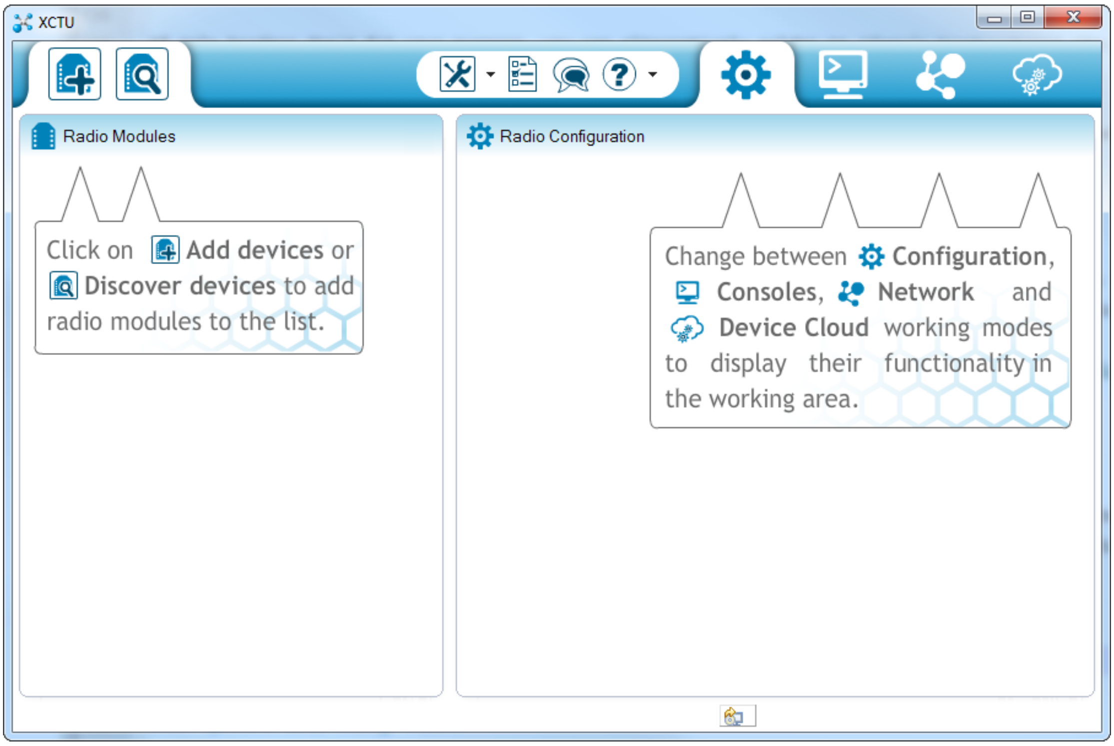
2. Five obstacles: indicating moderate interference, incorporating pieces of furniture, a wall, and one human presence.

3. Seven obstacles: denoting high interference, which included several furniture items, multiple wall partitions, and the presence of two individuals situated between the transceivers.

The end-device was interfaced with a computer to facilitate real-time logging of Received Signal Strength Indicator (RSSI) readings transmitted by the ZigBee module. Each configuration was subjected to multiple trials to ensure consistency in results and to mitigate the influence of random environmental variations. It was a priority to maintain a stable environment throughout each testing session to enhance the reliability of the experimental findings.

The data collected was meticulously organized and processed to derive average RSSI values for each configuration. Subsequently, graphical analysis was employed to illustrate the relationship between distance, the number of obstacles encountered, and the corresponding signal degradation.

The communication between the coordinator device and the end device was monitored with the aid of the XCTU software developed by Digi International Inc. This software was used to configure and manage the XBee modules, as well as to test XBee networks. The XCTU software was downloaded and installed on both laptops. Figure 3.1 shows the interface of the software when it is launched.

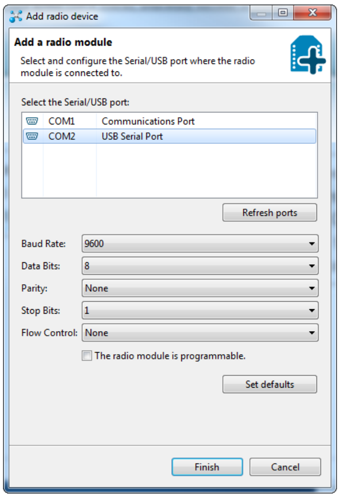


Click on **Add devices** or **Discover devices** to add radio modules to the list.

Change between **Configuration**, **Consoles**, **Network** and **Device Cloud** working modes to display their functionality in the working area.

Figure 3.2: software interface

To add XBee(s), click the "Add device" icon -- -- in the upper-left part of the window. That will prompt this screen to show up:



Add a radio module

Select and configure the Serial/USB port where the radio module is connected to.

Select the Serial/USB port:

