A COMPARATIVE ANALYSIS OF IEEE 802.15.4 ADAPTERS FOR WIRELESS RANGEFINDING

THESIS

Andrew P. Seitz, MSgt, USAF

AFIT-ENG-MS-16-M-045

DEPARTMENT OF THE AIR FORCE
AIR UNIVERSITY

AIR FORCE INSTITUTE OF TECHNOLOGY

Wright-Patterson Air Force Base, Ohio

AFIT-ENG-MS-16-M-045

A COMPARATIVE ANALYSIS OF IEEE 802.15.4 ADAPTERS FOR WIRELESS RANGEFINDING

THESIS

Presented to the Faculty

Department of Electrical and Computer Engineering

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

in Partial Fulfillment of the Requirements for the

Degree of Master of Science in Cyber Operations

Andrew P. Seitz, BS

MSgt, USAF

March 2016

AFIT-ENG-MS-16-M-045

A COMPARATIVE ANALYSIS OF IEEE 802.15.4 ADAPTERS FOR WIRELESS RANGEFINDING

THESIS

Andrew P. Seitz, BS
MSgt, USAF

Committee Membership:

Maj Benjamin W. Ramsey, PhD
Chair

LTC Mason J. Rice, PhD
Member

Barry E. Mullins, PhD
Member

AFIT-ENG-MS-16-M-045

Abstract

ZigBee wireless networks have become increasingly prevalent over the past decade. Based on the IEEE 802.15.4 low data rate wireless standard, ZigBee offers low-cost mesh connectivity in hospitals, refineries, building automation, and critical infrastructure.

This thesis explores two ZigBee Received Signal Strength Indicator (RSSI)-based rangefinding tool sets used for assessing wireless network security: Z-Ranger and Zbfind. Z-Ranger is a new tool set developed herein for the Microchip Zena Wireless Adapter that offers configurable distance estimating parameters and a RSSI resolution of 256 values. Zbfind is an application developed for the Atmel RZUSBstick with no configurable distance estimating parameters and a RSSI resolution of 29 values.

The two tool sets are evaluated while rangefinding four low-rate wireless devices indoors and two devices outdoors. Mean error is calculated at each of the 35 collection points and a 99% confidence interval and p-Test are used to identify statistically significant deviations between the two tool sets.

Results indicate that calibration of the reference Received Signal Strength (RSS) or an increase in RSSI resolution do not conclusively reduce mean distance estimation error. This conclusion is the result of three rounds of tool set evaluations. In the first round, Z-Ranger is calibrated with a reference RSS parameter and evaluated against Zbfind. In the second round, both tool sets are calibrated with unique distance estimating parameters in which Z-Ranger executes with similar results to that of Zbfind. In the final round of evaluation, RSS windowing is explored and presented for both tool sets; however, no conclusive gains in rangefinding accuracy are observed for either.

The result of this research is that Z-Ranger is found to be a rangefinding tool set that consistently performs at least as well as Zbfind. This in turn offers users an alternative open source tool set (hardware and software) for rangefinding low-rate wireless devices.

To my beautiful wife and daughters.

Table of Contents

Page

Abstract iv

List of Figures viii

List of Tables ix

List of Acronyms x

I. Introduction 1

1.1 Problem Statement 1
1.2 Hypothesis 3
1.3 Research Goals 3
1.4 Approach 3
1.5 Assumptions 4
1.6 Thesis Overview 4

II. Background and Related Research 5

2.1 Low Rate Wireless Technologies 5
2.1.1 IEEE 802.15.4 5
2.1.2 ZigBee 9
2.2 KillerBee Tool Set Suite 11
2.3 Zbfind Tool Set 12
2.3.1 Hardware 13
2.3.2 RSS Distance Calculation 14
2.4 Z-Ranger Tool Set 15
2.4.1 Hardware 15
2.4.2 Software 16
2.5 Related Research 19
2.5.1 RSSI-Based localization 19
2.5.2 LR-WPAN Tool Sets 20
2.6 Summary 22

III. Tool Set Development 23

3.1 Z-Ranger Development 23
3.1.1 Distance Estimation 24
3.2 Zbfind Code Modification 29
3.3 Summary 30

Page

IV. Methodology . . . 31

4.1 Overview . . . 31
4.2 System Boundaries . . . 31
4.3 Work Load . . . 32
4.3.1 Z-Ranger . . . 32
4.3.2 Zbfind . . . 32
4.4 Metrics . . . 32
4.4.1 Mean Absolute Percent Error . . . 32
4.4.2 Evaluating Accuracy . . . 33
4.5 System Parameters . . . 33
4.6 Factors . . . 35
4.6.1 Indoor Target Devices . . . 35
4.6.2 Outdoor Target Devices . . . 38
4.6.3 Antenna Orientation and Placement . . . 41
4.6.4 RSSI Samples Measured . . . 42
4.6.5 Factors Summary . . . 43
4.7 Evaluation Technique . . . 44
4.7.1 Indoor Evaluation . . . 46
4.7.2 Outdoor Evaluation . . . 46
4.8 K-fold Cross-Validation . . . 47
4.8.1 Indoors . . . 48
4.8.2 Outdoors . . . 50
4.9 Summary . . . 51

V. Results and Analysis . . . 52

5.1 Initial Tool Set Comparison . . . 52
5.1.1 Indoors . . . 52
5.1.2 Outdoors . . . 55
5.2 Best fit Parameter Refinement . . . 58
5.2.1 Indoors . . . 60
5.2.2 Outdoors . . . 64
5.3 RSS Windowing . . . 68
5.3.1 Indoor RSS Sliding Window . . . 69
5.3.2 RSS Windowing Results . . . 70
5.4 Z-Ranger Implementation . . . 71
5.5 Production Tool Set Comparison . . . 76
5.6 Conclusion . . . 78
5.7 Summary . . . 79

Page

VI. Conclusion and Recommendations 80

6.1 Conclusions of Research 80
6.1.1 Goal 1: Determine if an increase in RSSI resolution reduces mean distance estimation error 80
6.1.2 Goal 2: Determine if a configurable reference RSS parameter decreases mean distance estimation error 80
6.1.3 Goal 3: Develop a new low-rate wireless device rangefinding tool set that is at least as accurate as the existing Zbfind tool set 80
6.2 Research Contributions 81
6.3 Recommendations For Future Work 81
6.3.1 Exploring SDR Rangefinding 81
6.3.2 Rangefinding on an iOS Device 82
6.3.3 Selective RSSI-based Distance Estimation Technique 82

Appendix A. Source Files 83

A.1 Z-Ranger 83
A.2 RZUSBstick 83
A.3 NI USRP-2921 84
A.3.1 GNU Radio Installation 84
A.3.2 IEEE 802.15.4 Module 84

Appendix B. Data Tables 85

B.1 RSSI-to-RSS Conversion Tables 85
B.1.1 Published MRF24J40 Converion Table 85
B.1.2 Extended MRF24J40 Conversion Table 86
B.2 Best fit Parameter Discovery Tables 88
B.2.1 Indoor Targets 88
B.2.2 Outdoor Targets 92

Appendix C. Windowing Table Results 94

C.1 Z-Ranger 94
C.1.1 Indoor RSS Sliding Window 94
C.1.2 Outdoor RSS Sliding Window 94
C.1.3 Indoor RSS Sequential Window 95
C.1.4 Outdoor RSS Sequential Window 95

Bibliography 96

List of Figures

Figure		Page
1	IEEE 802.15.4 and ZigBee defined LR-WPAN layers.	6
2	An IEEE 802.15.4 PHY and MAC defined data frame [Ada06].	8
3	Two network architectures identified in the IEEE 802.15.4 standard. Adapted from [BPC+07].	10
4	Example of Zbfind rangefinding a low-rate wireless device.	13
5	Image of the Atmel RZ USB stick.	14
6	Image of the Microchip Inc. Zena Wireless Adapter.	16
7	ZenaNG.c application displaying collected packets from channel 15 in hex format.	18
8	The command `./zenang -h` is used to display all available features and version information for the ZenaNG.c application. Adapted from [Ver13]	18
9	The WiPry application and WiPry Pro hardware front-end [Osc15].	22
10	Zena USB packet schema for both short and long IEEE 802.15.4 packets. Adapted from [Des11].	24
11	The C struct used to hold the Zena USB packet and attributes, found within the Zena.c application [Ver13].	25
12	Example of Z-Ranger execution using default parameters.	29
13	Example of Z-Ranger execution with user specified parameters of: $A = -58.0$ dBm and $P = 3.0$.	29
14	Python print statements added to the Zbfind source code.	30
15	Terminal output of Python print statements added to Zbfind source code.	30
16	The defined System Under Test for this research.	31

Figure Page

17 Indoor ZigBee target devices a) Freescale MC13213, b) Phillips Hue bridge, c) Awarepoint S2, and d) Atmel RZUSBstick 36

18 The execution of Zbid and Zbstumbler on the RZUSBstick; used to send beacon request frames during indoor experiment. 38

19 The indoor collection corridor with dimensions measuring 3 m by 3 m by 125 m. The star indicates the position of the target device and the arrow indicates the direction the target device faces. 38

20 Outdoor ZigBee target devices a) Itron Openway CENTRON smart meter and b) NI USRP-2921 40

21 The CENTRON smart meter is positioned at the 0 m marker with RSSI measurements taken along the path of the measurement line. 41

22 The NI USRP-2921 is positioned at the 0 m marker with RSSI measurements taken along the path of the measurement line. 41

23 Both indoor and outdoor target device setup and orientation during collection trials. 42

24 Indoor RSSI sample measurement setup. 47

25 Outdoor RSSI sample measurement setup. 47

26 K-fold cross-validation technique used to discover the A parameter for Z-Ranger [Koh95]. 49

27 This figure depicts the MAPE produced by Z-Ranger during indoor rangefinding using parameters discovered from the cross-validation method. The MAPE produced by Zbfind is the result of using original values. 55

28 This figure depicts the MAPE produced by Z-Ranger during outdoor rangefinding using parameters discovered from the cross-validation method. The MAPE produced by Zbfind is the result of using original values. 58

Figure Page

29 This figure depicts the MAPE produced by Z-Ranger and Zbfind during indoor rangefinding using parameters discovered from the best fit method. 63

30 This figure depicts the MAPE produced by Z-Ranger and Zbfind during outdoor rangefinding using parameters discovered from the best fit method. 68

31 This figure depicts the MAPE produced by Z-Ranger during indoor rangefinding using parameters discovered from both the cross-validation and best fit log-distance path loss parameter discovery methods. 72

32 This figure depicts the MAPE produced by Z-Ranger during outdoor rangefinding using parameters discovered from both the cross validation and best fit parameter discovery methods. 73

33 Example execution of Z-Ranger rangefinding a RZUSBstick indoors. 75

34 Example execution of Z-Ranger rangefinding a NI USRP-2921 outdoors. 75

35 This figure depicts how the production tool sets compare in an indoor rangefinding scenario. Each tool set is configured to use default parameters for rangefinding select devices. 77

36 This figure depicts how the production tool sets compare in an outdoor rangefinding scenario. Each tool set is configured to use default parameters for rangefinding select devices. 77

37 Zbfind source code modification. 84

List of Tables

Table		Page
1	Overview of RF characteristics defined by PHY layer.	7
2	The RSSI-to-RSS conversion list for the AT86RF230 transceiver.	15
3	Comparison of the Microchip Zena wireless adapter and the Atmel RZUSBstick wireless adapter platforms.	16
4	The MRF24J40 published RSS-to-RSSI values. Adapted from [Mic10]. The full table can be found in Appendix B	26
5	Extended RSSI-to-RSS mapping for the Zena Wireless Adapter. The full table can be found in Appendix B.	27
6	Indoor target device transmission power levels.	34
7	Outdoor target device transmission power levels.	34
8	Summary of rangefinding experiment factors.	44
9	Five indoor folds and corresponding average RSS samples for Z-Ranger.	50
10	5-fold cross-validation for indoor Z-Ranger A parameter.	50
11	Three outdoor folds and corresponding average RSS samples for Z-Ranger.	51
12	3-fold cross validation for outdoor Z-Ranger A parameter.	51
13	Indoor distance estimates and corresponding MAPE produced by Z-Ranger using the values of $A = -43.46$ and $P = 3.0$.	53
14	Indoor distance estimates and corresponding MAPE produced by Zbfind using the parameters of $A = -58.0$ and $P = 3.0$.	54
15	Outdoor distance estimates and corresponding MAPE produced by Z-Ranger using the parameters of $A = -39.55$ and $P = 3.0$.	56

Table Page

16 Outdoor distance estimates and corresponding MAPE produced by Zbfind using the parameters of $A = -58.0$ and $P = 3.0$. 57

17 Identified path-loss exponents from different environments. Adapted from [Rap96]. 59

18 Best fit P and corresponding A parameters for the Z-Ranger tool set. The Best fit P and A parameters displayed are found to produce the least amount of MAPE for each indoor target device. 61

19 Indoor distance estimates and corresponding MAPE produced by Z-Ranger using the parameters of $A = -38.93$ and $P = 2.75$. 61

20 The best fit P and corresponding A parameters for the Zbfind tool set. The best fit P and A parameters displayed are found to produce the least amount of MAPE for each indoor target device. 62

21 Indoor distance estimates and corresponding MAPE produced by Zbfind using the parameters of $A = -49.33$ and $P = 2.25$. 62

22 Best fit P and corresponding A parameters for the Z-Ranger tool set. The Best fit P and A parameters displayed are found to produce the least amount of MAPE for each outdoor target device. 65

23 Outdoor distance estimates and corresponding MAPE produced by Z-Ranger using best fit parameters of $A = -26.2$ and $P = 2.5$. 65

24 Best fit P and corresponding A parameters for the Zbfind tool set. The best fit P and A parameters displayed are found to produce the least amount of MAPE for each outdoor target device. 66

25 Outdoor distance estimates and corresponding MAPE produced by Zbfind using best fit parameters of $A = -29.4$ and $P = 2.35$. 67

26 Indoor RSS sliding window MAPE comparison for Z-Ranger. 70

Table Page

27 Z-Ranger log-distance path loss parameter discovery method comparison for an indoor environment. 72

28 Z-Ranger log-distance path loss parameter discovery method comparison for an outdoor environment. 73

29 The MRF24J40 published RSS-to-RSSI values. Adapted from [Mic10]. 85

30 Extended RSSI-to-RSS mapping for the Zena Wireless Adapter. 86

30 Extended RSSI-to-RSS mapping for Zena wireless adapter. 87

31 Best fit values for P $\in$ {1.6-4.0} for the Phillips Hue Bridge 88

32 Best fit values for P $\in$ {1.6-4.0} for the Awarepoint S2 89

33 Best fit values for P $\in$ {1.6-4.0} for the Freescale MC13213 90

34 Best fit values for P $\in$ {1.6-4.0} for the Atmel RZUSBstick 91

35 Best fit values for P $\in$ {1.6-4.0} for the Openway CENTRON smart meter 92

36 Best fit values for P $\in$ {1.6-4.0} for the NI USRP-2921 93

37 Indoor RSS sliding window MAPE comparison for Z-Ranger. 94

38 Indoor RSS sliding window MAPE comparison for Zbfind. 94

39 Outdoor RSS sliding window MAPE comparison for Z-Ranger. 94

40 Outdoor RSS sliding window MAPE comparison for Zbfind. 94

41 Indoor RSS sequential window MAPE comparison for Z-Ranger. 95

Table Page

42 Indoor RSS sequential window MAPE comparison for Zbfind. 95

43 Outdoor RSS sequential window MAPE comparison for Z-Ranger. 95

44 Outdoor RSS sequential window MAPE comparison for Zbfind. 95

List of Acronyms

Acronym		Page
RSSI	Received Signal Strength Indicator	iv
WSN	Wireless Sensor Network	1
IEEE	Institute of Electrical and Electronics Engineers	1
LR-WPAN	Low-Rate Wireless Personal Area Network	1
RZUSBstick	Atmel RZ USB stick	2
RSSI	Received Signal Strength Indicator	2
RSS	Received Signal Strength	2
MAPE	Mean Absolute Percentage Error	3
CI	Confidence Interval	3
OS	Operating System	4
OSI	Open Systems Interconnection	5
PHY	Physical	5
MAC	Media Access Control	5
NWK	Network	5
APL	Application Layer	5
ED	Energy Detection	6
LQI	Link Quality Indictor	6
CCA	Clear Channel Assessment	6
RF	Radio Frequency	6
O-QPSK	Offset-Quadrature Phase Shift Keying	6
BPSK	Bi-Phase Shift Keying	6
SHR	Synchronization header	7

Abbreviation		Page
SFD	Start Frame Delimiter	7
PHR	PHY header	7
PSDU	PHY Service Data Unit	7
MHR	MAC header	7
PPDU	PHY Protocol Data Unit	7
MSDU	MAC Service Data Unit	7
FCS	Frame Check Sequence	7
MFR	MAC Footer	7
GTS	Guaranteed Time Slot	7
CSMA	Carrier Sense Multiple Access	7
CD	Collision Detection	8
CA	Collision Avoidance	8
FFD	Full Function Device	8
RFD	Reduced Function Device	8
PAN	Personal Area Network	8
ZDO	ZigBee Device Object	10
APS	Application Support	10
GUI	Graphical User Interface	12
USB	Universal Serial Bus	13
MCU	Microcontroller Unit	13
mW	milliwatt	15
WDS	Wireless Development Studio	16
SUT	System Under Test	31
LOS	Line Of Sight	35

Abbreviation		Page
SIP	System in a Package	36
NI	National Instruments	38
USRP	Universal Software Radio Peripheral	38
SDR	Software Defined Radio	39
GRC	GNU Radio Companion	39
GB	Gigabytes	44
VM	Virtual Machine	44
HP	Hewlett Packard	44
UHD	USRP Hardware Driver	45
FILO	First In Last Out	68
ICCWS	International Conference on Cyber Warfare and Security	76

A COMPARATIVE ANALYSIS OF IEEE 802.15.4 ADAPTERS FOR WIRELESS RANGEFINDING

I. Introduction

Implementing Wireless Sensor Network (WSN)s in everything from home automation to national critical infrastructure has become common practice over the last decade. Many WSNs are collections of energy-efficient, short-range sensors that conform to the Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 specification for Low-Rate Wireless Personal Area Network (LR-WPAN)s [IEE03]. The ZigBee alliance further defines interoperability between networked devices by publishing their network and application layer [Zig12] specifications. These standards build upon the IEEE 802.15.4 protocol foundation, improving network security and adding advanced routing features. Industry took notice, implementing tens of millions of upgraded ZigBee Smart Energy utility meters as part of an Advanced Metering Infrastructure [Whi07], tracking patients and equipment throughout hospitals [Jih11], and adapting smart cameras into legacy building automation systems [SKG12]. The use of LR-WPAN sensors in these sensitive facilities has prompted researchers and policy makers to question the secureness of the these networks. The sensitive data that traverse these simple wireless sensors elevates the need for a secure operational environment and the right tools to accurately assess network vulnerabilities.

1.1 Problem Statement

The main task of a wireless network security penetration tester (referred to as tester) is to assess the level of secureness by actively probing, exploiting, and attack-

ing. One attack vector, known as *warwalking*, is to physically locate a network device or end point by using a rangefinding tool while walking to its estimated location, recalculating a distance estimate at every step. Once the device is located, the tester can tamper with, break, or steal it. Otherwise, they may launch a more nefarious longterm data exfiltration attack. Recent work has shown network encryption keys of first and second generation ZigBee devices may be recovered by an attacker that has gained physical access to the device [Goo09]. Discovery of a network vulnerability before it can be leveraged by an attacker is a core function for any tester.