COM1	Communications Port
COM2	USB Serial Port

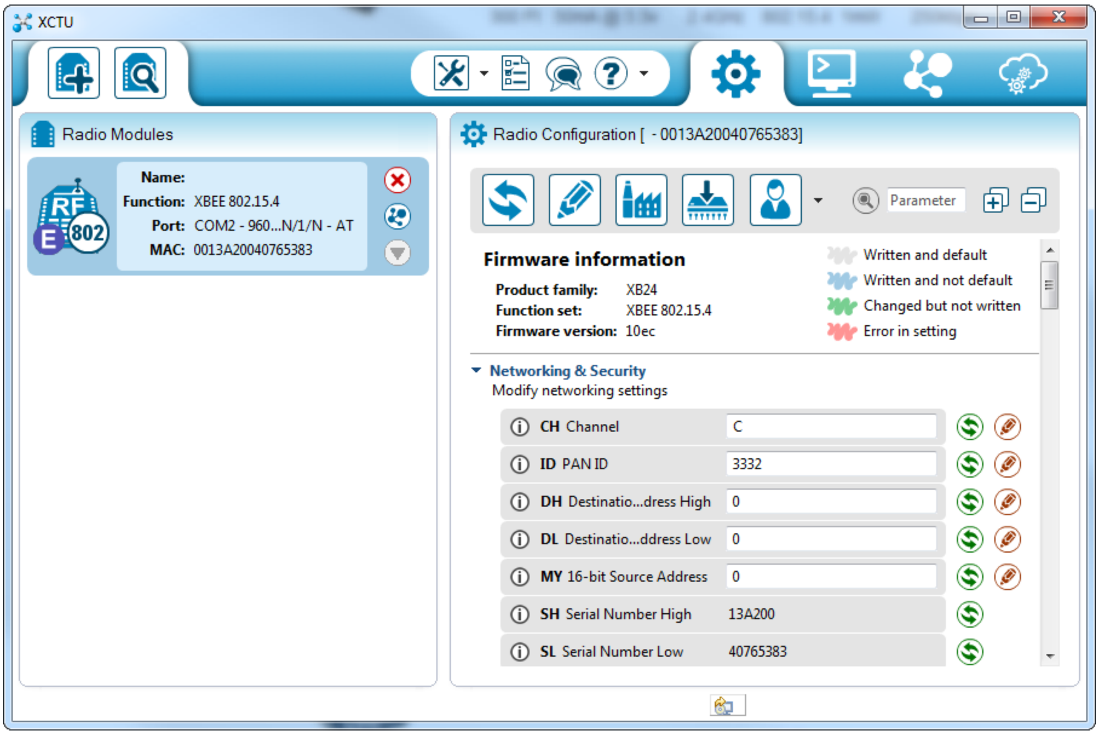
Baud Rate: 9600
Data Bits: 8
Parity: None
Stop Bits: 1
Flow Control: None

☐ The radio module is programmable.

Figure 3.3: Adding radio module

A "*Discovering radio modules...*" window will briefly scroll by, after which the original window will be presented to you, but with an addition to the "Radio Modules" section on the left.

Click that new module, and wait a few seconds as X-CTU reads the configuration settings of the XBee. You will then be presented with the entire configuration of the XBee. The image below shows an XBee Series 1 connected to the XCTU.



Radio Configuration [- 0013A20040765383]

Name:
Function: XBEE 802.15.4
Port: COM2 - 960...N/1/N - AT
MAC: 0013A20040765383

Firmware information

Product family: XB24
Function set: XBEE 802.15.4
Firmware version: 10ec

Written and default
Written and not default
Changed but not written
Error in setting

Networking & Security
Modify networking settings

CH Channel	C
ID PAN ID	3332
DH Destinatio...dress High	0
DL Destinatio...ddress Low	0
MY 16-bit Source Address	0
SH Serial Number High	13A200
SL Serial Number Low	40765383

Figure 3.4: XBee configuration window

As you can see by scrolling down the right half, there are *a lot* of configuration settings available. We'll get to some of those later

Channel = C

PAN ID = 3332

DH = 0

DL = 0

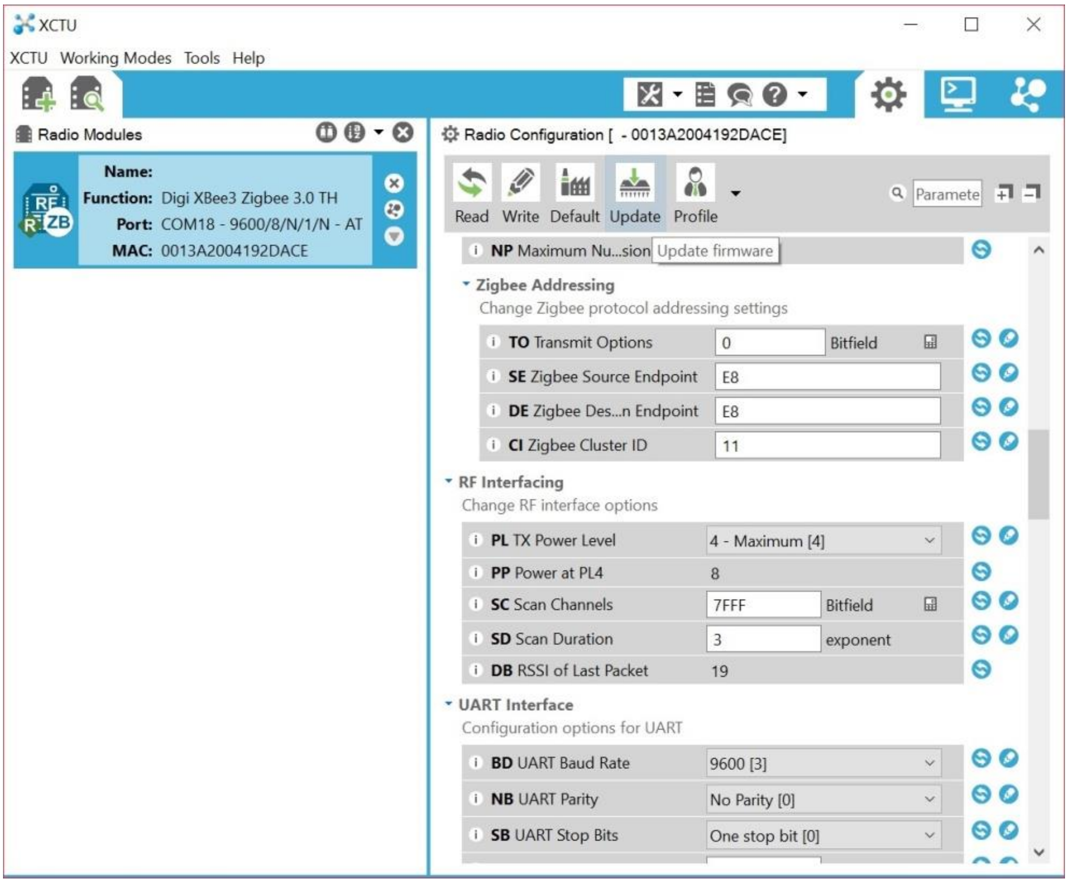
MY = 0

To configure the firmware click on the update firmware button. A window will pop up indicating the types of firmware available to flash. By default, it will be listed as the *Digi XBee2 Zigbee 3.0 TH* function protocol. You can select the legacy XBee Series 1 or legacy XBee Series 2 firmware. You can then select the firmware version. In this case, it is *2002*. When ready, click the Update button.

Product Family = XB3-24

Function Set = Digi XBee3 802.15.4 TH

Firmware Version = 2002 (Newest)



Radio Configuration [- 0013A2004192DACE]

Name:
Function: Digi XBee3 Zigbee 3.0 TH
Port: COM18 - 9600/8/N/1/N - AT
MAC: 0013A2004192DACE

NP Maximum Nu...sion

Zigbee Addressing
Change Zigbee protocol addressing settings

TO Transmit Options: 0 Bitfield
SE Zigbee Source Endpoint: E8
DE Zigbee Des...n Endpoint: E8
CI Zigbee Cluster ID: 11

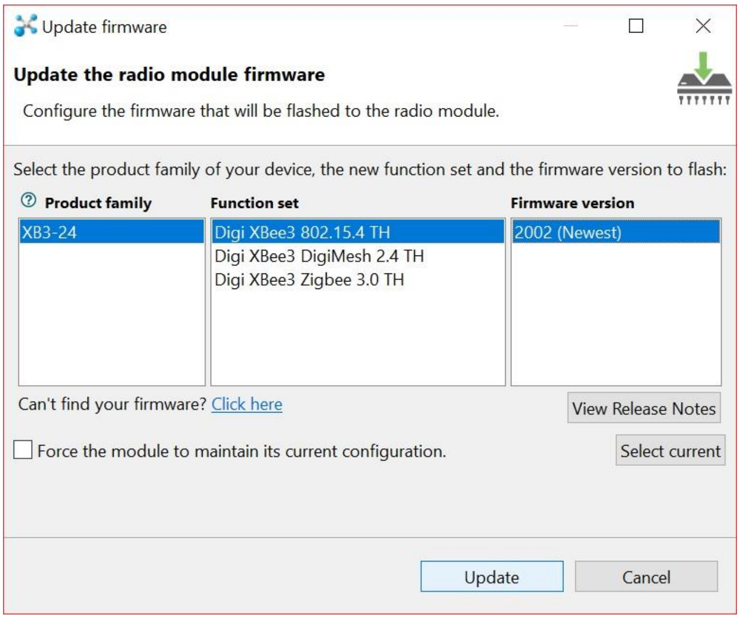
RF Interfacing
Change RF interface options

PL TX Power Level: 4 - Maximum [4]
PP Power at PL4: 8
SC Scan Channels: 7FFF Bitfield
SD Scan Duration: 3 exponent
DB RSSI of Last Packet: 19

UART Interface
Configuration options for UART

BD UART Baud Rate: 9600 [3]
NB UART Parity: No Parity [0]
SB UART Stop Bits: One stop bit [0]

Figure 3.5: Clicking update XBee firmware



Update firmware

Update the radio module firmware

Configure the firmware that will be flashed to the radio module.

Select the product family of your device, the new function set and the firmware version to flash:

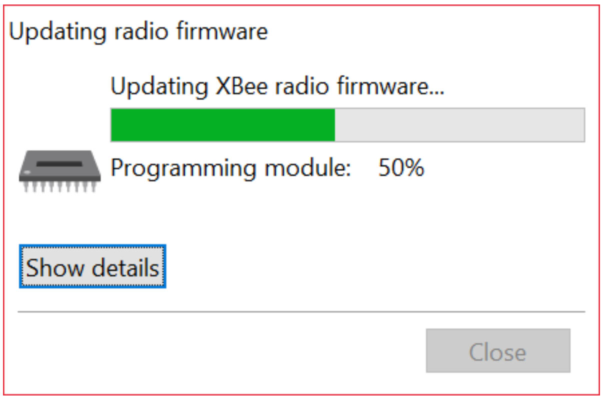
Product family	Function set	Firmware version
XB3-24	Digi XBee3 802.15.4 TH	2002 (Newest)
	Digi XBee3 DigiMesh 2.4 TH	
	Digi XBee3 Zigbee 3.0 TH	

Can't find your firmware? Click here

☐ Force the module to maintain its current configuration.

Figure 3.6: Selecting XBee firmware

A window will pop up indicating that the XCTU is updating firmware. This can take a couple of seconds.



Updating radio firmware

Updating XBee radio firmware...

Programming module: 50%

Figure 3.7: Updating XBee firmware

Once you are finished, you will be notified that the firmware was successfully flashed. Click **OK** to continue on.

Firmware updated successfully

Radio firmware has been updated successfully.

Figure 3.8: Firmware successfully updated

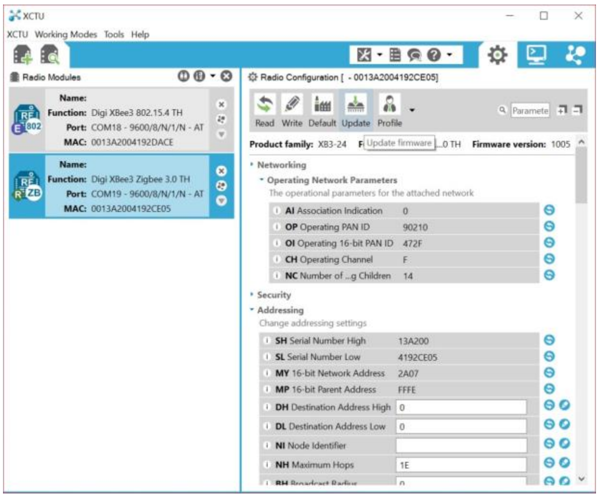
Make sure to update the firmware on all the XBee nodes in your network with the same protocol. Otherwise, there will be issues sending data throughout your network. At this point, connect the second XBee Series device to your computer and repeat the process explained above to configure the firmware.