One open source application used for rangefinding and locating ZigBee devices during penetration testing is called *Zbfind*. The Zbfind tool is a Python-based application found within the *KillerBee* IEEE 802.15.4 attack suite of tools, released by Joshua Wright in 2010 [WSM10]. Currently, the only supported hardware for Zbfind is the Atmel RZ USB stick (RZUSBstick). The term *tool set*, in the context of this thesis, makes reference to the software application and hardware as one complete set. During execution of the Zbfind application, the RZUSBstick quantifies Received Signal Strength Indicator (RSSI) with a resolution of 29 possible values. Compounding this hardware restricted range of values, the Zbfind application offers no target device selection or distance estimating parameter configuration, leaving the tool set to a one-size-fits-all approach to rangefinding wireless devices.

This research suggests an alternative platform to build a ZigBee rangefinding application upon. The Microchip Inc. *Zena* Wireless Adapter (henceforth referred to as Zena) quantifies RSSI at a resolution of 256 values, which is almost nine times greater than that of the former. Coupled with the Zena hardware, a software application is developed to offer the user a configurable environmental path-loss parameter and reference Received Signal Strength (RSS) parameter, two parameters critical for RSSI-based distance estimation [RMLS14]. This new tool set is named *Z-Ranger*.

1.2 Hypothesis

The hypothesis of this research is that there is a statistical difference in mean distance estimation error while rangefinding low-rate wireless devices as a result of an increase in RSSI resolution and configuration of the reference RSS parameter. Testing of the hypothesis requires two rangefinding tool sets. The Z-Ranger and Zbfind tool sets satisfy the outlined necessities. Z-Ranger offers an RSSI resolution of 256 values compared to the 29 values possible in Zbfind. Z-Ranger also offers the user an option to configure both environmental path-loss and reference RSS parameters, a feature not present in Zbfind.

1.3 Research Goals

The primary goal of this research is to: (1) determine if an increase in RSSI resolution reduces mean distance estimation error; (2) determine if a configurable reference RSS parameter reduces mean distance estimation error; and (3) develop a new low-rate wireless device rangefinding tool set that is at least as accurate as the existing Zbfind tool set. To achieve these goals, software development, indoor and outdoor distance estimation collection trials, and post collection analysis are conducted.

1.4 Approach

Both rangefinding tool sets are compared and evaluated over a series of indoor and outdoor collection trials, where 8120 RSS samples are measured from four indoor and two outdoor ZigBee devices. By comparing tool set (distance estimation to actual distance), Mean Absolute Percentage Error (MAPE) is calculated. A 99% Confidence Interval (CI) is then calculated for the error values to identify any difference in MAPE.

Comparing p values allows a statistically significant increase or decrease in accuracy to be identified, if one exists. Based on these calculated percentages, tool set refinements and recommendations are quantified and implemented.

1.5 Assumptions

This research evaluates the performance of the Zbfind application included in KillerBee (version 1.0) that is bundled with the Kali Linux (version 2.0) Operating System (OS) [Sec15]. This version of Zbfind represents the most widely distributed and easily accessible tool set. Improvements from previous work by Ramsey et al. [RMW12] have been incorporated into the Zbfind revision 47 (r47) distribution available for download from Github [WSM10]. However, since improvements from Ramsey et al. [RMW12] are not included in the Kali Linux distribution it is unlikely that a novice user would update it independently. Taking this into consideration, the Kali Linux distribution offers the most realistic representation of distance estimates from users in the field and thus it is used in this comparison analysis study.

1.6 Thesis Overview

Chapter II provides background and related work. Chapter III details the Z-Ranger tool set development and programming. Chapter IV discusses the system under test and experiment design. Chapter V describes the results and tool set refinement recommendations. Finally, Chapter VI offers a summary of this thesis and provides recommendations for future research based on the discoveries herein.

II. Background and Related Research

Section 2.1 discusses two common low-rate sensor specifications, IEEE 802.15.4 and ZigBee. Section 2.2 explains the KillerBee attack suite of tools. Section 2.3 provides an in-depth explanation of Zbfind, the defacto rangefinding tool set for ZigBee. Section 2.4 details the Zena Wireless Adapter. Section 2.5 concludes the chapter with related research and a summary of the topics discussed.

2.1 Low Rate Wireless Technologies

2.1.1 IEEE 802.15.4.

The IEEE is the largest technical expertise society with over 395,000 members from 130 countries [IEE15]. Members consist of software developers, medical doctors, physicists, and information technology professionals. One of their main objectives is to advance humanity through the use and standardization of technologies across the globe. Some well known and widely accepted standards include of the 802.11 wireless LAN, also known as Wi-Fi, and the 802.3 standard for wired Ethernet.

Released by the IEEE in 2003, the 802.15.4 standard outlines the requirements for low-cost, low-power, low-rate ($<$ 250 kb/s) LR-WPANs. Figure 1 depicts how the 802.15.4 and ZigBee defined layers, align with the Open Systems Interconnection (OSI) model layers. The 802.15.4 protocol specification defines the Physical (PHY) and Media Access Control (MAC) layers for LR-WPAN interconnectivity. The ZigBee specification details the upper Network (NWK) and Application Layer (APL).

2.1.1.1 PHY Layer.

The PHY layer is designed to manage access to the transmission medium and operation of the radio. The PHY layer offers the following features: transceiver

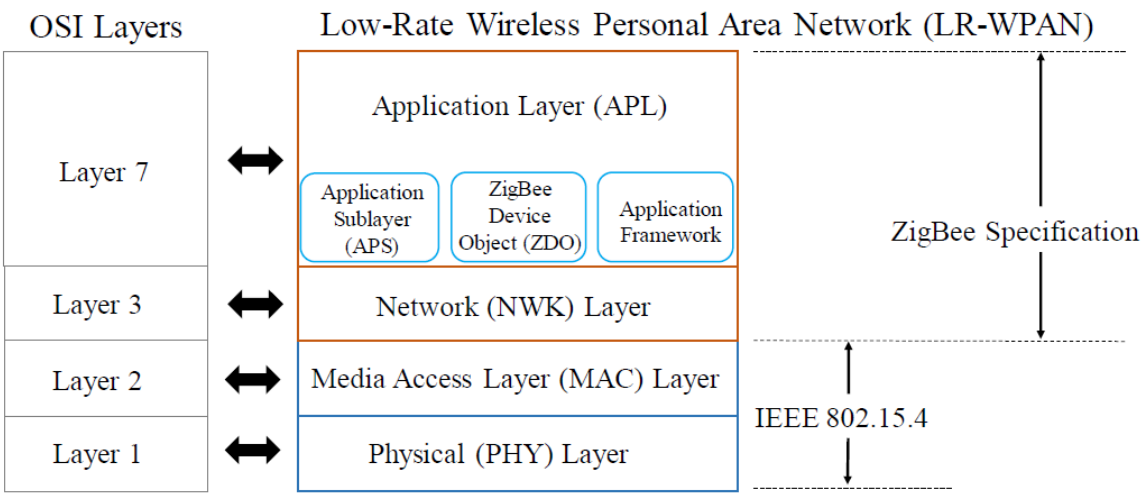


Figure 1. IEEE 802.15.4 and ZigBee defined LR-WPAN layers.

management, Energy Detection (ED), Link Quality Indictor (LQI), Clear Channel Assessment (CCA), data transmission, and Radio Frequency (RF) band management. Transceiver management ensures the radio is turned on and off for transmission or reception. ED is quantifying the received energy level into a numeric value, also known as RSSI. A CCA checks the energy levels in the medium before a transmission starts. This ensures one radio does not transmit at the same time as another nearby radio.

Table 1 provides an overview of the three RF bands defined by the PHY layer. The three defined bands for operation are: 868 MHz, 916 MHz, and 2450 MHz. The 868 MHz band is used in Europe and consists of one channel. The 915 MHz band is used North America and consists of 10 channels with 2 MHz spacing between each. The 2450 MHz band is used in North America and consists of 16 channels with 5 MHz spacing between each. The 2450 MHz band employs Offset-Quadrature Phase Shift Keying (O-QPSK) modulation, while the other two bands (868 MHz and 915 MHz) employ Bi-Phase Shift Keying (BPSK) modulation [IEE11].

The PHY layer also defines four types of frames used for transmission; they are: Beacon, Acknowledgment, Data, and MAC command. Figure 2 provides an example

Table 1. Overview of RF characteristics defined by PHY layer.

RF Band	Frequency Range (MHz)	Channels per Band	Modulation	Data Rate
868 MHz	868-868.6	1	BPSK	< 20 kb/s
916 MHz	902-928	10 (Numbered 1-10)	BPSK	< 40 kb/s
2450 MHz	2400-2483.5	16 (Numbered 11-26)	O-QPSK	< 250 kb/s

illustration of a Data frame and serves as a representation of the other three frame structures due to their similarity. The Synchronization header (SHR) contains two parts: the preamble, which is a sequence of bits that allow the receiver to synchronize and acquire an incoming signal; and the Start Frame Delimiter (SFD), which identifies the end of the preamble. The PHY header (PHR) is the sixth byte in the frame and contains the frame length byte, which identifies the length of the PHY Service Data Unit (PSDU). The PSDU contains the MAC header (MHR), composed of the frame control, data sequence number, and device addressing information. The SHR, PHR, and PSDU make up the overall PHY Protocol Data Unit (PPDU) frame. The payload of the frame is held in the MAC Service Data Unit (MSDU), and there is 16-bit Frame Check Sequence (FCS) in the MAC Footer (MFR) that marks the end of the frame.

2.1.1.2 MAC Layer.

The MAC layer mirrors the Data Link layer in the OSI model, offering similar features and device management services. All interaction between upper layer applications and the PHY radio channel is handled by the MAC layer. Some features and services the MAC layer offers are: association and disassociation of devices to the network, frame validation, Guaranteed Time Slot (GTS) management, network beacon generation, Carrier Sense Multiple Access (CSMA) mechanisms, and frame acknowledgment. Frame validation ensures each frame is properly addressed and fits the length requirements specified in the 802.15.4 standard. GTS assigns time slots to devices for uninterrupted access to the medium for transmission. Network bea-

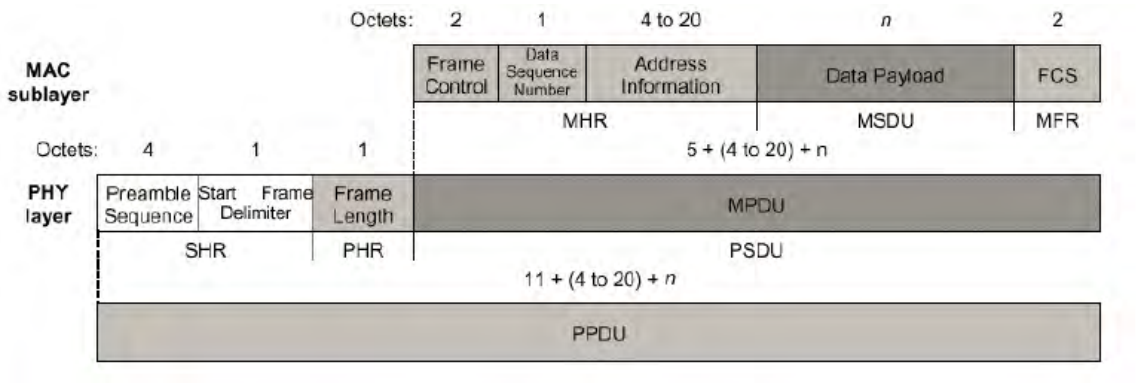


Figure 2. An IEEE 802.15.4 PHY and MAC defined data frame [Ada06].

cons are used for timing, synchronization, and network discovery. Some common CSMA mechanisms employed consist of: ALOHA, CSMA-Collision Detection (CD), and CSMA-Collision Avoidance (CA). These mechanisms allow multiple users access to the same wireless medium without interfering with each other. Frame acknowledgment occurs when successful reception and validation of a data or MAC command frame is observed, an *ACK* frame is sent to notify the sender.

2.1.1.3 Devices and Topologies.

As described in the 802.15.4 standard, LR-WPAN topologies consist of Full Function Device (FFD)s and Reduced Function Device (RFD)s. An FFD operates with all MAC functions and is able to organize other devices as the Personal Area Network (PAN) coordinator. FFDs are capable of addressing, routing, and forwarding frames throughout a network. Every LR-WPAN requires a PAN coordinator to assign a PAN ID and manage the network; only a FFD is capable of these functions. An RFD operates as a simple device with little implementation complexity. RFDs can only be used as end devices and can only communicate with FFDs.

Two network architectures supported in the 802.15.4 standard are *star* and *mesh* topologies. Figure 3a provides a diagram of a star network with a PAN coordinator managing all traffic from outlying devices. Star topologies provide all interconnec-

tivity between outlying devices through one central device. Communication frames are routed to the PAN coordinator for processing or are routed to the specified end device. This type of architecture is typically seen when all network data must be monitored or filtered by one central device (i.e., the PAN coordinator).

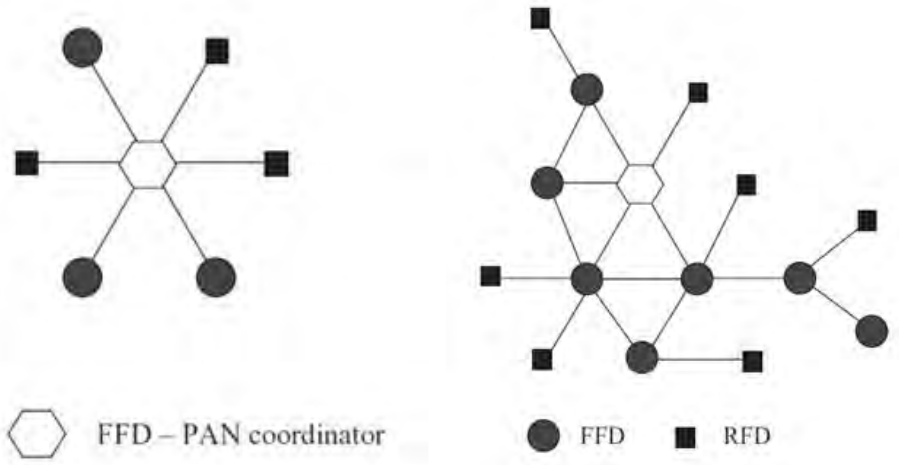
Figure 3b provides a diagram of a mesh network, where all routing is performed by FFDs. Mesh networking allows all nodes to communicate with each other without direct contact with the PAN coordinator. This network architecture provides the ultimate in flexibility and redundancy, minimizing network congestion and increasing the route failure tolerance level.

2.1.2 ZigBee.

The ZigBee Alliance is a global non-profit association comprised of government regulatory groups, corporate sponsors, and universities focused on the advancement of low-rate, energy efficient wireless networking standards [Zig15]. Released in 2003, with revisions in 2006 and 2007, the ZigBee protocol is a low-cost, low-power consumption, two-way wireless communication standard that operates in the 2450 MHz band [Zig12]. The ZigBee stack architecture is comprised of the NWK and APL that provide services to the next higher and lower layers. By standardizing these services, developers can expect a baseline capability for any device certified by the ZigBee Alliance.

2.1.2.1 NWK.

The NWK layer supports three device types: ZigBee end device, ZigBee router, and ZigBee coordinator. The ZigBee end device is similar to a RFD or FFD, acting as a node on the edge of a network. The ZigBee router, which must be an FFD, provides routing capabilities for the network. The third device is the ZigBee coordi-



(a) Star network. (b) Mesh network.

Figure 3. Two network architectures identified in the IEEE 802.15.4 standard. Adapted from [BPC+07].

nator, the equivalent of a PAN coordinator, which manages the entire network from one device. The NWK layer provides device addressing, neighbor discovery, route discovery, authentication, confidentiality, and configuration of new devices [Zig12].

Network establishment is also handled at this layer by the ZigBee coordinator. A beacon request is used to identify local ZigBee networks. Sent by any of the three types of ZigBee devices, a beacon request must be acknowledged by any device in an existing network within receiving distance. If no reply is received, a ZigBee coordinator may start a new network. ZigBee networks require a specified channel to operate on, along with the PAN ID, ZigBee version indicator, and security level [BPC+07].

2.1.2.2 APL.

The APL provides the Application Framework, the ZigBee Device Object (ZDO), and the Application Support (APS) sub-layer. These sub-layers provide a basic level

of service for all ZigBee compliant devices allowing ease of installation, lower costs, and a faster prototype development time line.

The Application Framework is the environment in which ZigBee application objects are hosted on devices [Zig12]. The application framework can host up to 254 application objects. The framework consists of application profiles and clusters. Application profiles (e.g., home automation, input devices, or light link) provide designers an agreed upon level of function based on a specific scenario. This allows designers to develop distributed systems that operate using the same profiles. Clusters identify groups of sensors that are unique to a particular application profile [Zig12].

The ZDO provides basic ZigBee functionality that must be implemented on all devices in a ZigBee network (e.g., device and service discovery). The ZDO presents a mechanism for controlling application objects from a public facing interface. This provides an interface between application objects, device profile, and the application sub-layer [Zig12].

The APS provides the interface between the network layer and the application layer through a general set of services for use by both the ZDO and the manufacturer-defined application objects [Zig12]. Some services and features that APS provides are fragmentation, reliable transport, device authentication, and security.

2.2 KillerBee Tool Set Suite

The KillerBee suite of tools is a Python-based framework used for assessing vulnerabilities and attacking ZigBee and IEEE 802.15.4 compliant LR-WPANs [WSM10]. KillerBee operates in the 2450 MHz band, with RF channels 11-26. Kali Linux, an OS designed for penetration testers, includes the KillerBee suite of tools [Sec15]. Tools included in KillerBee are described below.

Zbstumbler is used for discovering and identifying IEEE 802.15.4 active networks.

This application transmits beacon request frames on each channel in an attempt to solicit a response from nearby wireless sensor networks [WSM10].

Zbreplay is used for implementing replay attacks against an LR-WPAN. By retransmitting previously recorded frames, an attacker may be able to take control of a device and issue commands for execution [WSM10].

Zbid is an application used to identify computer interfaces that are currently associated with a KillerBee compatible hardware tool [WSM10]. A common interface used to attach KillerBee devices is a USB port.

Zbgoodfind is an application that imports previously captured encrypted payloads and executes a *decryption key* search function. Locating a key and decrypting the payload allows an attacker access to the sensitive data stored inside [WSM10].

Zbscapy is an application that implements the *Scapy* project library [Bio03] into the KillerBee framework, allowing an attacker to manipulate LR-WPAN packets. It provides resources to launch a variety of attacks (e.g., SYN flood and preamble manipulation) against the target network [WSM10].