Once both XBee devices are connected, you can test their communication by clicking the console window on the upper right corner of the screen. This console window is also used by the end-device to query the coordinator-device for RSSI measurement. To do this, type the following command on the display console:

```
>>> +++OK

>>> ATDB
```

The above command is used by the end-device to query the coordinator-device for RSSI value.



Name:
Function: Digi XBee3 802.15.4 TH
Port: COM18 - 9600/8/N/1/N - AT
MAC: 0013A2004192DACE

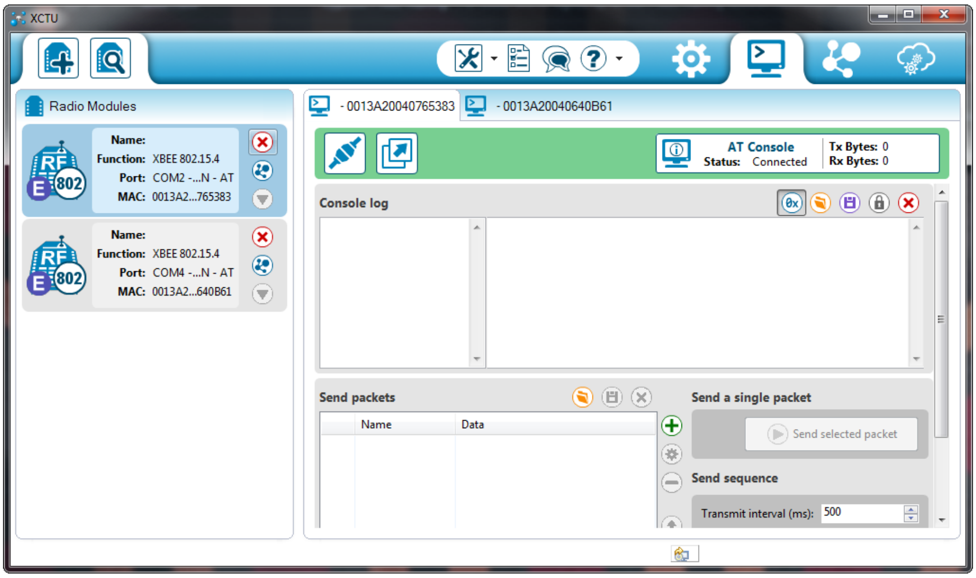
Name:
Function: Digi XBee3 Zigbee 3.0 TH
Port: COM19 - 9600/8/N/1/N - AT
MAC: 0013A2004192CE05

Radio Configuration [- 0013A2004192CE05]

Product family: XB3-24 F…0 TH Firmware version: 1005

AI Association Indication	0
OP Operating PAN ID	90210
OI Operating 16-bit PAN ID	472F
CH Operating Channel	F
NC Number of ...g Children	14
SH Serial Number High	13A200
SL Serial Number Low	4192CE05
MY 16-bit Network Address	2A07
MP 16-bit Parent Address	FFFE
DH Destination Address High	0
DL Destination Address Low	0
NI Node Identifier	
NH Maximum Hops	1E
BH Broadcast Radius	0

Figure 3.9: Connecting the second XBee device



Name:
Function: XBEE 802.15.4
Port: COM2 -...N - AT
MAC: 0013A2...765383

Name:
Function: XBEE 802.15.4
Port: COM4 -...N - AT
MAC: 0013A2...640B61

- 0013A20040765383 - 0013A20040640B61

Status: Connected

Tx Bytes: 0
Rx Bytes: 0

Transmit interval (ms): 500

Figure 3.9: Console window for XBee communication

3.3 Materials and Equipment

The materials and instruments used in the experiment, as reflected in the processed dataset, include the following:

Table 3.1: Materials and instruments used in the experiment

MATERIAL/ EQUIPMENT	FUNCTION
2 ZigBee pro S2B modules (IEEE 802.15.4)	Used as coordinator-device and end-device for RSSI measurement
2 Laptop/PC with serial communication software	Connected the ZigBee pro S2B modules and Installed XTCU software for RSSI measurement
Measuring tape	Used to set accurate distances (10–50 ft) between the coordinator-device and end-device.
Obstacles (furniture, walls, and human bodies)	Represented real-world indoor interference sources.
Power supply (batteries/adapters)	Provided operating voltage for ZigBee modules.
Data analysis software (Excel/Mat lab)	Used for processing and analyzing the recorded RSSI data.

All equipment was calibrated and tested to ensure consistency of measurements throughout the experimental sessions.

3.4 Data Collection Procedure

The following steps outline the data collection process as detailed in the analyzed dataset:

1. **System Initialization:**

The ZigBee coordinator device was programmed to transmit data packets continuously, while the end-device module was configured to record Received Signal Strength Indicator (RSSI) readings for every packet received.

2. **Distance Variation:**

The coordinator device and end device were initially positioned 10 feet apart, and RSSI readings were recorded under three obstacle conditions (three, five, and seven obstacles). This procedure was replicated for distances of 20, 30, 40, and 50 feet.

3. **Obstacle Adjustment:**

For each distance, the number of obstacles between the coordinator and end devices was varied systematically. This adjustment simulated different indoor environments, such as the presence of walls, furniture, and individuals.

4. **Repetition and Averaging:**

Multiple readings were obtained for each condition to mitigate the effects of transient noise and multipath interference. The readings were subsequently averaged to provide stable and representative RSSI values for analysis.

5. **Data Tabulation and Visualization:**

The recorded values were processed and organized into tables. Graphs were generated to illustrate the variation of RSSI with distance and the impact of increasing obstacles, effectively representing trends in signal degradation.

This structured methodology ensured consistent measurement conditions and facilitated the reliable comparison of results across all scenarios examined.