2.3 Zbfind Tool Set

The Zbfind application, also included in the KillerBee suite, is a Graphical User Interface (GUI) based tool used for rangefinding and locating ZigBee and IEEE 802.15.4 compliant devices. Figure 4 provides an example of Zbfind rangefinding a nearby ZigBee target device. In Figure 4 the following metadata is displayed in the top row for the user: dest PAN (destination PAN), dest addr (destination address), src addr (source address), distance, samples, and signal. Distance is the estimated distance

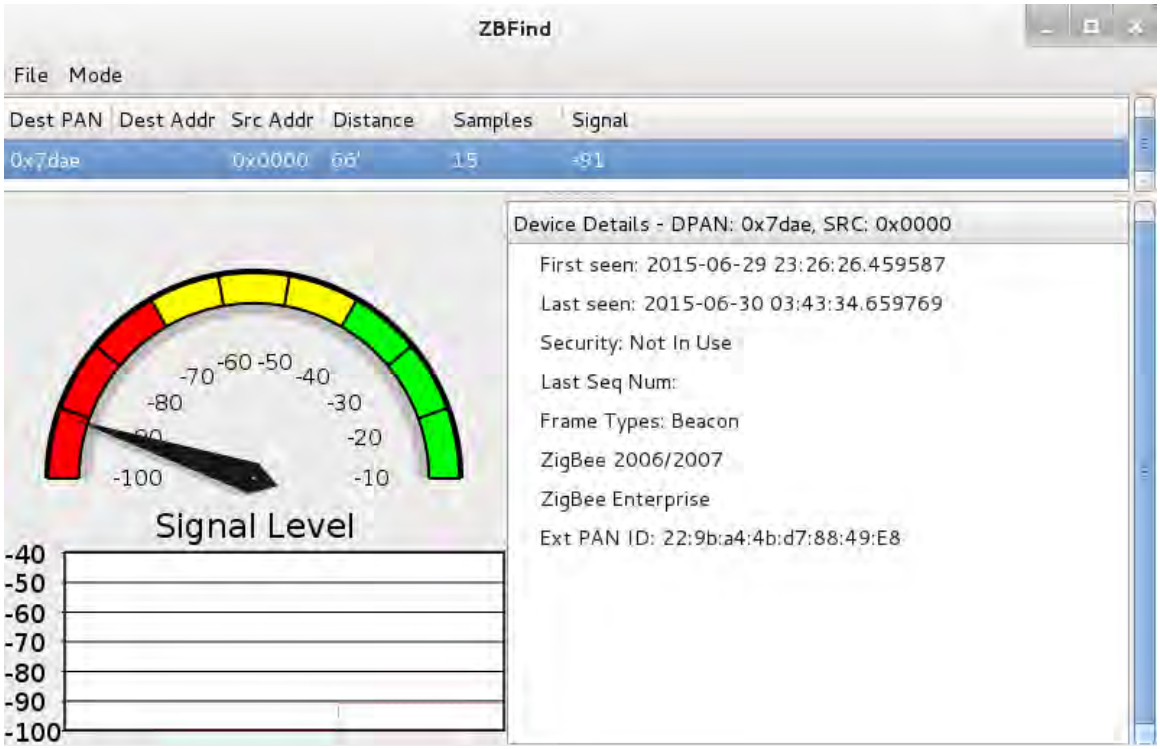


Figure 4. Example of Zbfind rangefinding a low-rate wireless device.

estimate between Zbfind and the target device, displayed in feet, and signal is the hardware measured RSS of the incoming frame [WSM10].

2.3.1 Hardware.

The Zbfind application is designed to only work with the Atmel RZUSBstick. The RZUSBstick, shown in Figure 5, is based on a Universal Serial Bus (USB) stick with an AT90USB1287 Microcontroller Unit (MCU) and an AT86RF230 transceiver [Atm12].

The AT86RF230 is a low-power 2.4 GHz transceiver designed for ZigBee and IEEE 802.15.4 compliant applications. The AT86RF230 measures RSSI over an eight symbol period upon receiving a frame larger than 2-bytes in length with a valid cyclic redundancy check (CRC) [Atm09b]. The RSSI is stored in the lowest five bits of the AT86RF230 8-bit register named *PHY_RSSI*. Although five bits are allocated for

Figure 5. Image of the Atmel RZ USB stick.

RSSI measurements, only a value from *0-28* can be assigned to a RSSI measurement. The AT86RF230 converts RSSI-to-RSS power levels by

$$r = -91 + 3 \cdot (RSSI - 1), \tag{1}$$

where r is the newly converted RSS power level value in dBm, -91 dBM is the RSSI base value for the AT86RF230, and *RSSI* is the hardware measured received signal strength quantified as an integer ranging from $0 - 28$ [Atm09b]. An RSSI value of 0 indicates a RSS < -91 dBm. An RSSI value of 28 represents RSS ≥ -10 dBm. Table 2 identifies all possible RSSI-to-RSS conversions for the AT86RF230. The first and third column display all possible RSSI values in a one-up sequential ordering. In the second column RSS increments in steps of 3 dB. As seen in previous work [RMW12], nearly identical collection scenarios have shown RSSI to vary by one to two values. This fluctuation translates to a three or six dB difference in RSS.

2.3.2 RSS Distance Calculation.

In Zbfind, RSS is calculated using (1) and is passed to the *Log-Distance Path Loss* model. This model calculates distance between transceivers using

$$d \approx 10^{\frac{A-r}{10 \cdot P}}, \tag{2}$$

Table 2. The RSSI-to-RSS conversion list for the AT86RF230 transceiver.

RSSI Value	RSS Value (dBm)	RSSI Value	RSS Value (dBm)
0	< -91	15	-49
1	-91	16	-46
2	-88	17	-43
3	-85	18	-40
4	-82	19	-37
5	-79	20	-34
6	-76	21	-31
7	-73	22	-28
8	-70	23	-25
9	-67	24	-22
10	-64	25	-19
11	-61	26	-16
12	-58	27	-13
13	-55	28	≥ -10
14	-52		

where d is the estimated distance between transceivers in meters, A is a reference received signal strength at $d = 1$ m, r is the sensed received signal strength at some unknown distance in dBm, and P is the environmental path loss constant [WSM10].

The A and P parameters found in Zbfind are hardcoded as $A = -58.0$ dBm and $P = 3.0$. These parameters are unique to each transceiver pair and in the case of Zbfind, these values are calibrated for a RZUSBstick rangefinding another RZUSBstick [WSM10].

2.4 Z-Ranger Tool Set

2.4.1 Hardware.

In early 2012, Microchip Technology Inc. released the 2.4 GHz Zena with an MRF24J40 transceiver, as shown in Figure 6. This wireless adapter is an upgrade to the 2010 first generation Zena that is shipped with a Texas Instruments CC2420 transceiver. The MRF24J40 is an IEEE 802.15.4 compliant transceiver with RF

sensitivity at -95 dBm and a max RF output power of 1 milliwatt (mW) [Mic10]. Along with the MRF24J40, the Zena incorporates the PIC18F46J50 MCU on a four layer printed board in the form a USB thumb drive [Mic11].

Table 3 provides a comparison between the Zena and RZUSBstick low-rate wireless adapters. Although both platforms offer competitive specifications and features, the Zena offers almost nine times more RSSI resolution than that of the RZUSBstick. The RSSI value is represented with an 8-bit integer value ranging from $0-255$, where higher values represent stronger signal strengths. The RSSI values are stored in the 8-bit memory register $0x210$ of the MRF24J40 and increment in 1 dB steps.

Figure 6. Image of the Microchip Inc. Zena Wireless Adapter.

Table 3. Comparison of the Microchip Zena wireless adapter and the Atmel RZUSB-stick wireless adapter platforms.

Attributes	Zena	RZUSBstick
Compatible Transceiver	MRF24J40	AT86RF230
Sensitivity	-94 dBm	-91 dBm
RSSI Resolution	8-bit [0-255]	5-bit [0-28]
RSS Step Increment	1 dB	3 dB
RSS Accuracy	$\pm$ 1 dB	$\pm$ 5 dB
Cost	$<$ 50USD	$<$ 50USD

2.4.2 Software.

The first and second generation Zena wireless adapters are manufactured to operate with the Wireless Development Studio (WDS) from Microchip. WDS is a Java based GUI allowing the user to configure the Zena for both ZigBee and the proprietary Microchip MiWi protocol stack [Mic12]. WDS allows the user to capture IEEE 802.15.4 compliant packets, displaying the frame number, RSSI, LQI, source address, destination address, and any plain text recovered from the packet body.

2.4.2.1 Zena.c.

Since WDS is restricted to Microsoft and Apple OSs, the *Zena.c* application is developed and released (the .c suffix distinguishes Zena.c source code from the Zena Wireless Adapter). Developed by Joe Desbonnet and written in the C programming language, the Zena.c application successfully ported the first generation Zena over

to the Linux OS and added the capability to capture and save LR-WPAN packets into the PCAP file format [Des11]. This gives users access to advanced analysis tools (e.g., Wireshark and Tshark) for packet analysis.

2.4.2.2 ZenaNG.c.

Soon after the release of the second generation Zena, Emeric Verschuur debuted an application named *ZenaNG.c* [Ver13], an update to the previous Zena.c application that adds compatibility for the second generation MRF24J40 transceiver. Along with support for the MRF24J40 transceiver, Verschuur added a capability whereby the Zena scans all 16 channels (11-26) in the 2.4 GHz band. Figure 7 gives an example output from the ZenaNG.c application where the command `./zenang -c 15 -f usbhex -d 9` is executed. The command options are as follows: `-c` specifies the RF channel, `-f usbhex` specifies the output format, and `-d 9` specifies the debug level.

Figure 8 shows the output when the command `./zenang -h` is executed. The `-h` option produces a help menu with all available features, usage, and version information.

```
root@kali:~/Zena/ZenaNG/build# ./zenang -c 15 -f usbhex -d 9
DEBUG: debug level 9
calling libusb_init() to initialize libusb
calling libusb_open_device_with_vid_pid() to open USB device handle to ZENA
calling libusb_claim_interface(0)
ZENA successfully located and claimed
zena_set_channel(), 802.15.4 channel = 15
calling libusb_transfer() to selected_profile->ep_control
ZENA is now set to 802.15.4 channel 15
1435655169.976138001 0f 00 01 4c 46 12 00 35 41 88 b3 dc 0a ff ff 01 00 09 12 fd ff 01 00
bf 0f 00 82 e2 06 01 01 88 17 00 00 4b f7 c3 0c 54 6d 5e 3b cd b6 a9 14 75 eb 00 00 00 00
1435655170.911096034 0f 00 02 58 8e 20 00 0c 03 08 e2 ff ff ff ff 07 7d a3 5c cd 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1435655170.915821648 0f 00 03 33 9f 20 00 1e 00 80 25 dc 0a 01 00 ff 0f 00 00 00 22 8c 7a
2c 72 e7 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
1435655172.982366181 0f 00 04 a9 25 40 00 35 41 88 b4 dc 0a ff ff 01 00 09 12 fd ff 01 00
bf 0f 00 82 e2 06 01 01 88 17 00 00 ff 05 23 38 a7 c1 b7 76 e8 2d 3d 75 73 d2 00 00 00 00
^C
root@kali:~/Zena/ZenaNG/build#
```

Figure 7. ZenaNG.c application displaying collected packets from channel 15 in hex format.

```
root@kali:~/Zena/ZenaNG/build# ./zenang -h
zenang, version 0.5.0, 22 Jul 2013

Copyright (c) 2011,2012 - Joe Desbonnet    <jdesbonnet@gmail.com>
Copyright (c) 2013      - Emeric Verschuur <emericv@openihs.org>

Usage: zena -c channel [-f format] [-b] [-q] [-v] [-x] [-h] [-d level]
  -c channel     Select 802.15.4 channel. Allowed: 11 .. 26
  -f format      Select packet capture format. Allowed: pcap (default) or usbhex.
  -d level       Set debug level, 0 = min [default], 9 = max verbosity
  -s interval    Scan through 802.15.4 channels with timeslice interval in milliseconds
  -x     Write the both LQI and RSSI bytes (applicable to the PCAP format)
  -b     Include corrupted packets. Applies to pcap output only.
  -q     Quiet mode: suppress warning messages.
  -v     Print version to stderr and exit
  -h     Display this message to stderr and exit

Packet capture output is sent to standard output. Use the following command to
display real time packet feed in wireshark:
  wireshark -k -i <( zenang -c 20 )

Project code and documentation is hosted at:
  https://github.com/Mr-TI/ZenaNG/

root@kali:~/Zena/ZenaNG/build#
```

Figure 8. The command `./zenang -h` is used to display all available features and version information for the ZenaNG.c application. Adapted from [Ver13]

2.5 Related Research

Previous work in the field of wireless sensor RSSI-based localization and security has underscored the value of new and improved tool set development. A brief survey of related works and wireless sensor security assessment tools is summarized below.

2.5.1 RSSI-Based localization.

Jianwu and Lu study three different data processing methods for RSSI-based localization [JL09]. Each method presents a different alternative at limiting RSSI fluctuations in an indoor environment. Using stationary ZigBee sensors and MATLAB simulation, they are able identify their Gaussian distribution method as the most successful in limiting distance measurement error to only 2.4 m within 20 m. Initial location of fixed nodes is required in order to achieve their results.

Xu and Chen discuss ZigBee node localization using a dynamic distance prediction algorithm to overcome indoor signal propagation issues (i.e., scattering, diffraction, and reflection) [XC11]. Xu and Chen advance their distance calculation algorithm by adding shadowing effects into their equation and increase their distance estimation. However, the work presented by Xu and Chen require that some known node locations are known a priori.

Gansemer et al. present a novel approach to localization using RSSI and the Euclidean Distance algorithm [GGH10]. They employ a calibration and positioning phase in their algorithm and achieve a median location estimation error of only 2.12 m while rangefinding. Gansemer et al. are able to further reduce location error by implementing a moving median approach in which estimation error is dropped to a scant 1.80 m. In order to conduct their study, calibrated points with known positions are needed for initial calibration.

Along with the work above, many RSSI rangefinding studies use simulated exper-

imentation and require that some node locations are known. In real-world conditions, network penetration testers may not have access to infrastructure plans, simulation software, or the time necessary to analyze and deduce the most advantageous route to a target using these methods. This thesis attempts to circumvent the known node location requirement and develop a tool set that can generate distance estimates on initial execution with no preparation needed.

2.5.2 LR-WPAN Tool Sets.

The popularity of ZigBee has caught a lot of attention from both the academic community and commercial sector. With this exploration of technology comes the emergence of various tool sets used for network vulnerability testing and attacks. The list below identifies recent tool sets designed and fielded for penetration testing of LR-WPANs.

The Api-do project has contributed significantly to the penetration testing community. Expanding upon the KillerBee framework, the Api-do team designed and developed the *OpenEar*, *Scapy dot15d4*, and *zbWarDrive* tool sets [MSB11]. The OpenEar tool pools together 16 RZUSBsticks to simultaneously scan all 16 channels assigned to the 2.4 GHz band. This allows an attacker to quickly locate ZigBee networks within range. The Scapy dot15d4 tool integrates Scapy, a packet manipulating tool, into the KillerBee project, allowing an attacker to forge and decode their own protocol packets [Bio03]. The zbWarDrive tool identifies nearby ZigBee networks by transmitting beacon request frames. If a response is received, then traffic capture is initiated, saving all collected data to a PCAP file.

Travis Goodspeed utilizes all three tools in a real-world security exploration scenario where a smart meter is targeted for a selective jamming and ACK spoofing exercise [GBM+12]. Goodspeed demonstrates the seriousness of wireless sensor at-

tacks and the potential impact they may have on critical infrastructure (e.g., electric grid, public water works, and natural gas pipelines).

Ramsey et al. explore RSSI-based rangefinding using Zbfind and three different hardware configurations during indoor warwalking scenarios [RMLS14]. In their study, Ramsey et al. evaluate the AT86RF230 transceiver found on the RZUSBstick against the Texas Instruments CC2420 transceiver found on the *TelosB* and *ApiMote* wireless hardware platforms. After concluding that the RZUSBstick is the most viable wireless platform adapter of the three, Ramsey et al. further evaluate warwalking in a hospital corridor and in an outdoor environment against an electric utility smart meter. The data presented in their study indicate Zbfind to be an effective tool set for rangefinding ZigBee devices, however, significant parameter tuning is required.

The *WiPry-Pro* 2.4 GHz wireless spectrum analyzer, shown in Figure 9, designed by Oscium Inc. is ZigBee node identification and RF spectrum monitoring tool [Osc15]. Designed to be used in conjunction with the *WiPry* iOS application, WiPry-Pro is the hardware front-end that turns an Apple iPhone, iPad, or iPod into a 2.4 GHz spectrum analyzer. Originally implemented as a Wi-Fi access point identification tool, WiPry can also be used to identify IEEE 802.15.4 LR-WPANs due to the RF band overlap between the two technologies. Included in the application is a spectrum measurement function and an RSSI reporting capability. In addition to this functionality, Oscium Inc. provides an open API for application developers to interact with the hardware front-end. The WiPry application and hardware may provide a future alternative tool set to explore for RSSI-based rangefinding; however, as originally implemented it does not provide the operational capability required. The application lacks a distance estimating algorithm necessary to implement a rangefinding function.

Figure 9. The WiPry application and WiPry Pro hardware front-end [Osc15].

2.6 Summary

Currently, the Zbfind tool set offers the most attractive method for penetration testers to rangefind and locate ZigBee devices. However, previous work by Ramsey et al. indicates that the Zbfind tool set is inaccurate as initially released [RMW12] and only after extensive field testing and tuning [RMLS14] does it become a viable tool for rangefinding.

The research herein investigates whether or not a rangefinding tool set, given configurable distance estimating parameters and an increased RSSI resolution, will outperform a tool set that lacks these features, as indicated by a statistically significant reduction in mean distance estimation error.

III. Tool Set Development

This chapter outlines the Z-Ranger application development and modifications to the Zbfind source code. Section 3.1 outlines implementation of the log-distance path loss model and programming modules used in Z-Ranger. Section 3.2 describes the Zbfind source code modifications necessary to save data for off-line analysis.

3.1 Z-Ranger Development

The Zena uses a 64-byte USB packet to exchange data and control information with the host computer. Figure 10 presents the two types of USB packets observed from the Zena. The *short* packet is used for IEEE 802.15.4 packets from 7 to 53 bytes. The *long* packet layout is used for IEEE 802.15.4 packets that are greater than 53 bytes. Byte 0 is always $x00$, bits 0-3 of byte 1 are used as a fragmentation indicator ($x0$=none, $x8$=more, and $x5$=done), bits 4-7 of byte 1 are used as a packet sequence number, bytes 2-5 are a packet timestamp, and byte 6 is the remaining packet length to include FCS, RSSI, and LQI bytes. Control information (e.g., RF channel specification) is passed to the Zena via USB endpoint $x01$ and data (e.g., received packets, RSSI, LQI, and FCS) is passed to the computer via USB endpoint $x81$ [Ver13]. An USB endpoint is a device dependent buffer used to send and receive data to or from a host [Mic16]. Endpoints are identified by their device dependent hexadecimal values.

ZenaNG.c is a Linux-based command line application that provides the necessary framework for implementing a rangefinding function with a configurable path-loss environment and reference RSS parameter, two variables hypothesized to reduce mean distance estimation error when compared to a distance estimating model with only static parameters. Bundling the Zena with this new rangefinding application, the

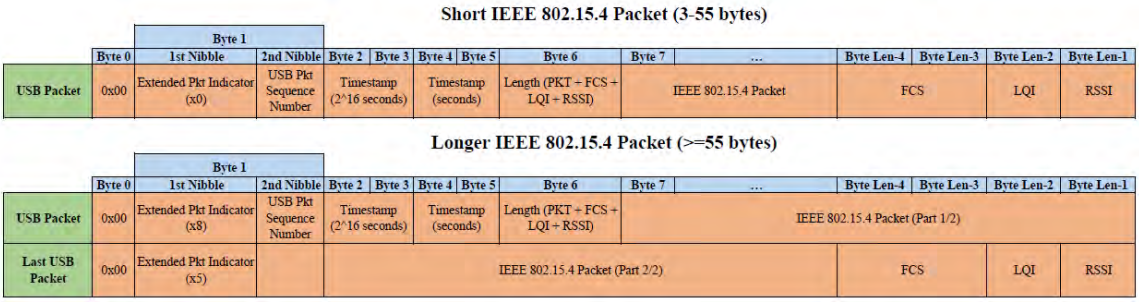


Figure 10. Zena USB packet schema for both short and long IEEE 802.15.4 packets. Adapted from [Des11].

Z-Ranger tool set is developed. The sections below outline implementation of (2) and user configuration options implemented in Z-Ranger.

3.1.1 Distance Estimation.

Distance estimation is obtained using (2). This requires the target device RSS, an environmental path-loss constant (P), and a reference RSS (A) at $d = 1$ m in order to calculate an estimated distance in meters between two transceivers.