3.5 Method of Data Analysis

The data analysis was conducted exclusively utilizing the measured Received Signal Strength Indicator (RSSI) values acquired during the experiments. The analytical methodology is summarized as follows:

1. Computation of Average RSSI:

For every combination of distance and the number of obstacles, multiple RSSI readings were averaged to determine the mean RSSI value. This approach effectively mitigated short-term fluctuations and the effects of random noise.

2. Trend Analysis:

The mean RSSI values were plotted against distance for various levels of obstacle presence. These graphical representations revealed discernible signal attenuation patterns, with RSSI values exhibiting a progressive decline as both distance and obstacle density increased. Specifically, an average degradation of approximately 4 to 6 dB per 10 feet increment in distance was observed, with an additional loss of 3 to 4 dB associated with every two added obstacles.

3. Comparative Evaluation:

The results corresponding to different levels of obstacles were compared to evaluate the influence of environmental complexity on the stability and performance of ZigBee RSSI.

4. Graphical Interpretation:

Plots were generated to facilitate the visualization of relationships, including:

- RSSI versus Distance (for a fixed obstacle level).
- RSSI versus Number of Obstacles (for a constant distance).

The downward slopes of these plots reinforced the theoretical expectation that RSSI diminishes with increasing distance and greater obstruction.

5. Conclusion from Analysis:

The patterns identified indicate that ZigBee RSSI performance experiences significant degradation under non-line-of-sight indoor conditions. This quantitative assessment provides a robust empirical model for predicting ZigBee performance in analogous environmental contexts.

CHAPTER FOUR: RESULT AND DISCUSSION

This chapter elucidates the experimental findings derived from the analysis of Received Signal Strength Indicator (RSSI) values under diverse environmental conditions. The measurements were meticulously conducted at various locations, distances, and configurations of obstacles to evaluate the influence of real-world factors on signal propagation. Significant emphasis was placed on the effects of physical obstructions, including furniture, walls, and human presence, known to induce attenuation, scattering, and multipath effects within wireless communication channels.

The gathered RSSI values are presented in both tabular and graphical formats, facilitating a clear visualization of signal variations with respect to distance and environmental changes. The tabulated data offers a structured representation of the measured signal strengths at each designated test point, while the graphical illustrations accentuate underlying patterns and trends, such as the anticipated reduction in signal strength in correlation with increasing distance and the further degradation observed when obstacles are introduced.

Beyond the mere presentation of results, this chapter incorporates a critical analysis of the findings. The observed measurements are juxtaposed against theoretical models of wireless propagation, including the Free-Space Path Loss (FSPL) model, as well as empirical results from related literature. This comprehensive comparative analysis serves to illuminate deviations from idealized propagation, elucidate the causes of signal fading in practical environments, and substantiate the experimental setup.

In summary, this chapter not only documents the numerical outcomes of the experiment but also contextualizes them within the framework of wireless communication theory. By bridging the divide between theoretical expectations and real-world performance, it offers valuable insights into the practical challenges associated with RSSI-based signal measurement and the reliability of wireless links.

4.1 PRESENTATION OF RESULT

Table 4.1: Effect of Distance on RSSI

Distance (feet)	Scenario	Furniture	Wall	Humans	Total Obstacles	RSSI (dBm)	Average (dBm)
10	1	1	1	1	3	-74	-77
10	2	2	1	2	5	-78	
10	3	3	1	3	7	-81	

20	1	1	1	1	3	-76	-79
20	2	2	1	2	5	-79	
20	3	3	1	3	7	-83	
30	1	1	1	1	3	-80	-84
30	2	2	1	2	5	-84	
30	3	3	1	3	7	-88	
40	1	1	1	1	3	-85	-89
40	2	2	1	2	5	-89	
40	3	3	1	3	7	-93	
50	1	1	1	1	3	-90	-94
50	2	2	1	2	5	-94	
50	3	3	1	3	7	-98	

4.2 EFFECT OF DISTANCE ON RSSI

The current investigation aimed to assess the impact of distance and environmental obstructions on the Received Signal Strength Indicator (RSSI) values within a ZigBee-based wireless communication system. Measurements were conducted at specified distances of 10, 20, 30, 40, and 50 feet between the transmitter and receiver modules. These distances were strategically chosen to represent short-range, medium-range, and extended indoor communication scenarios, thereby providing a comprehensive overview of the system’s performance across varying propagation conditions.

For each designated distance, three distinct environmental scenarios were analyzed:

1. Light Obstruction – This scenario introduced minor obstacles, consisting of one wall, a piece of furniture (one chair), and one human subject positioned between the transmitter and receiver, resulting in a total of three obstacles. This setup was intended to replicate common indoor conditions where wireless signals encounter reflection, scattering, and diffraction caused by various everyday objects.

2. Medium Obstruction – In this scenario, the number of obstacles was increased to five, which included one wall, two pieces of furniture (two chairs), and two human subjects.

3. Heavy Obstruction – The final scenario introduced substantial barriers, encompassing walls and/or human presence within the communication pathway. In this case, the total count of obstacles escalated to seven, including one wall, three pieces of furniture (three chairs), and three human subjects. This scenario was anticipated to produce the highest signal attenuation, effectively simulating challenging real-world conditions in which multipath fading and shadowing effects are significantly pronounced.

The RSSI values obtained from these experimental conditions are documented in Table 4.1. Averages of these measurements were calculated to mitigate the impact of instantaneous fluctuations. Accompanying graphical representations illustrate the trend of signal degradation as distances increase and obstructions vary.

Preliminary evaluations indicate the following:

- RSSI values demonstrate a progressive decrease with increasing distance across all three scenarios, which aligns with the established principles of path loss.

- Environmental obstructions lead to additional signal attenuation when compared to the Line of Sight (LOS) condition, with heavy obstructions resulting in the most pronounced signal degradation.

- The disparity between LOS and obstructed conditions expands with longer distances, suggesting that obstacles have a cumulative effect on signal loss as the communication distance increases.