3.1.1.1 RSSI-to-RSS Conversion.

The Z-Ranger application stores the received USB packet in a C struct type named `zena_packet_t`, pictured in Figure 11. The zena_packet_t struct holds the entire packet in the `packet[128]` array structure. The RSSI, LQI, FCS, and other values can then be pulled out of the packet[128] array based on their byte location in Figure 10. The `zena_packet_t` struct also contains the Zena reported timestamp, host reported timestamp, and calculated packet length, although they are not used during these experiments.

To obtain a RSS power level, the hardware calculated RSSI value must be recovered from the Zena USB packet and converted to a power level in dBm. To recover the RSSI value, the RSSI attribute is referenced from the `zena_packet_t` struct. The

```
// Used by zena_get_packet() to return 802.15.4 packet data
typedef struct  {
        int zena_ts_sec;        // time stamp reported by ZENA (seconds)
        int zena_ts_usec;       // time stamp reported by ZENA (microseconds)
        int host_ts_sec;        // time stamp reported by host (seconds)
        int host_ts_usec;       // time stamp reported by host (microseconds)
        int packet_len;         // 802.15.4 packet len (excluding FCS)
        uint8_t packet[128];    // holds entire Zena USB packet
        uint8_t rssi;           // holds RSSI from Byte Len-1
        uint8_t lqi;            // holds LQI from Byte Len-2
        uint8_t fcs_ok;         // set to TRUE (1) if FCS ok, else FALSE (0)
} zena_packet_t;
```

Figure 11. The C struct used to hold the Zena USB packet and attributes, found within the Zena.c application [Ver13].

conversion from a RSSI value to a RSS power level is unique for differing transceiver models due to hardware setup and configuration. Table 4 presents an adapted version of the Microchip Inc. [Mic10] mapping of RSSI values to corresponding RSS power levels for the Zena. For select RSSI values in the range of 1-254, there is a one-to-one mapping to corresponding RSS power level. The RSSI lower and upper bound values of 0 and 255 are mapped in a 1:Many scheme. On the low end of the power spectrum, the Zena maps RSS power levels ranging from -90 dBm to -100 dBm to the RSSI value of 0. At the high end, the Zena maps RSS power levels ranging from -35 dBm to -10 dBm to the RSSI value of 255.

Because [Mic10] maps RSS units in whole dB values to RSSI, Table 4 does not publish all available RSSI values that the Zena produces. Thus, a new mapping is developed to fill in the missing RSSI values, shown in Table 5. The missing RSSI values from Table 4 are mapped to fractional RSS power levels in Table 5. The full rendering of Table 4 and Table 5 can be found in Appendix B. For example, the Zena RSSI value of 27 maps to a RSS power level of -82 dBm. The next documented RSSI value available is 32, which maps to a RSS value of -81 dBm, leaving a gap of four values between the two published RSSI values (i.e., 28, 29, 30, and 31). These four RSSI values are then mapped to the fractional RSS value (i.e., 28 = -81.8 dBm,

Table 4. The MRF24J40 published RSS-to-RSSI values. Adapted from [Mic10]. The full table can be found in Appendix B

RSS (dBm)	RSSI	RSS (dBm)	RSSI	RSS (dBm)	RSSI	RSS (dBm)	RSSI
-100	0	-80	37	-60	138	-40	239
-99	0	-79	43	-59	143	-39	245
-98	0	-78	48	-58	148	-38	250
-97	0	-77	53	-57	153	-37	253
-96	0	-76	58	-56	159	-36	254
-95	0	-75	63	-55	165	-35	255
-94	0	-74	68	-54	170	-34	255
-93	0	-73	73	-53	176	-33	255
-92	0	-72	78	-52	183	-32	255
-91	0	-71	83	-51	188	-31	255
-90	0	-70	89	-50	193	-30	255
-89	1	-69	95	-49	198	-29	255
-88	2	-68	100	-48	203	-28	255

29 = −81.6 dBm, 30 = −81.4 dBm, and 31 = −81.2 dBm). This practice continues for all unpublished RSSI-to-RSS value mappings.

To recover the RSS power value in the Z-Ranger application a C array named `RSSI_to_RSS` is developed to hold all 256 RSS power levels. The Zena holds the RSSI value in the last byte of the USB packet, as depicted in Figure 10. Once access to the RSSI value is gained via the `zena_packet_t` struct, the `RSSI_to_RSS` array is called and the corresponding RSS value is placed in a variable named `rss`. The assignment statement `rss = RSSI_TO_RSS[zena_packet.rssi];` is used to perform this function.

3.1.1.2 Environmental Path Loss.

Path loss (P) quantifies the reduction in power density of an electromagnetic wave or signal as it propagates through the environment [Poo15]. This power value is reduced by many variables, including the atmosphere, vegetation, buildings, and free space. To model the reduction in signal power, a constant integer value, P, is

Table 5. Extended RSSI-to-RSS mapping for the Zena Wireless Adapter. The full table can be found in Appendix B.

RSS (dBm)	RSSI	RSS (dBm)	RSSI	RSS (dBm)	RSSI	RSS (dBm)	RSSI	RSS (dBm)	RSSI
-90	0	-77.4	51	-67.71	102	-57	153	-47.75	204
-89	1	-77.2	52	-67.56	103	-56.83	154	-47.5	205
-88	2	-77	53	-67.42	104	-56.66	155	-47.25	206
-87.66	3	-76.8	54	-67.28	105	-56.5	156	-47	207
-87.33	4	-76.6	55	-67.14	106	-56.33	157	-46.8	208
-87	5	-76.4	56	-67	107	-56.17	158	-46.6	209
-87.75	6	-76.2	57	-66.75	108	-56	159	-46.4	210
-86.5	7	-76	58	-66.5	109	-55.83	160	-46.2	211
-86.25	8	-75.8	59	-66.25	110	-55.66	161	-46	212
-86	9	-75.6	60	-66	111	-55.5	162	-45.75	213
-85.75	10	-75.4	61	-65.83	112	-55.33	163	-45.5	214
-85.5	11	-75.2	62	-65.66	113	-55.17	164	-45.25	215
-85.25	12	-75	63	-65.5	114	-55	165	-45	216

used in (2). As each environment changes, the corresponding P value also needs to change to reflect new obstructions. Implementing a configurable P value in Z-Ranger allows the user to improve accuracy based on the specific operating environment.

There are two environments under investigation in this research, an indoor office corridor and an outdoor free space with few obstructions within the signal propagating path. Warwalking collection experiments are conducted in both environments. Analyses conducted in Chapter V determine the corresponding P value for each environment. Both the indoor and outdoor P values found herein are hardcoded as *default* values for each environment. The Z-Ranger application prompts the user to specify either an indoor or outdoor collection environment using the default values or allow the user to specify an alternative value for P.

3.1.1.3 Reference RSS.

The Reference RSS (A) parameter used in (2) is specified as the RSS from a target device at distance $d = 1$ m. The A parameter for Z-Ranger follows the

cross-validation method for initial parameter discovery as this is an improvement over existing techniques [RMLS14]. The cross-validation method allows for an A parameter to be derived from and tested against the same dataset. The implementation of the cross-validation method is detailed in Chapter IV. The dataset used to realize the A value is collected from a series of RSS measurements against four indoor and two outdoor ZigBee target devices. An A parameter for each target device in each of the two environments is calculated. These new A parameters are then hardcoded as default parameters in the Z-Ranger application.

As with the P parameter, the Z-Ranger application prompts the user to enter their own A parameter or use the A parameters found herein. This feature gives the user flexibility when rangefinding ZigBee devices, whether the target is known or unknown.

3.1.1.4 Z-Ranger Execution.

Figure 12 presents an example of how the Z-Ranger application executes against an indoor target using the command `./z-ranger -f ranger -c 20`. The `-f ranger` option calls the rangefinding function within the script. This implicitly uses the default P and A parameters for all distance calculations there after. The `-c` option specifies the operating channel.

If the user wants to specify P and A parameters, the option `-r` is used. Figure 13 presents Z-Ranger executing with this option. The user specifies whether the warwalk is indoor or outdoor (i.e., "i" or "o") and then presents the user a prompt to enter the A and P parameters. The A and P parameters used in this example are just place holders and not actual values found in Chapter V. The Z-Ranger application displays packet count, source ID, destination ID, LQI, RSS, and a distance estimate in meters.

```
root@kali:~/Desktop/ZR Test/build# ./z-ranger -c 26 -f ranger -d 9
DEBUG: debug level 9
calling libusb_init() to initialize libusb
calling libusb_open_device_with_vid_pid() to open USB device handle to ZENA
calling libusb_claim_interface(0)
ZENA successfully located and claimed
zena_set_channel(), 802.15.4 channel = 26
calling libusb_transfer() to selected_profile->ep_control
ZENA is now set to 802.15.4 channel 26
Packet Count:0, Src ID:0007,    Dst ID: 0255,   LQI:113,        RSS:-36.00,     Dist Est:0.78m
Packet Count:1, Src ID:0007,    Dst ID: 0255,   LQI:110,        RSS:-35.00,     Dist Est:0.72m
Packet Count:2, Src ID:0007,    Dst ID: 0255,   LQI:115,        RSS:-35.00,     Dist Est:0.72m
Packet Count:3, Src ID:0007,    Dst ID: 0255,   LQI:108,        RSS:-35.00,     Dist Est:0.72m
^C
root@kali:~/Desktop/ZR Test/build#
```

Figure 12. Example of Z-Ranger execution using default parameters.

```
root@kali:~/Desktop/ZR Test/build# ./z-ranger -c 26 -f ranger -d 9 -r
Will you be targeting indoor (i) or outdoor (o)?
i
Enter a reference RSS (A) to use:
-58.0
Enter an environment path-loss constant(P) to use:
3.0
DEBUG: debug level 9
calling libusb_init() to initialize libusb
calling libusb_open_device_with_vid_pid() to open USB device handle to ZENA
calling libusb_claim_interface(0)
ZENA successfully located and claimed
zena_set_channel(), 802.15.4 channel = 26
calling libusb_transfer() to selected_profile->ep_control
ZENA is now set to 802.15.4 channel 26
Packet Count:0, Src ID:0007,    Dst ID: 0255,   LQI:114,        RSS:-38.40,     Dist Est:0.22m
Packet Count:1, Src ID:0007,    Dst ID: 0255,   LQI:113,        RSS:-38.20,     Dist Est:0.22m
Packet Count:2, Src ID:0007,    Dst ID: 0255,   LQI:112,        RSS:-37.00,     Dist Est:0.20m
Packet Count:3, Src ID:0007,    Dst ID: 0255,   LQI:109,        RSS:-37.66,     Dist Est:0.21m
^C
root@kali:~/Desktop/ZR Test/build#
```

Figure 13. Example of Z-Ranger execution with user specified parameters of: $A = -58.0$ **dBm and** $P = 3.0$**.**

3.2 Zbfind Code Modification

Figure 14 shows the Python print statements added to Zbfind, and Figure 15 displays the result of this addition. The Zbfind source code is modified in order to print all collected data to the terminal. This aids in the collection experiments by allowing all data to be saved for off-line analysis. The information collected from Zbfind includes: received packets, date, timestamp, receiving channel, RSSI, RSS, and calculated distance.

```
rss = (3*packetlist[2])-91 # RSSI converted to RSS
dist = zbpoll.zb_distance(rssi) # Distance to Tx device
rssi = packetlist[2] # Receive Signal Strength [0-28] from register 13 on RZUSBSTICK
dt = datetime.datetime.now().strftime("%Y-%m-%d %H:%M:%S:%f")

"""Print DATE,TIME, RSSI, DISTANCE"""
pdata = rxcount, dt, channel, rss, rssi, dist
print ("Rxcount: %d, Time: %s, Channel: %d, RSSI: %d, RSS: %ddBm, Distance: %s" % pdata)
```

Figure 14. Python print statements added to the Zbfind source code.

```
root@kali:/# zbfind_modified.py
Warning: You are using pyUSB 1.x, support is in beta.
Rxcount: 0, Time: 2015-11-10 15:34:48:154924, Channel: 26, RSSI: 6, RSS: -73dBm, Distance: 16'
Rxcount: 0, Time: 2015-11-10 15:34:50:169325, Channel: 26, RSSI: 6, RSS: -73dBm, Distance: 16'
Rxcount: 0, Time: 2015-11-10 15:34:52:188848, Channel: 26, RSSI: 6, RSS: -73dBm, Distance: 16'
Rxcount: 0, Time: 2015-11-10 15:34:54:203095, Channel: 26, RSSI: 6, RSS: -73dBm, Distance: 16'
Rxcount: 0, Time: 2015-11-10 15:34:56:221632, Channel: 26, RSSI: 6, RSS: -73dBm, Distance: 16'
Rxcount: 0, Time: 2015-11-10 15:34:58:235167, Channel: 26, RSSI: 6, RSS: -73dBm, Distance: 16'
Rxcount: 0, Time: 2015-11-10 15:35:00:254609, Channel: 26, RSSI: 6, RSS: -73dBm, Distance: 16'
Rxcount: 0, Time: 2015-11-10 15:35:02:269068, Channel: 26, RSSI: 6, RSS: -73dBm, Distance: 16'
Rxcount: 0, Time: 2015-11-10 15:35:04:287945, Channel: 26, RSSI: 7, RSS: -70dBm, Distance: 13'
Rxcount: 0, Time: 2015-11-10 15:35:06:302309, Channel: 26, RSSI: 7, RSS: -70dBm, Distance: 13'
```

Figure 15. Terminal output of Python print statements added to Zbfind source code.

3.3 Summary

The A and P parameters used in (2) need to be calibrated for each collection environment and target transceiver. The Z-Ranger application development and design gives the user the flexibility to identify her own distance estimating parameters or use preset default parameters suggested herein. Saving the Zbfind measured data to a text file allows for offline analysis and evaluation between tool sets.

IV. Methodology

4.1 Overview

This chapter presents the rangefinding experiment methodology. The system under test, work load, parameters, and metrics used are all explained. The target devices and collection environments are detailed, along with a list of factors contributing to the experiments.

4.2 System Boundaries

As shown in Figure 16, the System Under Test (SUT) consists of the rangefinding tool set. Each tool set consists of the LDPL model, the respective application (Z-Ranger or Zbfind), and the corresponding hardware platform (Zena or RZUSBstick). The system parameters are limited to the A and P. The workload parameter is the measured RSSI from the target device and the metric used for evaluating the SUT is the mean distance estimation error produced by each tool set. The following sections detail each component of the SUT.

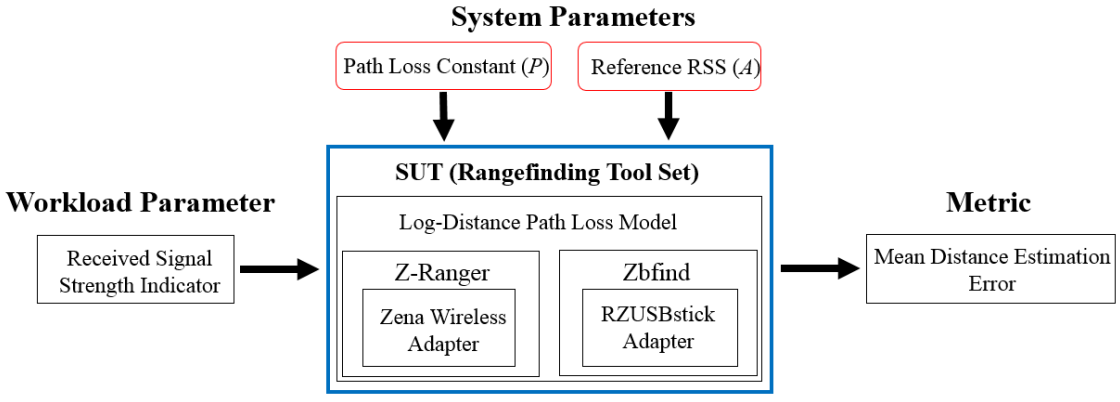


Figure 16. The defined System Under Test for this research.

4.3 Work Load

Each target transmits a beacon request frame at a rate of one per second. The SUT receives the transmitted beacon request frames, measures signal strength, and a corresponding RSSI is recorded.

4.3.1 Z-Ranger.

The MRF24J40 transceiver computes RSSI as an average over the first eight symbols following the SFD, identified in Figure 2. RSSI is assigned an integer from $0-255$ by the transceiver, where a higher value represents a stronger received signal. If the FCS is correct, the RSSI value is attached to the end of a USB packet [Mic10].

4.3.2 Zbfind.

The AT86RF230 updates the 8-bit register named *PHY_RSSI* every 2 μs with an RSSI value ranging from $0 - 28$ [Atm09a]. The RSSI reflects not only the strength of the received packet but also acts as an indicator that the FCS is correct [Atm09a]. The RSSI is appended to the end of each packet in the received packet buffer.

4.4 Metrics

4.4.1 Mean Absolute Percent Error.

Using (2) to estimate distance produces a percentage of error, either positive or negative. Taking the absolute value of this calculated error at each collection point and then averaging all collection point error values (14 indoor and 21 outdoor) for each environment produces MAPE. M is the percentage of error defined by

$$M = \frac{100\%}{n} \sum_{t=1}^{n} \left(\left| \frac{A_d - F_d}{A_d} \right| \right), \tag{3}$$

where n is number of collection points, A_d is actual distance between transceivers, and F_d is the calculated distance estimate.

4.4.2 Evaluating Accuracy.

In order to identify either an increase or decrease in accuracy, a 99% CI is calculated over the MAPE values produced by each target device in each respective environment. A statistically significant difference in MAPE is identified for $p \leq .01$.

4.5 System Parameters

Several parameters affect system performance:

- Target Device: There are four indoor and two outdoor target devices used in the distance estimation experiments. Each device has a different manufacturer, thus the manufacturing process varies. These variances in design and models introduce differences in signal properties and performance. Although each target is different, all devices conform to the IEEE 802.15.4 specification, ensuring at least a baseline performance from each target.

- External Interference: The 2.4 GHz band is populated with many different RF transmission devices (e.g., Wi-Fi, cordless telephones, and microwave ovens) thus there is a possibility of interference from outside sources during collection trials [Ada06]. In an effort to minimize interference, all experiments are conducted after 5 pm, as most building and surrounding occupants have left for the day. To minimize an inadvertent capture of other LR-WPAN sensors, a 5 minute RF scan of channels $11 - 26$ is conducted to ensure no other sensor devices are transmitting in the vicinity. The Zbstumbler application with the RZUSBstick are utilized to perform this procedure. The command used to exe-

cute the scan is `zbstumbler -i 1:4`. The `-i` option identifies the interface the RZUSBstick occupies on the host computer.

- Target Transmission Strength: The transmission power for each device is within the normal operating range as described by their respective manufacturers and indicated in Table 6 and Table 7. Although most of the target devices are capable of fluctuating transmission power levels, all levels are stationary for this study. Indoor transmission power levels range between $0 - 9.57$ dBm while outdoor devices transmit between $18.2 - 18.8$ dBm. Antenna gain, measured in dBi, is noted in column three, and columns four and five present the calculated Transmission (Tx) power as the radiated power level at the antenna, displayed in mW and dBm.

Table 6. Indoor target device transmission power levels.

Device	Power	Antenna Gain	Tx Power	Tx Power
Hue	9.81 mW	0 dBi	9.81 mW	9.57 dBm
S2	5.5 mW	1.9 dBi	8.52 mW	9.3 dBm
MC13212	1.0 mW	0 dBi	1.0 mW	0.0 dBm
RZUSBstick	2.0 mW	0 dBi	2.0 mW	3.0 dBm

Table 7. Outdoor target device transmission power levels.

Device	Power	Antenna Gain	Tx Power	Tx Power
CENTRON	66.1 mW	0 dBi	66.1 mW	18.2 dBm
NI USRP-2921	63.1 mW	3 dBi	76.8 mW	18.8 dBm

- Signal Strength Attenuation: The strength of a transmitting signal degrades as soon as it leaves the antenna. Factors that could affect signal propagation during this study include the following:

– Obstructions: Objects present varying signal degradation based on their composition. Indoor obstructions found in this experiment consist of drywall, wood doors, tile flooring, and ceiling tiles. The outdoor environment is clear of all obstructions, and a visual Line Of Sight (LOS) is established between the target and SUT.

– Distance Between Devices: As distance between devices increases, signal strength decreases. The distance intervals between collection points in this study are the same for all devices based on each respective environment (2 m indoors and 5 m outdoors).

4.6 Factors

4.6.1 Indoor Target Devices.

The indoor targets range from smart home solutions to hospital patient tracking sensors. The broad range of target devices provides a realistic data set for analysis and distance estimate calibration. Figure 17 highlights the four indoor target devices used during the collection trials: the *Philips Hue bridge*, *Awarepoint S2*, *Freescale MC13213*, and *Atmel RZUSBstick*.

1. The Philips HUE Bridge (Figure 17a) provides a connection between a Phillips Hue LED light bulb and a user LAN. The bridge translates an incoming command (e.g., light on) received from the LAN to a ZigBee frame and transmits it to the associated LED(s), allowing a user to control up to 254 LED bulbs from one bridge. Once the Hue is powered on, it begins transmitting beacon request frames in an attempt to identify surrounding HUE devices. Based on the RSSI of these beacon frames, a distance estimate is calculated and used for evaluation of each SUT. The bridge used in this study operates on channel 15.

(a) Hue (b) S2 (c) MC13213 (d) RZUS-Bstick

Figure 17. Indoor ZigBee target devices a) Freescale MC13213, b) Phillips Hue bridge, c) Awarepoint S2, and d) Atmel RZUSBstick

2. The Awarepoint S2 (Figure 17b) is a ZigBee compliant sensor used for patient and equipment tracking within hospitals. Acting as a wireless bridge, the S2 compiles location data collected from wireless sensors attached to tracked objects. It aggregates the collected data to form a real-time mapping of inventory. After plugging the S2 into a 120V A/C power outlet, it begins transmitting beacon request frames in an attempt identify other Awarepoint devices within the surrounding area. Based on the RSSI of these beacon frames, a distance estimate is calculated and used for evaluation of each SUT. The S2 used in this experiment operates on channel 26.

3. The Freescale Semiconductor starter development kit (Figure 17c) comes with the MC13213 System in a Package (SIP), printed F-type antenna, and the 8-bit HCS08 MCU [Fre09]. The transmitter is intended for experimentation and fast prototyping [Fre09]. Power is applied to the MC13213 by its connection to a USB 2.0 laptop port. Once power is applied, the MC13213 broadcasts a beacon request once per second. Based on the RSSI of these beacon frames, a distance estimate is calculated and used for evaluation of each SUT. The MC13213 used

in this experiment operates on channel 26.

4. The Atmel RZUSBstick (Figure 17d) is a 2.4 GHz transceiver designed for a wide range of low-rate, low-power networking projects and scenarios. The RZUSBstick is powered by a USB 2.0 port laptop port. Figure 18 displays the commands used to execute frame transmission from the RZUSBstick. Once the RZUSBstick is connected to the laptop, the *Zbid* tool is used to identify the host port the RZUSBstick is connected to (i.e., 1:14). Once identified, the *Zbstumbler* tool is used to transmit beacon request frames. The commands executed are `zbid` and `zbstumbler -i 1:14 -c 26`. The RZUSBstick used in this experiment operates on channel 26. For clarification, the RZUSBstick doubles as both a SUT and a target device in this research. When the Zbfind tool set is collecting against the RZUSBstick, two RZUSBsticks are used.

4.6.1.1 Indoor Device Location.

Figure 19 shows the indoor office corridor used for indoor RSSI sample measurements. The corridor dimensions measure 3 m by 3 m by 125 m. The red star indicates the 0 m marker and location of the target device. The direction of the red arrow indicates which way the target device is facing. The SUT measures RSSI samples at measured increments along the red arrow line until the experiment is complete.

```
root@kali:~/Zbfind# zbid
          Dev Product String        Serial Number
         1:14 KILLERB001            0004251CA001
root@kali:~/Zbfind# zbstumbler -i 1:14 -c 26
Warning: You are using pyUSB 1.x, support is in beta.
zbstumbler: Transmitting and receiving on interface '1:14'
```

Figure 18. The execution of Zbid and Zbstumbler on the RZUSBstick; used to send beacon request frames during indoor experiment.

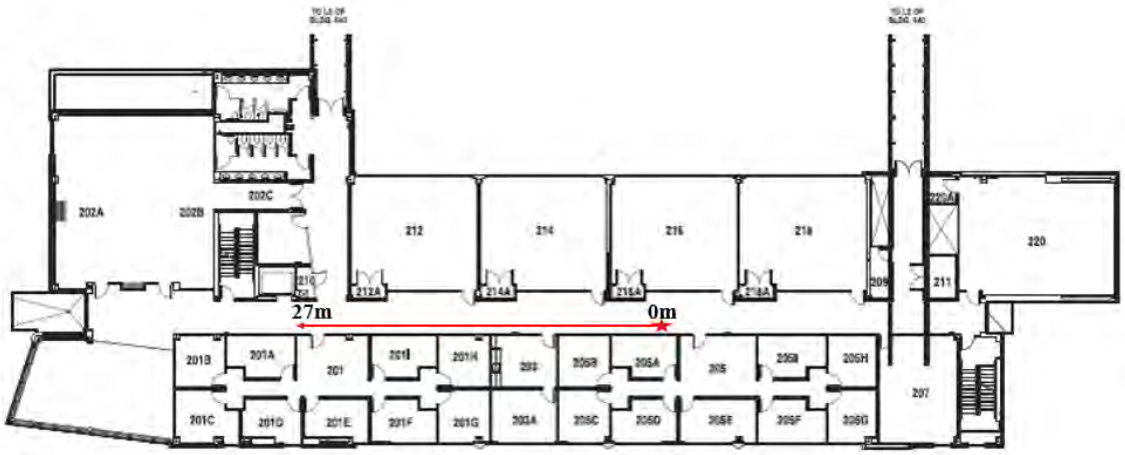


Figure 19. The indoor collection corridor with dimensions measuring 3 m by 3 m by 125 m. The star indicates the position of the target device and the arrow indicates the direction the target device faces.

4.6.2 Outdoor Target Devices.

There are two targets used in the outdoor rangefinding experiment and evaluation, the Itron Openway CENTRON smart meter and National Instruments (NI) Universal Software Radio Peripheral (USRP) (henceforth referred to as the NI USRP-2921).

The Itron Openway CENTRON advanced smart meter (Figure 20a) is a wireless solution for gathering customer billing and usage data by the local electric utility company. This ZigBee certified metering device is configured in a mesh network, working with thousands of other smart meters to relay customer data back to a main data processing hub. The CENTRON used in this experiment is configured to regularly transmit frames at one beacon request per second. Based on the RSSI of

these beacon frames, a distance estimate is calculated and used for evaluation of each SUT. The CENTRON used in this experiment operates on channel 26.

The NI USRP-2921 (Figure 20b) is a programmable Software Defined Radio (SDR). In this experiment, the NI USRP-2921 is operated by the GNU Radio software development toolkit [Rad15], a free signal processing software application designed specifically for low-cost external RF hardware and commodity processors. The GNU Radio includes a GUI application called GNU Radio Companion (GRC), allowing a user to design, build, and execute software radios using a modular "block" system to implement traditionally hardware based components.

The GNU radio blocks used to develop and transmit an IEEE 802.15.4 compliant frame in this experiment are adapted from Bloessl [Blo12], who in turn modernized Schmid's [Sch06] initial contribution from 2006. The instructions for downloading, installing, and executing both GNU Radio and Bloessl's extended code can be found in Appendix A. The NI USRP-2921 is connected to a laptop, via CAT-5e cable, where the GRC software is installed. An IP address of 192.168.10.2 is given to the USRP, and the host laptop receives the IP address 192.168.10.1. The GRC application is then launched and executed, transmitting beacon request frames every second until termination. A survey of 200,000 smart meters identifies the median transmission power level to be 18.2 dBm (66.1 mW) [EPR10] with an upper value of 20.6 dBm (114.8 mW). Based on this prior work, the USRP transmission power level is set to 18 dBm for this experiment. The NI USRP-2921 used in this experiment comes equipped with the Vert 2450 antenna, adding 3 dBi of gain to the radiated power level. Calculating the added gain by the antenna, a transmission power level of 18.8 dBm (76.8 mW) is achieved. Based on the RSSI of these beacon frames, a distance estimate is calculated and used for evaluation of each SUT. The NI USRP-2921 used in this experiment operates on channel 26.

(a) Itron Openway CENTRON (b) NI USRP-2921

Figure 20. Outdoor ZigBee target devices a) Itron Openway CENTRON smart meter and b) NI USRP-2921

4.6.2.1 Outdoor Device Location.

The CENTRON smart meter is connected to the exterior side of an industrial warehouse and adjacent to an open field, as pictured in Figure 21. The field measures approximately 70 m by 130 m with a clear LOS between the target device and the SUT.

The NI USRP-2921 is placed 4 m off the exterior side of a residential house and adjacent to an open field, as pictured in Figure 22. The field measures approximately 100 m by 150 m with a clear LOS between the target device and the SUT.

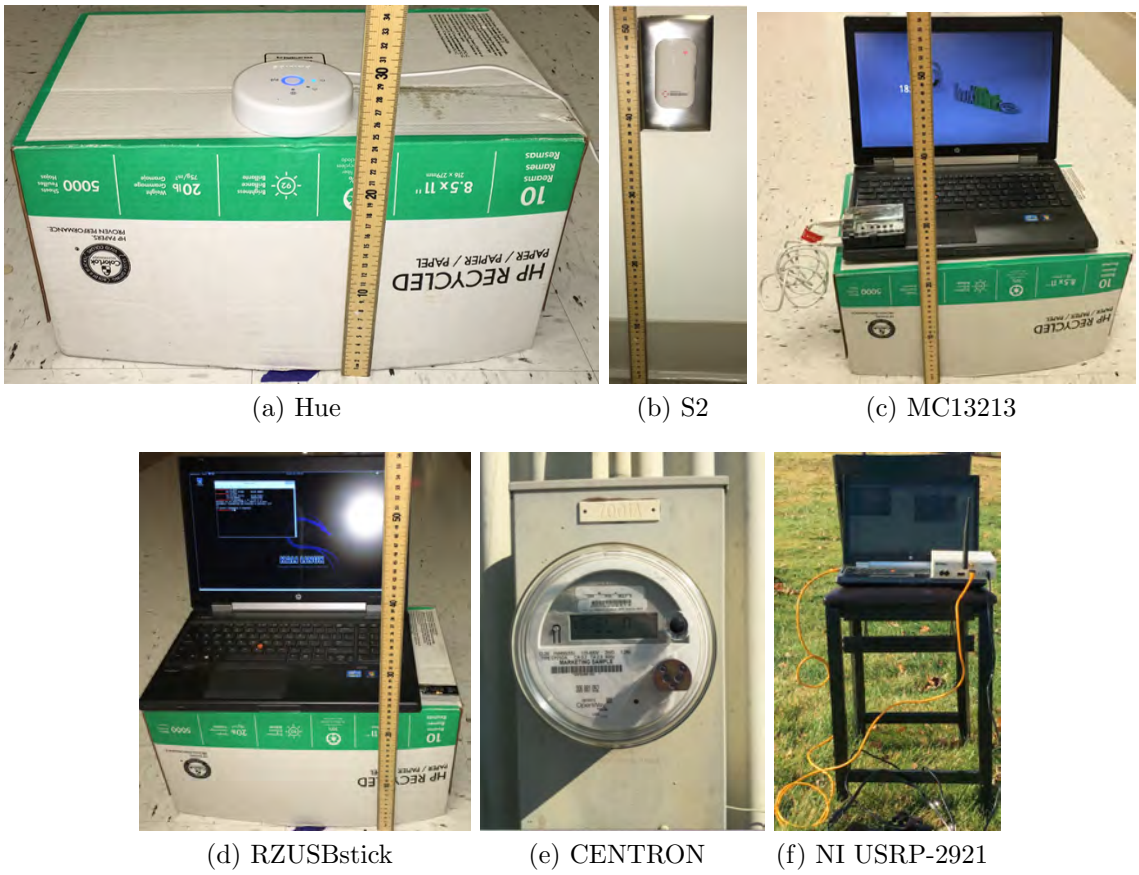
Figure 21. The CENTRON smart meter is positioned at the 0 m marker with RSSI measurements taken along the path of the measurement line.

Figure 22. The NI USRP-2921 is positioned at the 0 m marker with RSSI measurements taken along the path of the measurement line.

4.6.3 Antenna Orientation and Placement.

With the exception of the NI USRP-2921, all target devices have an enclosed and/or board printed antenna. The NI USRP-2921 uses a SMA attached Vert 2450 antenna, as pictured in Figure 20b. All target device antennas operate in an omni-directional transmission radiation pattern.

Figure 23 shows the setup and orientation of each target device during collection trials. Indoor target devices pictured in Figures 23a, 23c, and 23d are executed from the top of a cardboard box, at a height of 24 cm, placed in the middle of the 3 m hallway, and a clear LOS to the SUT. Figures 23e and 23f depict the outdoor target device collection setup. Both outdoor targets transmit with a clear LOS to the SUT.



(a) Hue (b) S2 (c) MC13213

(d) RZUSBstick (e) CENTRON (f) NI USRP-2921

Figure 23. Both indoor and outdoor target device setup and orientation during collection trials.

4.6.4 RSSI Samples Measured.

4.6.4.1 Indoor Environment.

RSSI measurements are taken in 2 m increments at distances $d \in \{1, 3, 5, ..., 27\}$ m. An increment of 2 m is used as it provides a closer interval than the 3 m interval used in related previous work [RMLS14]. The target device is stationary at the 0 m marker (indicated by star in Figure 19), and the SUT measures 50 RSSI samples at each collection point for each target device. The basis for determining sample size is the Central Limit theorem where a sample of at least 30 must be used to accurately represent the population being sampled. Taking this into account, a value of 50 is

used as it provides more than enough samples for analysis. Each SUT measures 50 RSSI samples at each of the 14 collection points across all four target devices totaling 2800 RSSI measurements collected ($4 \cdot 50 \cdot 14 = 2800$). Each SUT measures 2800 RSSI samples for a grand total of 5600 RSSI samples measured in the indoor experiment.

4.6.4.2 Outdoor Environment.

RSSI measurements are taken in 5 m increments at $d \in \{1, 6, 11, ..., 101\}$ m. Due to the significant increase in overall transmission distance between a target device and SUT, the increment distance between collection points is raised to 5 m. The target device is stationary at the 0 m marker and the SUT measures 30 RSSI samples at each collection point for each target device. In this experiment, 30 RSSI samples are measured compared to the 50 measured in the indoor experiment. This is due to the increased number of collection points (14 versus 21), changing outdoor conditions, and the minimum number of samples necessary to represent the population based on the Central Limit theorem. Measuring 30 RSSI samples at each of the 21 collection points across both target devices, totaling 1260 RSSI samples collected per SUT ($2 \cdot 30 \cdot 21 = 1260$). Each SUT measures 1260 RSSI samples for a grand total of 2520 RSSI samples measured in the outdoor experiment.

4.6.5 Factors Summary.

The multiple of factors presented in the section previous are presented in a condensed table format below. The two environments, SUT, target devices, and the number of RSSI measurements sampled are presented in Table 8.

Table 8. Summary of rangefinding experiment factors.

Factor	Value
Physical Layout	Indoor
	Outdoor
Tool Set	Zbfind & RZUSBstick
	Z-Ranger & Zena
Target Device (Indoor)	HUE
	S2
	MC13213
	RZUSBstick
Target Device (Outdoor)	CENTRON
	NI USRP-2921
Distance Interval (Indoor)	{1, 3, 5, ..., 27} m
Distance Interval (Outdoor)	{1, 6, 11, ..., 101} m
RSSI Samples Measured	5600 (Indoor)
	2520 (Outdoor)
	8120 (Total)

4.7 Evaluation Technique

A Lenovo ThinkPad laptop with an Intel Core i3-4000m CPU, clocked at 2.6 GHz with 16 Gigabytes (GB) of RAM, is used during this experiment. The Lenovo runs a 64-bit version of Windows 7 Professional with service pack one. On top of the Windows OS, Virtual Machine (VM) Player 6.0.6 is virtualizing the Kali Linux OS, version 2.0. From within the Kali Linux VM, both Z-Ranger and Zbfind are executed.

In order to transmit IEEE 802.15.4 frames from the NI USRP-2921 target device, another laptop is required. For this purpose, a Hewlett Packard (HP) Envy 17 with

an Intel i7-720Q CPU and 16 GB of RAM running 32-bit Linux Mint 17 OS is used. The HP Laptop is configured with USRP Hardware Driver (UHD) version 003.009 and GNU Radio Companion 3.7.8.

Direct physical measurement of signal strength from each target device is accomplished by each respective SUT. Measured RSSI is first converted to RSS and then saved into a text file for each SUT at each collection point in each environment. The collection process is the same regardless of the environment in which it is executed, and is outlined below.

1. Position target device at 0 m marker.

2. Plug SUT into Lenovo laptop and position at 1 m marker.

3. Execute respective collection application for each SUT (Z-Ranger or Zbfind). The collection of RSS measurement is confirmed once RSS measurement is displayed on the Lenovo laptop screen via terminal. The measurement, along with a packet number, is then saved for post collection analysis.

4. Apply power and/or execute required software for target device operation. The RZUSBstick and NI USRP-2921 require the HP laptop to execute transmission.

5. Monitor SUT for the number of samples needed for experiment (50 for indoor and 30 for outdoor). Once sample minimums are achieved, discontinue the SUT collection and close application.

6. Discontinue target device transmission.

7. Move the SUT to next collection interval and repeat the process. Continue to repeat the process until collection at the maximum distance (27 m for indoor and 101 m for outdoor) is completed.

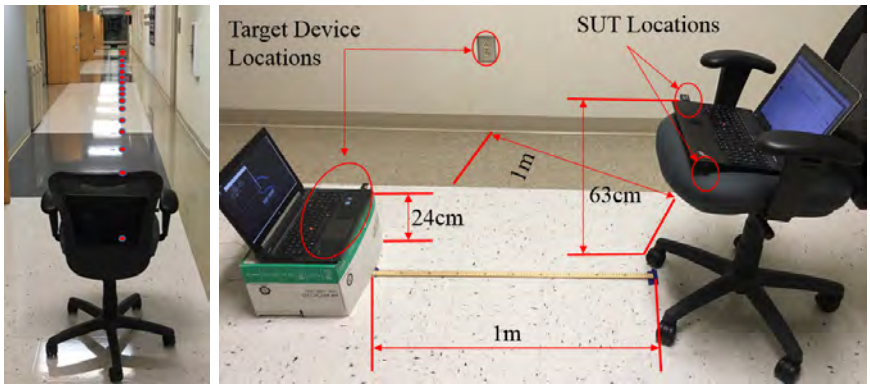
The CENTRON is a fully functioning smart meter and not permitted to be powered off or moved. Due to this limitation, Step 1 and 6 are not executed during this collection trial for the CENTRON data collection. All data is collected in the respective environments, and no RSSI values are simulated. The following subsections describe the specific collection process details for each environment.