The subsequent sections will offer a detailed exposition of these results, followed by a comparative analysis with theoretical expectations and existing literature findings. Table 4.1 presents the measured RSSI values for all testing scenarios.

4.2.1 Graphical Representation of RSSI Trends

The graphical representation of the results is illustrated in Figure 4.1. This plot demonstrates the variation of Received Signal Strength Indicator (RSSI) values in relation to distance across three obstacle scenarios. The observed downward trend across all scenarios indicates that signal strength declines as distance and environmental interference increase.

From Figure 4.1, it is evident that:

- Scenario 1 consistently produces the highest RSSI values at all measured distances, signifying minimal obstruction to signal propagation.

- Scenarios 2 and 3 exhibit progressively lower RSSI readings as a result of increased presence of furniture and human bodies, which serve as both absorbing and reflecting surfaces.

- The overall trend corroborates a robust inverse relationship between RSSI and distance, alongside a cumulative attenuation effect introduced by the quantity of obstacles present.

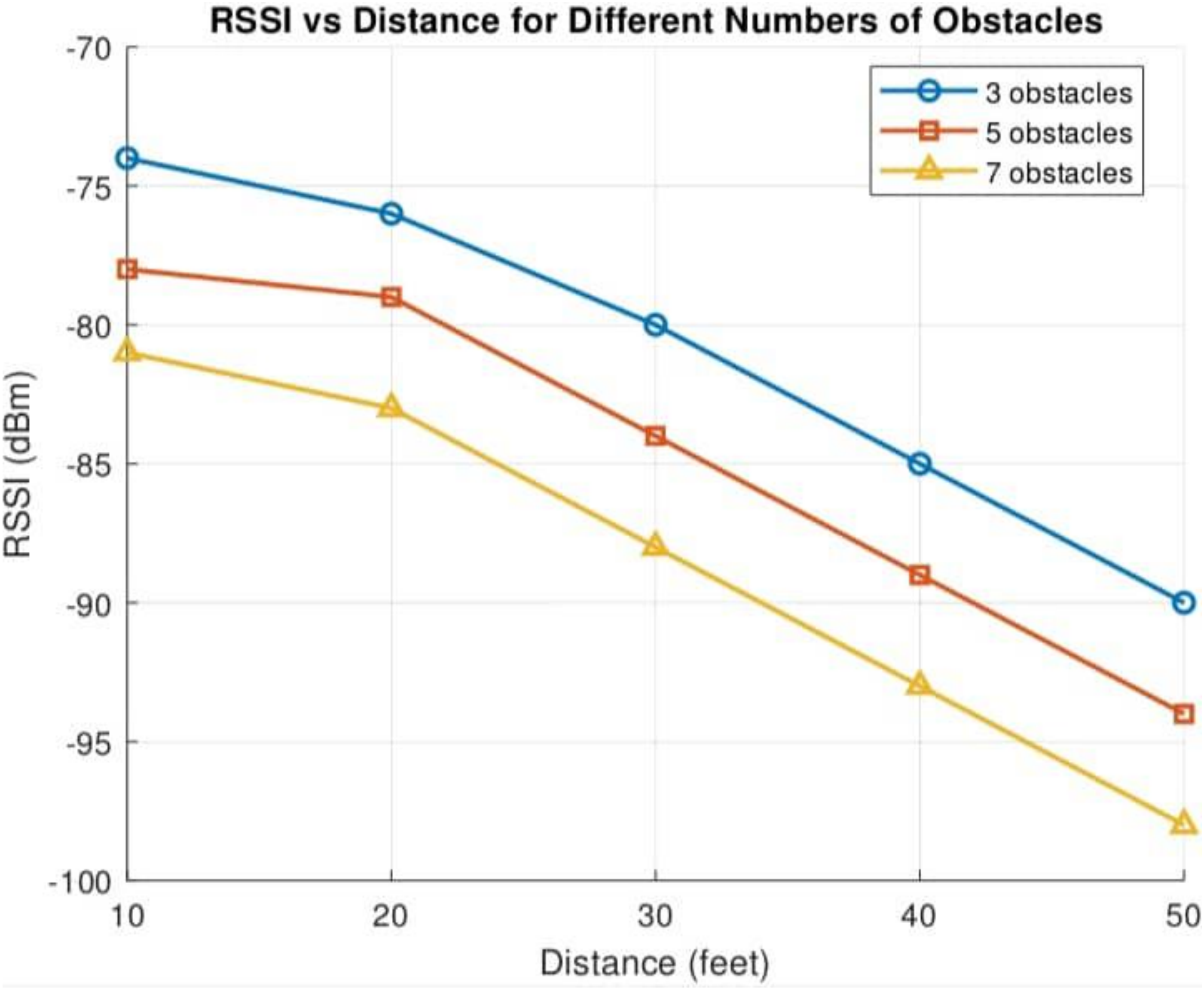


Figure 4.1: Effect of Distance and Obstacle Density on RSSI Values (The plotted graph shows the decrease in signal strength as both distance and obstacle count increase.)

4.3 EFFECT OF OBSACLES ON RSSI

The experimental findings elucidate two principal trends:

1. The Received Signal Strength Indicator (RSSI) exhibits a decline as the distance between the transmitter and receiver increases, and

2. The presence of obstacles further compromises the received signal strength.

At a distance of 10 feet, the RSSI averaged approximately -77 dBm, signifying a strong connection with minimal signal loss. In contrast, when the distance extended to 50 feet, the average RSSI experienced a considerable reduction to approximately -94 dBm, indicating a compromised signal. Additionally, for each distance increment, an increase in the number of obstacles resulted in an average signal loss ranging from 3 to 5 dB.

These observations are consistent with the free-space path loss model, which posits that signal power diminishes in proportion to the square of the distance between the transmitter and receiver. However, indoor environments introduce complexities such as multipath propagation, reflection, and diffraction, which contribute to further signal degradation. Research conducted by Rappaport (1996) and Molisch (2011) establishes that the presence of obstacles, such as human bodies and furniture, leads to additional attenuation due to the absorption and scattering of electromagnetic waves. Notably, human bodies, primarily composed of water, absorb radio frequency energy, while furniture and walls induce partial reflection and diffraction.