4.7.1 Indoor Evaluation.

The corridor is marked off in 2 m increments, out to a maximum of 27 m as shown in Figure 24a. The Lenovo and SUT are perched on top of a rolling arm chair, measuring 63 cm in height and positioned at the 1 m marker. Figure 24b presents the positioning of the target devices and SUT. The S2 is plugged into an outlet measuring 42 cm in height at the 0 m marker. The remaining three targets are positioned on top of a cardboard box measuring 24 cm in height, also at the 0 m marker. After RSSI sample measurement is completed at the 1 m marker, the SUT is rolled to the next interval marker and the collection process repeats.

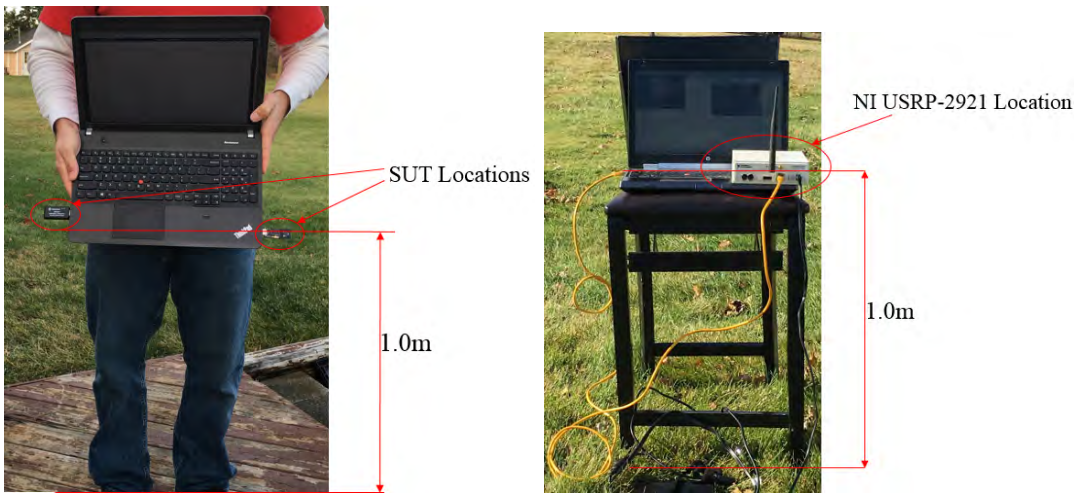
4.7.2 Outdoor Evaluation.

Figure 25a shows the Lenovo and connected SUT as held during the experiment at a height of 1 m. Both targets are stationary at the 0 m marker throughout the collection experiment. Markers are set at 5 m intervals out to a maximum of 101 m. Initial collection starts with the SUT set at the 1 m marker, measuring 30 RSSI samples. Once finished, the SUT is moved to the next increment and the process is repeated. Figure 25b shows the NI USRP-2921 target device setup. The NI USRP-2921 is placed on top the HP laptop that is positioned on top of a stool, measuring 1 m in height. The CENTRON is affixed to an exterior warehouse wall at a height of 1.5 m.



(a) Office corridor (b) Indoor collection setup

Figure 24. Indoor RSSI sample measurement setup.



(a) SUT Collection (b) Target Device

Figure 25. Outdoor RSSI sample measurement setup.

4.8 K-fold Cross-Validation

Unlike Zbfind, Z-Ranger has no initial P or A parameter. For initial distance calculations the P parameter for Z-Ranger is borrowed from Zbfind and set to $P = 3.0$. The A parameter must be found empirically since it is unique to each transceiver. Observing the transmission power levels of the indoor and outdoor targets used in this research, it can be concluded that indoor devices operate at lower transmission power levels than outdoor devices, thus a different A parameter is required for each

environment. To establish an A parameter, the K-fold cross-validation method is used.

Figure 26 presents a diagram illustrating the K-fold cross-validation process for training and testing data sets. The K-fold cross-validation method randomly [Ran15] splits a limited data set into K mutually exclusive folds, without using replacement [Koh95]. The folds are randomly chosen and stratified, as this lessens the chance of producing a biased estimate of accuracy [Koh95]. The folds are then divided into two groups, one for testing data and one for training data. The training group is comprised of $K - 1$ folds and the testing group is comprised of the remaining Kth fold. The training group is then compared to the testing group and the amount of error produced is quantified using (3), this completes one round of testing. This process is repeated K times in order to incorporate all folds into each group; thus, a user is able to train and test using the entire data set. After all K rounds are completed, the training group value that produces the least amount of MAPE is used for the A parameter in (2). Since all data is incorporated into training and testing, model overfitting is limited, producing a more accurate model to use [Koh95].

4.8.1 Indoors.

All RSS samples recovered at $d = 1$ m for all four target devices are grouped together, resulting in a group of 200 samples. The samples are then randomly divided into five mutually exclusive folds containing 40 samples each. Table 9 depicts the five randomly chosen folds from the 200 samples and the corresponding average RSS sample values.

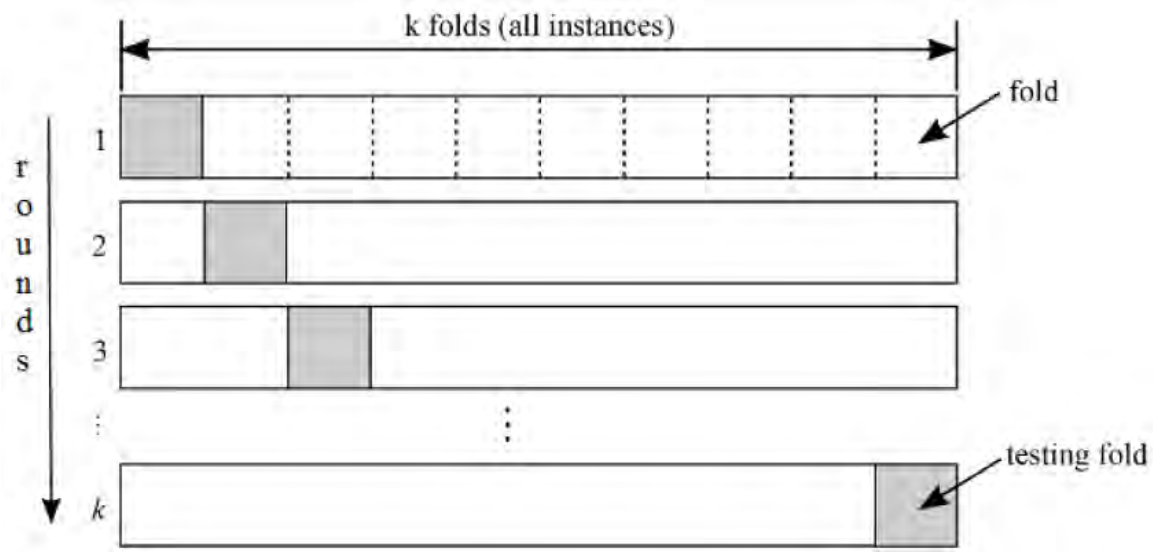


Figure 26. *K*-**fold cross-validation technique used to discover the** ***A*** **parameter for Z-Ranger [Koh95].**

The training group is formed by combining four of the five folds and averaging the RSS values together. The five training folds, associated RSS, testing fold, and associated MAPE are presented in Table 10. The RSS value of -43.46 dBm, originating from the combination of folds $\{5, 1, 2, 3\}$, is chosen as the initial indoor A parameter for Z-Ranger, as it offers the best indicator of future performance with MAPE at $M = 0.06\%$.

Table 9. Five indoor folds and corresponding average RSS samples for Z-Ranger.

Fold Number	Avg RSS (dBm)
1	-43.29
2	-43.13
3	-44.02
4	-43.49
5	-43.41

Table 10. 5-fold cross-validation for indoor Z-Ranger A parameter.

Train folds	Train RSS (dBm)	Test fold	Test RSS (dBm)	MAPE
1, 2, 3, 4	-43.48	5	-43.41	0.18%
2, 3, 4, 5	-43.51	1	-43.29	0.51%
3, 4, 5, 1	-43.55	2	-43.13	0.97%
4, 5, 1, 2	-43.33	3	-44.02	1.57%
5, 1, 2, 3	**-43.46**	4	-43.49	**0.06%**

4.8.2 Outdoors.

All RSS samples from both outdoor targets at $d = 1$ m are grouped together, resulting in a pool of 60 samples. The value of $K = 3$ is used due to the decreased sample size for outdoor targets (60 outdoor versus 200 indoor). The group is then subdivided into three folds of 20 RSS samples each. Table 11 presents the averaged RSS values for each of the three mutually exclusive folds used for cross-validation.

In the same fashion as used above, the training groups are formed by combining two folds and averaging the RSS values together. The three training groups, associated RSS, testing group, and associated MAPE is presented in Table 12. The RSS value of -39.55 dBm, originating from folds {1 and 2}, is chosen as the initial outdoor A parameters for Z-Ranger as it offers the best indicator of future performance with MAPE $M = 0.51\%$.

Table 11. Three outdoor folds and corresponding average RSS samples for Z-Ranger.

Fold Number	Avg RSS (dBm)
1	-40.43
2	-38.67
3	-39.35

Table 12. 3-fold cross validation for outdoor Z-Ranger *A* parameter.

Train folds	Train RSS (dBm)	Test folds	Test RSS (dBm)	MAPE
1 and 2	**-39.55**	3	-39.35	**0.51%**
2 and 3	-39.00	1	-40.43	3.53%
3 and 1	-39.89	2	-38.67	3.17%

4.9 Summary

This IEEE 802.15.4 rangefinding and evaluation experiment is conducted in both indoor and outdoor environments, against an array of target devices. Varying factors include LR-WPAN sensor targets, antenna type, and executing software. The methodology outlined in this chapter presents an experiment that measures 50 RSSI samples at 14 collection points from four different targets by two different tool sets in an indoor environment. The experiment continues outside, measuring 30 RSSI samples at 21 collection points against two different targets using the same two tool sets under test.

V. Results and Analysis

In this chapter distance estimates are calculated based on recovered RSS samples from Chapter IV. Comparing actual distance to estimated distance, a corresponding MAPE value is produced for each SUT at each collection point. A 99% CI is then calculated for each SUT using the recovered MAPE values. Analysis of each SUT is presented and further refinements are presented.

5.1 Initial Tool Set Comparison

5.1.1 Indoors.

5.1.1.1 Z-Ranger.

The A parameter derived from the cross-validation method in Chapter IV, $A = -43.46$, and borrowing $P = 3.0$ from the Zbfind tool set a distance estimate is calculated at each collection interval d $\in \{1, 3, 5, ..., 27\}$ m using (2). Table 13 presents the estimated distance, absolute error percentage, MAPE per device, and average MAPE for the tool set.

Average MAPE across all four targets is $M = 54.00\%$ with the lowest MAPE value of $M = 45.87\%$, found while rangefinding the S2 target. The highest MAPE value of $M = 66.67\%$ is produced while rangefinding the Hue target. With the exception of the S2, which is plugged into the wall, all three targets produce the most amount of error at the 27 m collection point with an average MAPE of $M = 78.77\%$. This spike in MAPE may be the result from multi-path fading due to the location of the target devices in the middle of the corridor.

Table 13. Indoor distance estimates and corresponding MAPE produced by Z-Ranger using the values of $A = -43.46$ and $P = 3.0$.

	Hue		**S2**		**MC13213**		**RZUSBstick**	
Dst	Est Dst	MAPE	Est Dst	MAPE	Est Dst	MAPE	Est Dst	MAPE
1m	0.53m	47.4%	0.97m	21.2%	1.22m	21.8%	1.60m	60.4%
3m	1.13m	62.2%	2.24m	25.2%	1.70m	43.2%	3.91m	30.2%
5m	1.30m	74.1%	1.91m	61.8%	2.50m	49.9%	4.68m	6.4%
7m	1.22m	82.6%	1.57m	77.5%	2.29m	67.3%	3.62m	48.3%
9m	1.46m	83.8%	1.88m	79.1%	3.03m	66.3%	10.61m	17.9%
11m	9.02m	18.0%	7.46m	32.3%	7.09m	35.6%	11.72m	6.5%
13m	7.02m	46.0%	5.53m	57.5%	4.06m	68.8%	4.08m	68.6%
15m	4.07m	72.8%	6.71m	55.3%	8.11m	45.9%	5.37m	64.2%
17m	8.11m	52.3%	9.42m	44.6%	5.98m	64.8%	5.52m	67.5%
19m	3.83m	79.9%	6.10m	67.9%	8.15m	57.1%	7.74m	59.3%
21m	4.32m	79.4%	11.31m	46.2%	7.10m	66.2%	7.44m	64.6%
23m	5.88m	74.5%	15.23m	33.8%	6.57m	71.4%	14.09m	38.7%
25m	6.36m	74.5%	15.79m	36.8%	11.49m	54.1%	11.71m	53.1%
27m	3.82m	85.8%	21.20m	21.5%	6.28m	76.7%	7.07m	73.8%
	MAPE=66.66%		MAPE=45.87%		MAPE=56.37%		MAPE=47.11%	

Average MAPE over all four targets=54.00%

5.1.1.2 Zbfind.

Using (2) and the Zbfind original values of $A = -58.0$ and $P = 3.0$, a distance estimate is calculated at each collection interval d $\in \{1, 3, 5, ..., 27\}$ m. An absolute error value is also calculated at each collection point. The second to last row of Table 14 presents the MAPE over all collection points and the last row presents the average MAPE produced by the four target devices during indoor collection.

The average MAPE produced by all four target during indoor rangefinding is $M = 70.22\%$. The Hue device produced the highest MAPE value at $M = 86.63\%$. This may be due to poor or degraded signal strength as the Hue also produced the most MAPE during Z-Ranger collection. The least amount of MAPE produced comes while rangefinding the S2 target device with $M = 58.54\%$. The S2 also produced the least amount of MAPE during Z-Ranger rangefinding.

Table 14. Indoor distance estimates and corresponding MAPE produced by Zbfind using the parameters of $A = -58.0$ and $P = 3.0$.

	Hue		**S2**		**MC13213**		**RZUSBstick**	
Dst	Est Dst	MAPE	Est Dst	MAPE	Est Dst	MAPE	Est Dst	MAPE
1m	0.40m	59.8%	1.15m	15.1%	0.82m	17.6%	1.26m	26.5%
3m	0.33m	89.0%	2.33m	22.5%	0.68m	77.3%	2.28m	24.0%
5m	0.58m	88.5%	1.66m	66.8%	1.49m	70.2%	1.57m	68.6%
7m	0.89m	87.3%	2.13m	69.6%	1.64m	76.5%	2.21m	68.5%
9m	1.44m	84.0%	3.18m	64.7%	1.73m	80.8%	3.28m	63.5%
11m	1.11m	89.9%	2.19m	80.1%	2.26m	79.4%	2.17m	80.3%
13m	1.08m	91.7%	3.06m	76.4%	1.7m	87.0%	3.25m	75.0%
15m	1.2m	92.0%	6.37m	57.6%	2.18m	85.4%	7.48m	50.1%
17m	2.88m	83.1%	8.68m	49.0%	2.0m	88.2%	8.39m	50.6%
19m	2.24m	88.2%	7.73m	59.3%	3.41m	82.0%	7.08m	62.7%
21m	2.04m	90.3%	8.09m	61.5%	2.52m	88.0%	7.94m	62.2%
23m	3.0m	87.0%	6.48m	71.8%	6.09m	73.5%	6.34m	72.4%
25m	1.86m	92.6%	10.56m	57.8%	3.11m	87.6%	11.48m	54.1%
27m	2.81m	89.6%	8.65m	67.9%	4.0m	85.2%	10.19m	62.3%
	MAPE=86.63%		MAPE=58.54%		MAPE=77.06%		MAPE=58.63%	

Average MAPE over all four targets=70.22%

5.1.1.3 Summary Analysis.

A 99% CI is calculated from the MAPE produced for each target device and presented in Figure 27.

There is no significant difference between Z-Ranger and Zbfind when rangefinding the Hue (Z-Ranger: $M = 66.66\%, SD = 19.34\%$; Zbfind: $M = 86.63\%, SD = 8.19\%$), S2 (Z-Ranger: $M = 45.87\%, SD = 22.11\%$; Zbfind: $M = 58.54\%, SD = 18.76\%$), MC13213 (Z-Ranger: $M = 56.37\%, SD = 15.54\%$; Zbfind: $M = 77.06\%, SD = 18.02\%$), and the RZUSBstick (Z-Ranger: $M = 47.11\%, SD = 23.3\%$; Zbfind: $M = 58.63, SD = 16.6\%$) target devices, $p \geq .01$.

Results from the indoor trials do not suggest any significant functional differences in rangefinding error between the two tool sets for indoor warwalking.

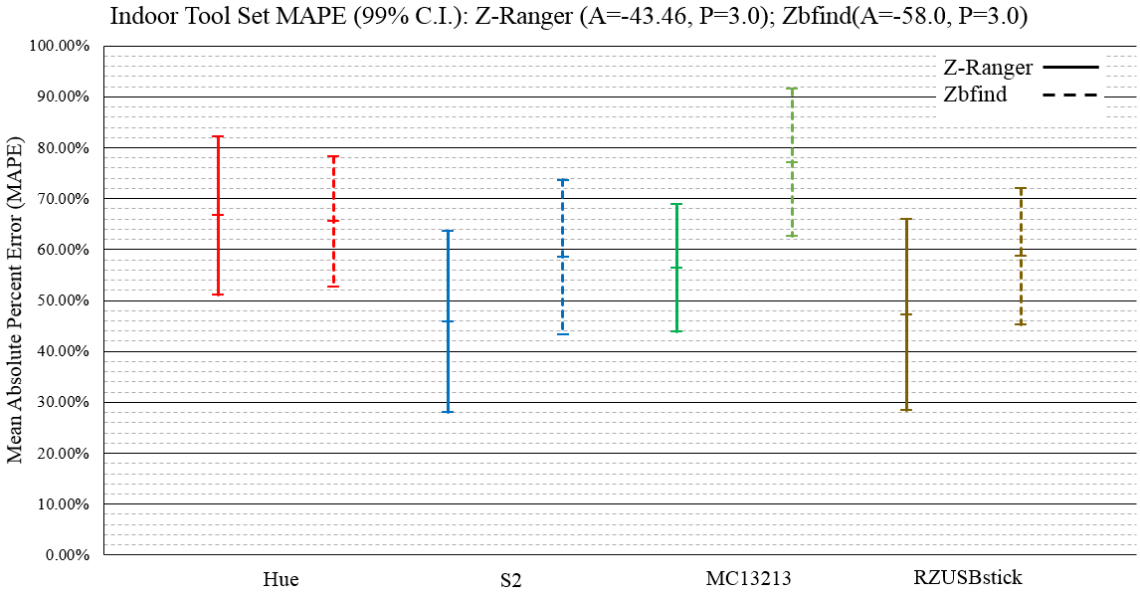


Figure 27. This figure depicts the MAPE produced by Z-Ranger during indoor rangefinding using parameters discovered from the cross-validation method. The MAPE produced by Zbfind is the result of using original values.

5.1.2 Outdoors.

5.1.2.1 Z-Ranger.

The A parameter derived from the cross-validation parameter discovery method, $A = -39.55$, coupled with $P = 3.0$ from the Zbfind tool set, a distance estimate is calculated at each collection interval d $\in \{1, 6, 11, ..., 101\}$ m using (2). Table 15 presents the estimated distance, absolute error percentage, MAPE per device, and overall MAPE for the tool set.

While rangefinding the NI USRP-2921 target, a MAPE value of $M = 88.32\%$ is recorded, the highest of the two outdoor targets. The MAPE produced while rangefinding the CENTRON target sensor is $M = 70.20\%$, with an average MAPE of $M = 79.26\%$ between the two target devices.

Table 15. Outdoor distance estimates and corresponding MAPE produced by Z-Ranger using the parameters of $A = -39.55$ and $P = 3.0$.

	NI USRP-2921		CENTRON	
Dst	Est Dst	MAPE	Est Dst	MAPE
1m	0.71m	29.5%	1.39m	39.4%
6m	0.79m	86.8%	1.86m	69.1%
11m	1.06m	90.4%	2.52m	77.1%
16m	1.30m	91.9%	3.13m	80.5%
21m	1.41m	93.3%	7.43m	64.6%
26m	1.44m	94.4%	11.50m	55.8%
31m	1.66m	94.6%	10.81m	65.1%
36m	2.09m	94.2%	13.94m	61.3%
41m	2.72m	93.4%	9.06m	77.9%
46m	3.56m	92.3%	17.00m	63.0%
51m	3.81m	92.5%	12.98m	74.6%
56m	3.54m	93.7%	14.01m	75.0%
61m	4.80m	92.1%	9.76m	84.0%
66m	7.15m	89.2%	13.28m	79.9%
71m	6.96m	90.2%	20.57m	71.0%
76m	5.49m	92.8%	16.73m	78.0%
81m	4.60m	94.3%	30.51m	62.3%
86m	10.22m	88.1%	19.03m	77.9%
91m	14.56m	84.0%	22.99m	74.7%
96m	6.93m	92.8%	28.82m	70.0%
101m	15.75m	84.4%	27.14m	73.1%
	MAPE=88.32%		MAPE=70.20%	

Average MAPE for both targets=79.26%

5.1.2.2 Zbfind.

Using (2) and the Zbfind original values of $A = -58.0$ and $P = 3.0$, a distance estimate is calculated at each collection interval d $\in \{1, 6, 11, ..., 101\}$ m. An absolute error value is also calculated at each collection point. The second to last row of Table 16 presents the MAPE over all collection points and the last row presents the average MAPE produced by both target devices during outdoor collection. While rangefinding outdoor targets, MAPE produced by Zbfind is $M = 98.01\%$ for the NI USRP-2921 and $M = 87.33\%$ for the CENTRON smart meter. An average MAPE of $M = 92.67\%$ for both targets.

Table 16. Outdoor distance estimates and corresponding MAPE produced by Zbfind using the parameters of $A = -58.0$ and $P = 3.0$.

	NI USRP-2921		CENTRON	
Dst	Est Dst	MAPE	Est Dst	MAPE
1m	0.05m	95.1%	0.41m	58.9%
6m	0.22m	96.3%	1.03m	82.8%
11m	0.27m	97.5%	1.95m	82.3%
16m	0.30m	98.1%	1.74m	89.1%
21m	0.33m	98.4%	2.93m	86.1%
26m	0.33m	98.7%	3.95m	84.8%
31m	0.40m	98.7%	5.17m	83.3%
36m	0.40m	98.9%	4.14m	88.5%
41m	0.54m	98.7%	5.98m	85.4%
46m	0.74m	98.4%	3.77m	91.8%
51m	0.70m	98.6%	4.97m	90.2%
56m	0.66m	98.8%	6.12m	89.1%
61m	0.71m	98.8%	6.12m	90.0%
66m	1.30m	98.0%	5.33m	91.9%
71m	1.89m	97.3%	7.47m	89.5%
76m	1.55m	98.0%	6.12m	91.9%
81m	1.57m	98.1%	7.24m	91.1%
86m	1.95m	97.7%	6.61m	92.3%
91m	1.61m	98.2%	7.64m	91.6%
96m	2.11m	97.8%	7.59m	92.1%
101m	2.11m	97.9%	8.84m	91.2%
	MAPE=98.01%		MAPE=87.33%	

Average MAPE for both targets=92.67%

5.1.2.3 Summary Analysis.

A 99% CI is calculated from the MAPE produced for each target device and presented in Figure 28. Analysis concludes there is a significant reduction in MAPE produced by Z-Ranger while rangefinding the USRP NI-2921 ($M = 88.32\%, SD = 13.85\%$) and CENTRON ($M = 70.20\%, SD = 10.24\%$) targets, as compared to Zbfind for the NI USRP-2921 ($M = 98.01\%, SD = .90\%$) and CENTRON ($M = 87.33\%, SD = 7.30\%$) targets, $p \leq .01$.

Outdoor results suggest a statistically significant reduction in MAPE when Z-Ranger is used versus Zbfind ($p \leq .01$).

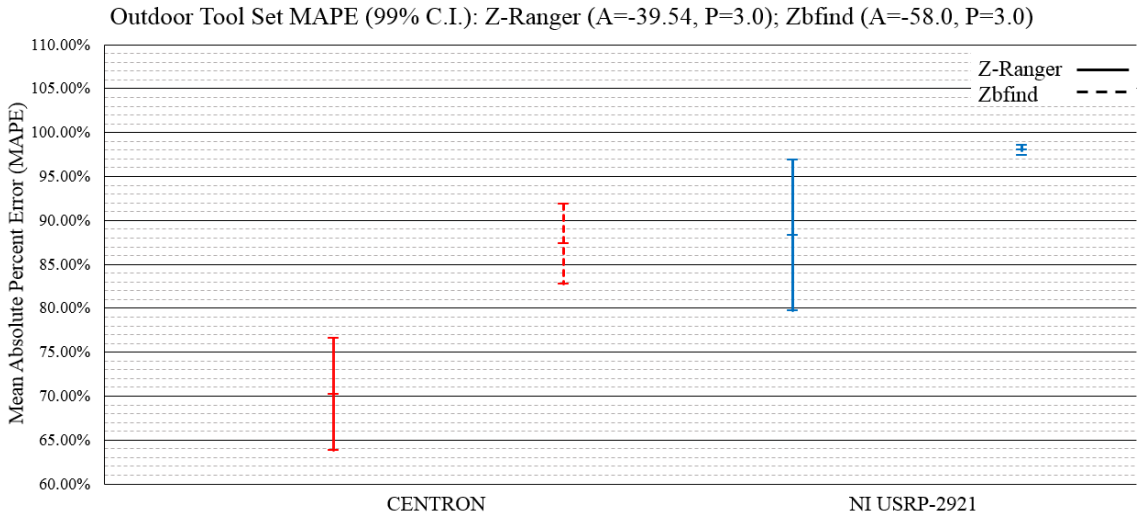


Figure 28. This figure depicts the MAPE produced by Z-Ranger during outdoor rangefinding using parameters discovered from the cross-validation method. The MAPE produced by Zbfind is the result of using original values.

5.2 Best fit Parameter Refinement

The Z-Ranger tool set outperforms Zbfind during outdoor collection trials only. The relatively high MAPE results suggest a penetration tester may still have a difficult time in locating outdoor devices and an even more difficult assignment locating indoor devices. Calibration of both the A and P value used in (2) may be necessary to achieve a more accurate rangefinding tool set.

An alternative to the cross-validation method of parameter discovery is to identify the best overall A and P parameters that produce the least amount of MAPE over all collection points. The corresponding A and P parameters can then be averaged together across all target devices in each respective environment (indoor or outdoor). This produces a versatile combination of A and P parameters that can be used as "default" parameters when rangefinding unknown devices. Rappaport identifies common path-loss values for differing environments [Rap96] and these are presented in Table 17.

Table 17. Identified path-loss exponents from different environments. Adapted from [Rap96].

Environment	Path Loss Values
Free Space	2
Urban area cellular radio	2.7 to 3.5
Shadowed urban cellular radio	3 to 5
In building line-of-sight	1.6 to 1.8
Obstructed in building	4 to 6
Obstructed in factories	2 to 3

Based on the previous work by Rappaport [Rap96], adjustment of the P parameter between a range of $1.6 - 4.0$, at increments of 0.1 is conducted. The range selected for P is chosen to encompass many different propagation environments, even though these experiments are conducted in an office corridor and an outdoor open field, both with an established LOS. This range allows for uncontrolled factors to be compensated for and thus not overlook the most advantageous P parameter. The A parameter is set at -65 dBm and increments towards 19 dBm until the lowest MAPE value is observed. This range for the A parameter is chosen as it encompasses all transmission power levels of the target devices used in this study. The A parameter, along with the P parameter under test, is then applied to (2) and a distance estimate is produced at each collection point interval. A corresponding MAPE value is calculated over all collection points for each device. Identification of the corresponding A and P parameters that produce the least amount of overall MAPE is identified.

This process is executed for each device in each respective environment. The corresponding A and P parameters that produce the least amount of MAPE are then averaged across all devices for each respective environment. This produces default A and P parameters for each environment. This process is repeated for both Z-Ranger and Zbfind tool sets and is referred to as the *best fit* parameter discovery method.

5.2.1 Indoors.

5.2.1.1 Z-Ranger.

Using the process described in Section 5.2, the P, the A, and calculated MAPE over all indoor collection points is found for the Z-Ranger tool set and presented in Table 18. The full range of parameters can be found in Appendix B. Each best fit P parameter is listed in the second column, followed by the corresponding A parameter, and MAPE is presented in column four. The parameters are then averaged and presented in the last row. The indoor best fit parameters for Z-Ranger are $A = -38.93$ and $P = 2.75$.

Table 19 presents the four indoor targets evaluated using the best fit parameters of $A = -38.93$ and $P = 2.75$. In Table 19, a distance estimate is calculated at each collection point, along with a corresponding MAPE value. MAPE for each device over all collection points and average MAPE across all four devices is calculated and presented in the bottom two rows.

The average MAPE produced across all four targets is $M = 44.56\%$. Comparing Table 19 to the initial rangefinding figures in Table 13, the S2 device still produces the least amount of MAPE with $M = 31.72\%$, a reduction of 30.9%. The highest amount of MAPE is produced while rangefinding the RZUSBstick with 58.64%, counter to the previous MAPE value of 47.11% identified in Table 13.

Table 18. Best fit *P* and corresponding *A* parameters for the Z-Ranger tool set. The Best fit *P* and *A* parameters displayed are found to produce the least amount of MAPE for each indoor target device.

Device	***P***	***A* (dBm)**	**MAPE**
Hue	3.5	-27.7	41.13%
S2	2.8	-40.4	29.13%
MC13213	2.6	-38.0	31.13%
RZUSBstick	2.1	-49.6	46.17%
Averaged best fit parameters, $A = -38.93$ and $P = 2.75$			

Table 19. Indoor distance estimates and corresponding MAPE produced by Z-Ranger using the parameters of $A = -38.93$ and $P = 2.75$.

	Hue		**S2**		**MC13213**		**RZUSBstick**	
Dst	Est Dst	MAPE	Est Dst	MAPE	Est Dst	MAPE	Est Dst	MAPE
1m	0.73m	27.3%	1.42m	42.4%	1.81m	81.3%	2.45m	144.7%
3m	1.68m	44.1%	3.53m	17.6%	2.61m	12.9%	6.46m	115.4%
5m	1.94m	61.2%	2.96m	40.7%	3.98m	20.4%	7.87m	57.3%
7m	1.81m	74.1%	2.40m	65.8%	3.60m	48.5%	5.95m	15.0%
9m	2.21m	75.5%	2.92m	67.6%	4.91m	45.5%	19.23m	113.6%
11m	16.10m	46.4%	13.09m	19.0%	12.38m	12.5%	21.42m	94.8%
13m	12.24m	5.8%	9.44m	27.4%	6.73m	48.2%	6.77m	47.9%
15m	6.77m	54.9%	11.66m	22.3%	14.34m	4.4%	9.15m	39.0%
17m	14.34m	15.6%	16.89m	0.6%	10.28m	39.5%	9.43m	44.5%
19m	6.32m	66.7%	10.50m	44.7%	14.41m	24.2%	13.62m	28.3%
21m	7.22m	65.6%	20.60m	1.9%	12.40m	41.0%	13.05m	37.8%
23m	10.09m	56.1%	28.51m	24.0%	11.40m	50.4%	26.20m	13.9%
25m	11.01m	56.0%	29.65m	18.6%	20.96m	16.2%	21.41m	14.3%
27m	6.31m	76.6%	40.90m	51.5%	10.85m	59.8%	12.34m	54.3%
	MAPE=51.86%		MAPE=31.67%		MAPE=36.06%		MAPE=58.64%	
Average MAPE over all four targets=44.56%								

5.2.1.2 Zbfind.

Using the best fit method described above, new recommended default P and A parameters for Zbfind are found and presented in Table 20. Best fit parameters for the Zbfind tool set are found to be $P = 2.25$ and $A = -49.33$.

Table 21 presents the four indoor targets evaluated using the new best fit parameters of $A = -49.33$ and $P = 2.25$. Table 21 presents the distance estimate at each collection point, along with a corresponding MAPE value. MAPE for each device

Table 20. The best fit P and corresponding A parameters for the Zbfind tool set. The best fit P and A parameters displayed are found to produce the least amount of MAPE for each indoor target device.

Device	P	A (dBm)	**MAPE**
Hue	2.8	-32.8	33.87%
S2	2.0	-59.0	31.06%
MC13213	2.1	-46.8	37.88%
RZUSBstick	2.1	-58.7	33.00%
Averaged best fit parameters, $A = -49.33$ and $P = 2.25$			

Table 21. Indoor distance estimates and corresponding MAPE produced by Zbfind using the parameters of $A = -49.33$ and $P = 2.25$.

	Hue		**S2**		**MC13213**		**RZUSBstick**	
Dst	Est Dst	MAPE	Est Dst	MAPE	Est Dst	MAPE	Est Dst	MAPE
1m	0.72m	28.0%	2.93m	193.1%	1.87m	87.5%	3.32m	232.2%
3m	0.56m	81.5%	7.49m	149.5%	1.46m	51.5%	7.29m	143.0%
5m	1.17m	76.7%	4.77m	4.7%	4.12m	17.5%	4.43m	11.3%
7m	2.08m	70.3%	6.63m	5.2%	4.71m	32.7%	6.98m	0.3%
9m	3.95m	56.1%	11.34m	26.0%	5.03m	44.1%	11.84m	31.5%
11m	2.81m	74.5%	6.92m	37.1%	7.22m	34.4%	6.81m	38.1%
13m	2.69m	79.3%	10.81m	16.9%	4.91m	62.2%	11.69m	10.0%
15m	3.11m	79.3%	28.66m	91.0%	6.88m	54.1%	35.54m	136.9%
17m	9.93m	41.6%	43.29m	154.7%	6.14m	63.9%	41.43m	143.7%
19m	7.13m	62.5%	37.12m	95.4%	12.49m	34.3%	33.01m	73.7%
21m	6.29m	70.1%	39.43m	87.7%	8.34m	60.3%	38.49m	83.3%
23m	10.49m	54.4%	29.36m	27.6%	26.98m	17.3%	28.49m	23.9%
25m	5.54m	77.8%	56.24m	125.0%	11.00m	56.0%	62.9m	151.6%
27m	9.64m	64.3%	43.15m	59.8%	15.42m	42.9%	53.62m	98.6%
	MAPE=65.45%		MAPE=76.96%		MAPE=47.05%		MAPE=84.15%	
Total MAPE over all four targets=68.33%								

over all collection points and average MAPE across all four devices is calculated in the bottom two rows.

The average MAPE produced across all four targets is $M = 68.33\%$. Comparing MAPE values from Table 21 to the previous MAPE figures in Table 14, a reduction in average MAPE by 2.68% is achieved using the best fit parameters found herein.

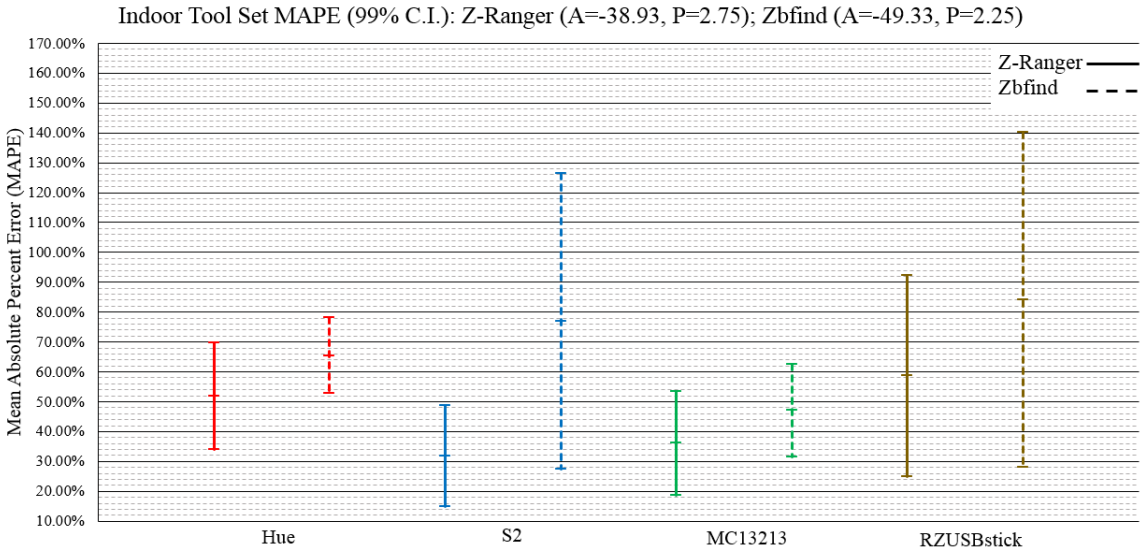


Figure 29. This figure depicts the MAPE produced by Z-Ranger and Zbfind during indoor rangefinding using parameters discovered from the best fit method.

5.2.1.3 Summary Analysis.

A 99% CI is calculated from the MAPE produced for each target device and presented in Figure 29. Analysis concludes there is not a significant difference in MAPE produced by Z-Ranger when rangefinding any of the indoor targets using the best fit method. The Hue ($M = 51.86\%, SD = 22.07\%$), S2 ($M = 31.66\%, SD = 21.02\%$), MC13213 ($M = 36.06\%, SD = 21.69\%$), and RZUSBstick ($M = 58.63\%, SD = 41.95\%$) targets produced no significant difference in MAPE as compared to Zbfind for the Hue ($M = 65.44\%, SD = 15.79\%$), S2($M = 76.96\%, SD = 61.55\%$), MC13213 ($M = 47.05\%, SD = 19.18\%$), and RZUSBstick ($M = 84.15\%, SD = 69.58\%$) targets, $p \geq .01$.

With no significant reduction in MAPE produced by Z-Ranger during the indoor rangefinding experiment, it can be concluded that a higher RSSI resolution does not reduce mean distance estimation error. Therefore, the hypothesis is not supported by these results.

5.2.2 Outdoors.

5.2.2.1 Z-Ranger.

Using the best fit method described above, the recommended default parameters of $A = -26.2$ and $P = 2.5$ are found for the two outdoor target devices. Table 22 presents all the calibrated A parameters for the range of P values under test. The corresponding MAPE over all collection points is presented in columns three and five.

Table 23 presents the distance estimates produced at each collection point for each outdoor target. Corresponding MAPE is also calculated at each collection point, with an average MAPE of $M = 71.85\%$ presented in the final row of Table 23.

Table 22. Best fit *P* and corresponding *A* parameters for the Z-Ranger tool set. The Best fit *P* and *A* parameters displayed are found to produce the least amount of MAPE for each outdoor target device.

Device	***P***	***A* (dBm)**	**MAPE**
CENTRON	2.3	-36.4	31.82%
NI USRP-2921	2.7	-16.0	54.34%
Averaged Best-fit parameters, $A = -26.2$ and $P = 2.5$			

Table 23. Outdoor distance estimates and corresponding MAPE produced by Z-Ranger using best fit parameters of $A = -26.2$ and $P = 2.5$.