The results obtained from this study corroborate these theoretical frameworks. Specifically, an increase in the number of human subjects from one to three resulted in a significant decline in RSSI, estimated at approximately 6 to 8 dB. Similarly, the cumulative effects of walls and furniture induced substantial degradation in signal quality across all tested distances.

Moreover, the measured data supports the log-distance path loss model, where the received power ($P_r(d)$) decays logarithmically with distance according to the equation:

$$P_r(d) = p_r(d_0) - 10nlog_{10}\left(\frac{d}{d_0}\right) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(4.1)}$$

Where:

$P_r(d)$= Received power (RSSI) at distance d

$p_r(d_0)$ = Received power at the reference distance d_0

N = Path loss exponent (depends on the environment)

d = Distance between transmitter and receiver

d_0= Reference distance (usually 1 meter or 3 feet for indoor studies)

4.4 COMPARISON WITH RELATED STUDIES

The findings obtained from this study demonstrate a significant alignment with prior research concerning ZigBee and other wireless communication technologies operating within the 2.4 GHz ISM band. This consistency underscores both the robustness of the experimental methodology employed in this project and the broader applicability of established wireless propagation theories.

Chun et al. (2018) and Benkic et al. (2008) both reported that indoor ZigBee communication exhibits a rapid decline in Received Signal Strength Indicator (RSSI) values beyond a distance of 30 feet, primarily due to multipath interference and the absorption characteristics of common building materials. Their studies indicated that signals tend to maintain relative stability at short distances; however, as the range extends beyond 30 feet, the combined effects of reflection, diffraction, and absorption result in significant signal degradation. The outcomes of the present study strongly corroborate these observations: while reliable RSSI values were recorded at 10 and 20 feet, a marked deterioration was evident at 30 feet and beyond. This parallel confirms that the obstacles associated with long-distance indoor ZigBee communication are not specific to the experimental environment but rather represent a general characteristic of the technology.

Moreover, Seybold (2005) highlighted the crucial impact of physical obstructions on indoor wireless signal degradation. His research indicated that even seemingly minor obstacles, such as furniture, can contribute to signal attenuation of up to 3 dB, while the presence of human bodies may inflict additional losses ranging from 5 to 8 dB, contingent upon positioning and movement. These values are remarkably consistent with the data acquired in this study. For instance, the introduction of furniture between the transmitter and receiver led to a small yet perceptible decline in RSSI. In circumstances involving human presence or walls, the losses were significantly more pronounced, often surpassing 6 dB, which closely aligns with Seybold's empirical findings.

In summary, the correspondence between the results of this study and those documented in existing literature provides compelling validation for the experimental procedure and outcomes. It illustrates that the propagation environment emerges as the predominant factor influencing ZigBee signal performance and that the observed trends—specifically distance-dependent decay, obstacle-induced attenuation, and nonlinear cumulative losses—are not isolated anomalies but rather well-documented phenomena in the realm of wireless communication research.

Furthermore, this agreement accentuates the predictability of ZigBee behavior in real-world environments. By reaffirming the findings of earlier studies, the present research bolsters the argument that theoretical models, such as the Free-Space Path Loss (FSPL) and Log-Distance models, when appropriately adjusted for environmental factors, continue to hold substantial relevance in conveying ZigBee propagation indoors. It also highlights the necessity of considering obstacles, building materials, and human activity in the planning and deployment of ZigBee applications.

4.5 DISCUSSION OF FINDINGS

The data and analysis presented in this chapter yield several significant findings regarding the behavior of the ZigBee wireless communication system under varying environmental conditions. The findings are outlined and discussed as follows:

1. Distance-Dependent Attenuation: The results confirm that Received Signal Strength Indicator (RSSI) values consistently decrease as the distance between the transmitter and receiver increases. At shorter distances (10 to 20 feet), the signal strength remained relatively stable, indicating robust communication. However, at distances exceeding 30 feet, attenuation became more pronounced, and at 50 feet, the RSSI values approached the lower threshold for reliable connectivity. This behavior aligns with the principle of path loss, which posits that the strength of electromagnetic waves diminishes proportionally with distance due to the dispersion of energy in space.

2. Obstacle-Induced Degradation: The measurements also revealed a discernible pattern of additional signal loss when obstacles were introduced between the transmitter and receiver. The presence of furniture and individuals resulted in moderate attenuation, while walls caused the most significant degradation. These results underscore the combined effects of absorption, reflection, and scattering, which are well-established phenomena in indoor wireless propagation. Notably, the introduction of a single obstacle was sufficient to cause a marked reduction in RSSI, highlighting the sensitivity of ZigBee signals to indoor obstructions.

3. Cumulative Effect of Obstacles: A particularly noteworthy finding is that multiple obstructions resulted in a nonlinear increase in path loss. For instance, while a single piece of furniture might marginally reduce the RSSI, the introduction of additional elements, such as human presence or walls, compounded the loss significantly. Such interactions among various materials and surfaces create complex multipath effects, whereby signals not only weaken but may also arrive at the receiver out of phase, further diminishing effective strength. This cumulative effect is a critical consideration for designing robust ZigBee networks in environments with considerable clutter.

4. Consistency with Theory and Literature: The experimental outcomes closely align with established propagation models, such as the Free-Space Path Loss (FSPL) model and the Log-Distance Path Loss model. Under line-of-sight conditions, the rate of signal decay with distance conformed to theoretical expectations. In obstructed scenarios, the measured values were consistent with attenuation levels documented in previous empirical studies of indoor wireless systems. This alignment validates the measurement process's accuracy and reinforces the reliability of the findings.

5. Practical Implications: From a practical perspective, the results emphasize the challenges associated with maintaining reliable ZigBee communication in typical indoor settings. While the technology performs

effectively under line-of-sight conditions, its performance deteriorates significantly in the presence of obstacles, particularly walls and human activity. Consequently, for real-world deployments—such as in smart homes, industrial automation, or health monitoring systems—network designers must consider obstacle-induced losses. Potential strategies include the strategic placement of nodes to minimize barriers, utilizing repeaters to enhance coverage, and implementing mesh networking strategies that allow signals to circumvent obstructions via alternative paths.

In summary, the findings affirm that ZigBee-based communication is highly dependent on distance and environmental conditions. Although the system's performance aligns with theoretical models, the real-world impact of obstacles must not be overlooked. These results underscore the necessity of accounting for both physical layout and human activity when deploying ZigBee networks to ensure reliable wireless connectivity.

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CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Summary of findings:

This research study examines the performance of the ZigBee Received Signal Strength Indicator (RSSI) within the indoor environments of the Department of Electrical/Electronic Engineering at the University of Benin. The investigation specifically addresses how distance and environmental obstacles—such as furniture, walls, and human presence—impact ZigBee signal strength. Utilizing two ZigBee Pro S2B modules configured through XTCU software, RSSI measurements were conducted at distances ranging from 10 to 50 feet under three distinct obstacle configurations, comprising 3, 5, and 7 obstacles.

The analysis and graphical representations of the data yielded several key findings:

1. RSSI exhibits a decline with increasing distance, demonstrating an average degradation of 4 to 6 dB for every 10-foot increment.

2. The presence of obstacles significantly diminishes signal strength, resulting in an additional loss of approximately 3 to 5 dB for every two obstructions introduced.

3. Walls and human bodies accounted for the greatest signal attenuation, with walls causing substantial reflection and absorption, while human interference led to reductions of 6 to 8 dB due to water content absorption.

4. The cumulative effects of multiple obstacles were found to be nonlinear, leading to compounded losses that exceeded simple additive measures.

5. The findings were consistent with the log-distance path loss model and closely aligned with empirical results from previous studies (e.g., Seybold 2005; Chun et al. 2018).

6. The practical implications indicate that the reliability of ZigBee technology indoors is significantly dependent on environmental conditions, exhibiting optimal performance in line-of-sight (LOS) scenarios while rapidly deteriorating in non-line-of-sight (NLOS) or cluttered environments.

In conclusion, this study provides quantitative, real-world data elucidating the variability of ZigBee RSSI across controlled distances and varying densities of obstacles, thereby addressing empirical gaps identified in prior qualitative investigations.

5.2 Conclusion:

The study effectively assessed the performance of ZigBee Received Signal Strength Indication (RSSI) in indoor environments, affirming that signal degradation is predominantly influenced by distance and the density of obstacles. The collected RSSI data aligned with the theoretical predictions established by wireless propagation models; however, it also underscored how environmental factors exacerbate attenuation in practical applications.

The following conclusions can be drawn from the study:

1. ZigBee networks demonstrate efficacy for short-range communication, specifically at distances below 30 feet, yet necessitate optimization within cluttered indoor environments.

2. Interference from obstacles, particularly walls and the presence of individuals, represents the most significant constraint on signal reliability.

3. Notwithstanding these challenges, ZigBee technology remains applicable for Internet of Things (IoT) and sensor-based indoor applications when appropriately configured and deployed, utilizing optimal node placement and mesh topologies.

In summary, this study offers empirical evidence that enhances the design of wireless sensor networks and advances the understanding of propagation dynamics in academic and comparable indoor settings.

5.3 Recommendations

Based on the findings and analysis, the following recommendations are proposed to enhance the performance of ZigBee networks:

1. Optimal Node Placement – It is advisable to position ZigBee nodes to maintain line-of-sight links whenever feasible and to space them no farther than 30 feet apart in environments with obstructions.

2. Implementation of Mesh Networking – ZigBee should be deployed using a mesh topology to facilitate automatic rerouting of data through intermediate nodes when direct communication paths are obstructed.

3. Conducting Environmental Mapping – Prior to installation, it is essential to perform site surveys to identify significant signal blockers—such as walls, metallic structures, and dense furniture—and to strategically plan node placement in accordance with these findings.

4. Signal Enhancement Strategies – The use of repeaters or routers in areas with high interference is recommended to reinforce connectivity and mitigate packet loss.

5. Channel Optimization Techniques – It is important to select ZigBee communication channels that have minimal overlap with Wi-Fi and Bluetooth frequencies to reduce the likelihood of cross-interference.

6. Regular Maintenance Protocols – Regular assessments of Received Signal Strength Indicator (RSSI) and link quality indicators should be conducted to identify any environmental changes that could impact communication.

The implementation of these measures is expected to significantly enhance the robustness and reliability of ZigBee networks in indoor applications, particularly within academic institutions and smart building environments.

5.4 Suggestions for Future Work

Although this study successfully achieved its objectives, several areas warrant further investigation:

1. Inclusion of Additional Environmental Variables – Future research could examine the effects of humidity, temperature, and building materials on Received Signal Strength Indicator (RSSI) behavior.

2. Comparative Performance Studies – A comparative analysis of ZigBee with other 2.4 GHz technologies, such as Wi-Fi, or Bluetooth under controlled conditions, would enhance the understanding of their respective trade-offs.

3. Real-Time Dynamic Testing – It is recommended to conduct experiments incorporating dynamic obstacles, such as the movement of individuals, to accurately model time-varying fluctuations in RSSI.

4. Extended Range and Multi-Floor Analysis – Assessing performance across multiple floors and over extended distances will facilitate the development of three-dimensional propagation models.

5. Machine Learning-Based RSSI Prediction – Future investigations should consider the integration of predictive algorithms to estimate signal strength and optimize node placement in a dynamic manner.

These proposed extensions will yield deeper insights into the performance of indoor wireless communication and further enhance the reliability of ZigBee-based Internet of Things (IoT) systems.

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