	CENTRON		**NI USRP-2921**	
Dst	Est Dst	MAPE	Est Dst	MAPE
1m	5.09m	409.2%	2.25m	124.9%
6m	7.18m	19.6%	2.59m	56.8%
11m	10.35m	5.9%	3.66m	66.7%
16m	13.44m	16.0%	4.69m	70.7%
21m	37.94m	80.7%	5.18m	75.4%
26m	64.06m	146.4%	5.32m	79.5%
31m	59.52m	92.0%	6.28m	79.7%
36m	80.72m	124.2%	8.27m	77.0%
41m	48.13m	17.4%	11.37m	72.3%
46m	102.47m	122.8%	15.70m	65.9%
51m	74.11m	45.3%	17.02m	66.6%
56m	81.21m	45.0%	15.60m	72.1%
61m	52.62m	13.7%	22.49m	63.1%
66m	76.20m	15.5%	36.25m	45.1%
71m	128.80m	81.4%	35.11m	50.5%
76m	100.51m	32.3%	26.39m	65.3%
81m	206.72m	155.2%	21.32m	73.7%
86m	117.27m	36.4%	55.62m	35.3%
91m	147.14m	61.7%	85.05m	6.5%
96m	193.01m	101.1%	34.92m	63.6%
101m	179.61m	77.8%	93.49m	7.4%
	MAPE=80.93%		MAPE=62.78%	
Average MAPE for both targets=71.85%				

5.2.2.2 Zbfind.

The best fit method is also applied to the Zbfind dataset. After completing the calculations, the default parameters of $A = -29.4$ and $P = 2.35$ are found for the two outdoor target devices. Table 24 presents the calibrated P and corresponding A

Table 24. Best fit *P* and corresponding *A* parameters for the Zbfind tool set. The best fit *P* and *A* parameters displayed are found to produce the least amount of MAPE for each outdoor target device.

Device	***P***	***A* (dBm)**	**MAPE**
CENTRON	2.0	-45.9	17.66%
NI USRP-2921	2.7	-12.9	28.80%
Averaged best fit parameters, $A = -29.4$ and $P = 2.35$			

parameters under test. The calculated MAPE over all collection points is presented in columns three and five.

Table 25 lists the distance estimates produced at each collection point for each outdoor target using the best fit parameters found in Table 24. Corresponding MAPE is calculated at each collection point with a combined MAPE presented in the final row of Table 25.

MAPE produced while rangefinding the CENTRON smart meter is $M = 191.0\%$, an increase of 54.3% over the initial MAPE value of $M = 87.3\%$ presented in Table 16. Rangefinding the NI USRP-2921 produced a MAPE value of $M = 72.2\%$, a reduction of 35.8% over the initial MAPE value of $M = 98.0\%$. Average MAPE for both devices is $M = 131.6\%$, an increase of 29.6% over the initial average MAPE value of $M = 92.7\%$, as presented in Table 16.

5.2.2.3 Summary Analysis.

A 99% CI is calculated from the MAPE produced for each target device and presented in Figure 30. Analysis concludes there is a significant difference in MAPE produced by Z-Ranger when rangefinding the CENTRON ($M = 81.08\%, SD = 90.45\%$) target, as compared to Zbfind for the CENTRON ($M = 190.94\%, SD = 84.00\%$) target, $p \leq .01$.

There is no significant difference in MAPE for Z-Ranger when rangefinding the NI USRP-2921 ($M = 62.78\%, SD = 25.17\%$) target, as compared to Zbfind for the

Table 25. Outdoor distance estimates and corresponding MAPE produced by Zbfind using best fit parameters of $A = -29.4$ and $P = 2.35$.

	CENTRON		NI USRP-2921	
Dst	Est Dst	MAPE	Est Dst	MAPE
1m	5.29m	428.9%	0.35m	64.5%
6m	17.14m	185.7%	2.37m	60.5%
11m	38.66m	251.4%	3.07m	72.1%
16m	33.37m	108.6%	3.45m	78.5%
21m	64.98m	209.4%	3.87m	81.6%
26m	95.22m	266.2%	3.94m	84.8%
31m	134.17m	332.8%	4.92m	84.1%
36m	100.98m	180.5%	4.96m	86.2%
41m	161.63m	294.2%	7.22m	82.4%
46m	89.78m	95.2%	10.69m	76.8%
51m	127.76m	150.5%	10.00m	80.4%
56m	166.45m	197.2%	9.17m	83.6%
61m	166.45m	172.9%	10.10m	83.4%
66m	139.53m	111.4%	21.54m	67.4%
71m	214.74m	202.5%	34.47m	51.4%
76m	166.45m	119.0%	26.86m	64.7%
81m	206.49m	154.9%	27.38m	66.2%
86m	183.58m	113.5%	35.82m	58.3%
91m	221.15m	143.0%	28.18m	69.0%
96m	218.99m	128.1%	39.43m	58.9%
101m	266.40m	163.8%	39.43m	61.0%
	MAPE=190.94%		MAPE=72.18%	

Average MAPE for both targets=131.56%

NI USRP-2921 ($M = 72.18\%, SD = 10.78\%$), $p \geq .01$.

The significant difference in MAPE produced by Z-Ranger is observed during 50% of the outdoor rangefinding experiment. However, the reduction in MAPE shown by Z-Ranger is not consistent and therefore does not support the hypothesis that configured distance estimating parameters, along with an increased RSSI resolution, reduces MAPE produced.

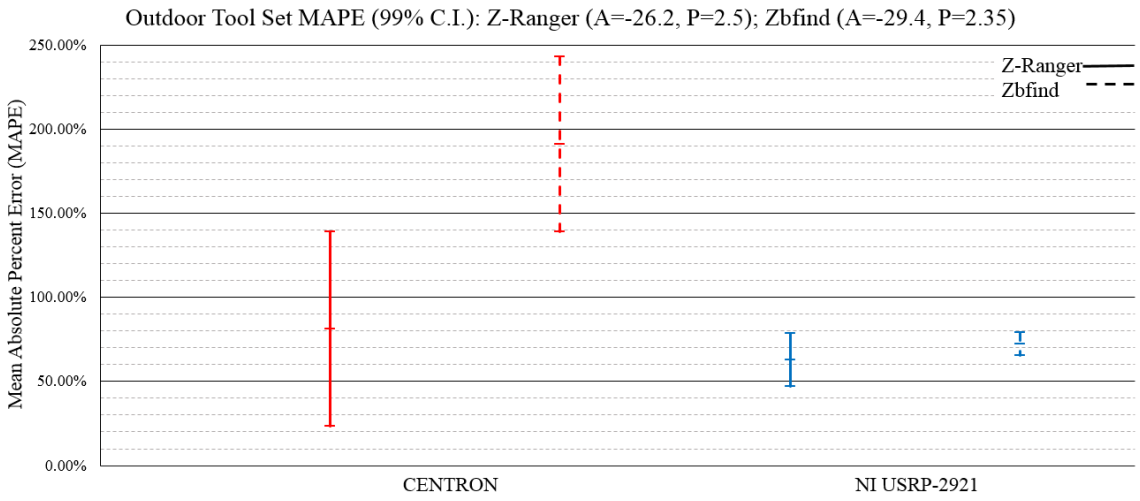


Figure 30. This figure depicts the MAPE produced by Z-Ranger and Zbfind during outdoor rangefinding using parameters discovered from the best fit method.

5.3 RSS Windowing

An alternative method for improving distance estimation may be to take the mean of multiple RSS measurements and calculate a distance estimate from this value. This process is then repeated as new RSS measurements are taken. Since signals propagate, deflect, and refract off objects, walls, and other obstructions, it is posited that by taking the mean of two or three RSS measurements, a more accurate representation of signal strength can be obtained. Therefore, a distance calculation based on this mean RSS value can more accurately reflect the true distance between transceivers. This method is commonly referred to as *windowing*.

In this section, two types of windowing are examined: a *sliding* and a *sequential* window.

- A sliding window is the mean of multiple RSS measurements based on the size on a designated window. Once a new RSS measurement is taken, the window *slides* to incorporate the new measurement into the mean and pushes the first RSS measurement out. This method of replacement is referred to as the First In Last Out (FILO) method. This slide allows the window to continually

incorporate new RSS measurements into the mean RSS product. The sliding window method reuses each RSS measurement and the amount of reuse is based on the designated window size.

- Sequential windowing takes the mean of multiple RSS measurements based on the size of the window. Once enough new RSS measurements are taken to fill the next window, a new mean RSS value is found. This method uses each RSS measurement only once and must wait until the window is "filled" again before producing a new mean RSS value.

Two window sizes of each type are examined. Results are quantified based on the amount of MAPE produced by each tool set over all collection points, similar to the experiments presented previously. The A and P parameters used for distance calculations are the parameters discovered from the best fit method, presented in Section 5.2.

5.3.1 Indoor RSS Sliding Window.

5.3.1.1 Z-Ranger.

Table 26 presents the MAPE produced over all collection points for each indoor target device. A comparison between the best-fit, two-, and three-window methods finds a slight improvement with the sliding two-window method, yielding an average MAPE reduction of 4.2% when compared to the average MAPE value of 44.56%, as identified in Table 19.

Table 26. Indoor RSS sliding window MAPE comparison for Z-Ranger.

Method	Hue	S2	MC13213	RZUSBstick	MAPE	Improvement
Best-fit	51.86%	31.67%	36.06%	58.64%	44.56%	-
two-Window	51.97%	26.29%	33.10%	59.39%	42.69%	4.2%
three-Window	52.03%	26.98%	33.09%	59.36%	42.87%	3.8%

This window simulation process is repeated, in the same fashion as above, for all sliding and sequential windowing scenarios. Full windowing tables are presented in Appendix C.

5.3.2 RSS Windowing Results.

Examining the overall results from the RSS windowing experiment for Z-Ranger, in only two instances did windowing outperform the best fit method; the indoor sliding two-window and the indoor sequential two- and three-window. The indoor sliding two-window (Table 26) average MAPE is found to be reduced by 4.2%. Similarly, by using the indoor sequential two- and three-window method (Table 41) average MAPE is reduced by 2.8%. The success of these results is limited to this simulation and is not incorporated into the Z-Ranger application due to the inconsistency in reducing MAPE production.

Examining the overall results for Zbfind, it is found windowing did not produce significant improvement in the average MAPE. In every case, the best fit method produced the least amount of average MAPE for the tool set.

5.4 Z-Ranger Implementation

5.4.0.1 Indoor Parameter Discovery Comparison.

Table 27 provides a summary and comparison of the A and P parameters found from both the cross-validation and best fit methods of parameter discovery for Z-Ranger during the indoor experiment. A 99% CI is calculated from the MAPE produced while rangefinding each target device and presented in Figure 31.

Analysis suggests there is no significant difference while rangefinding the Hue ($M = 51.86\%, SD = 22.07\%$), S2 ($M = 31.66\%, SD = 21.02\%$), MC13213 ($M = 36.06\%, SD = 21.69\%$), and RZUSBstick ($M = 58.63\%, SD = 41.95\%$) targets using the best fit method, as compared to the cross-validation method for the Hue ($M = 66.66\%, SD = 19.34\%$), S2($M = 45.87\%, SD = 22.11\%$), MC13213 ($M = 56.37\%, SD = 15.54\%$), and RZUSBstick ($M = 47.11\%, SD = 23.30\%$) targets, $p \geq .01$.

The results from the parameter discovery comparison marginally favor the best fit method over the cross-validation method. This conclusion suggests the parameters of $A = -38.93$ and $P = 2.75$ offer the most versatility for indoor rangefinding, and thus are hard coded into the final version of Z-Ranger.

Table 27. Z-Ranger log-distance path loss parameter discovery method comparison for an indoor environment.

	Cross-Validation			Best fit		
	P	A (dBm)	MAPE	P	A (dBm)	MAPE
Indoor	3.0	-43.46	54.00%	2.75	-38.93	44.56%

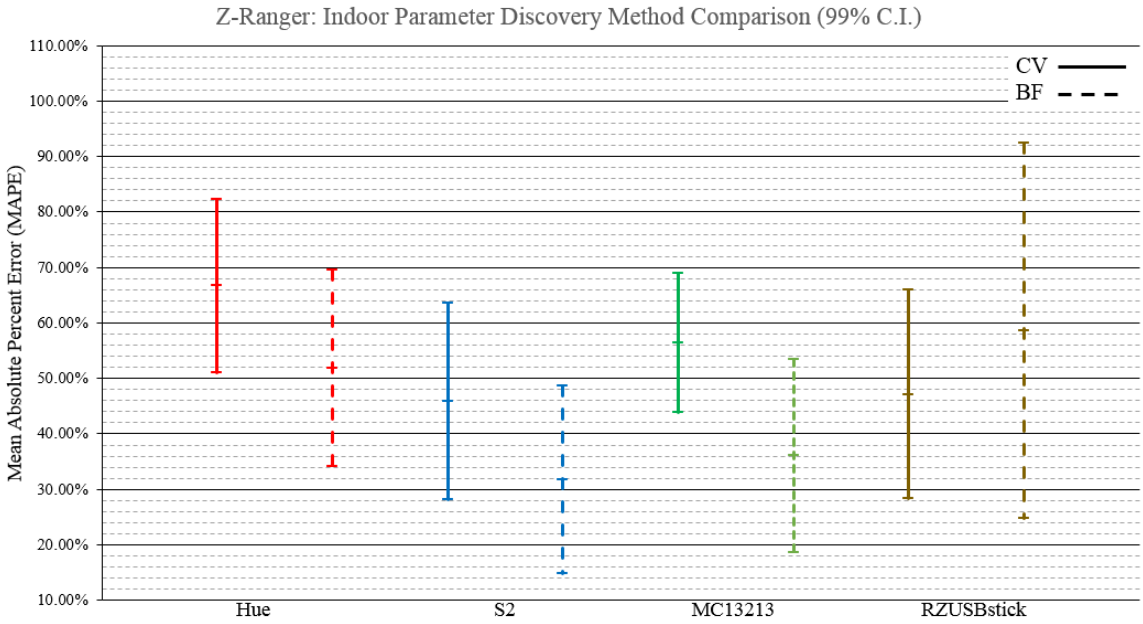


Figure 31. This figure depicts the MAPE produced by Z-Ranger during indoor rangefinding using parameters discovered from both the cross-validation and best fit log-distance path loss parameter discovery methods.

5.4.0.2 Outdoor Parameter Discovery Comparison.

Table 28 provides a summary and comparison of the A and P values found from both the cross-validation and best fit parameter discovery methods for the Z-Ranger tool set during the outdoor experiment. A 99% is calculated from the MAPE produced while rangefinding each target device and presented in Figure 32. Analysis concludes there is a significant reduction in MAPE produced by Z-Ranger when rangefinding the NI USRP-2921 using the best fit method ($M = 62.78\%, SD = 25.17\%$) as compared to the cross-validation method ($M = 88.32\%, SD = 3.02\%$), $p \leq .01$.

There was no significant difference while rangefinding the CENTRON ($M = 81.08\%, SD = 90.45\%$) target using the best fit method, as compared to the cross-validation

Table 28. Z-Ranger log-distance path loss parameter discovery method comparison for an outdoor environment.

	Cross-Validation			Best-fit		
	P	A (dBm)	MAPE	P	A (dBm)	MAPE
Outdoor	3.0	-39.55	79.26%	2.50	-26.20	71.85%

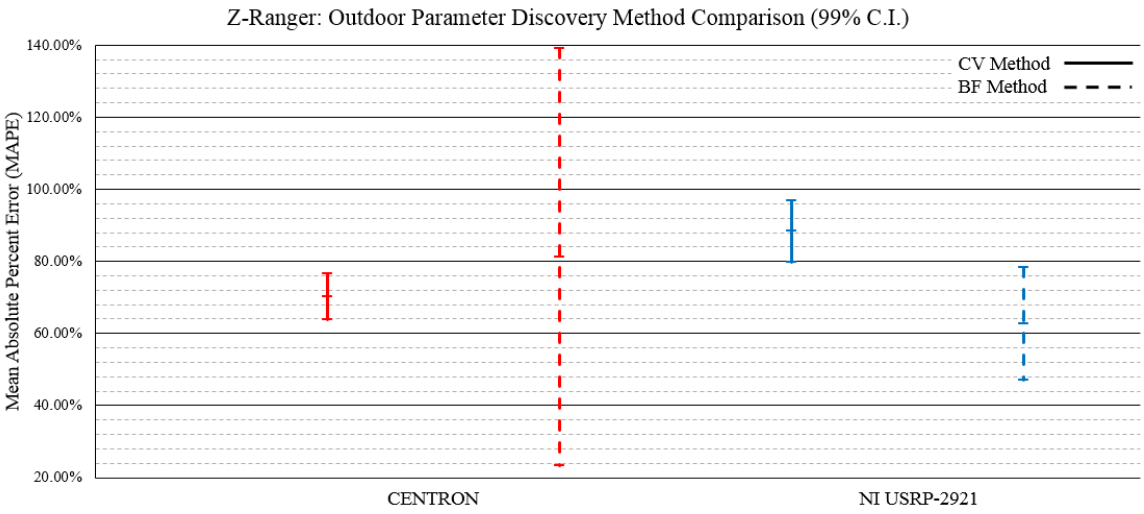


Figure 32. This figure depicts the MAPE produced by Z-Ranger during outdoor rangefinding using parameters discovered from both the cross validation and best fit parameter discovery methods.

method for the CENTRON ($M = 70.20\%, SD = 10.24\%$) target, $p \geq .01$.

Although the best fit method did not consistently outperform the cross-validation method, it did present a reduced MAPE value against the NI USRP-2921 target and thus the parameters discovered from the best fit method are chosen for final implementation into the Z-Ranger application.

The Z-Ranger application requires default parameters for use during both indoor and outdoor rangefinding exercises. Based on the evidence presented previously, the A and P parameters discovered using the best fit method are chosen for final implementation in the application. The indoor and outdoor default parameters for Z-Ranger are $A = -38.93$ and $P = 2.75$, and $A = -26.2$ and $P = 2.50$.

The individual best fit parameters found in Table 18 and Table 22 are also included in the final version of the Z-ranger application. These parameters are displayed via the

terminal when a penetration tester adds the `-r` option to the `./z-ranger` command, indicating she would like to manually enter the A and P parameters used for distance calculation. Figure 33 and Figure 34 present examples of the releasable open source version of Z-Ranger targeting a RZUSBstick while indoors and a NI USRP-2921 while outdoors.

Individualized A and P parameters produce the least amount of MAPE out of all methods discussed in this Thesis. Additional discovery of A and P parameters for other devices not studied herein can be added to future versions of the Z-Ranger application.

```
root@kali:~/Desktop/ZR Test/build# ./z-ranger -c 26 -f ranger -d 9 -r
Will you be targeting indoor (i) or outdoor (o)?
i
Documented A and P parameters:
Indoor:
        Phillips Hue Bridge:    A=-27.7 & P=3.5
        Awarepoint S2:          A=-40.4 & P=2.8
        FreeScale MC13213:      A=-38.0 & P=2.6
        Atmel RZ USBstick:      A=-49.6 & P=2.1
        Default:                A=-38.93 & P=2.75
Enter a reference RSS (A) to use:
-49.6
Enter an environment path-loss constant(P) to use:
2.1
DEBUG: debug level 9
calling libusb_init() to initialize libusb
calling libusb_open_device_with_vid_pid() to open USB device handle to ZENA
calling libusb_claim_interface(0)
ZENA successfully located and claimed
zena_set_channel(), 802.15.4 channel = 26
calling libusb_transfer() to selected_profile->ep_control
ZENA is now set to 802.15.4 channel 26
Packet Count:0, Src ID:0007,    Dst ID: 0255,   LQI:112,        RSS:-36.00,     Dist Est:0.23m
Packet Count:1, Src ID:0007,    Dst ID: 0255,   LQI:111,        RSS:-36.00,     Dist Est:0.23m
Packet Count:2, Src ID:0007,    Dst ID: 0255,   LQI:107,        RSS:-37.33,     Dist Est:0.26m
Packet Count:3, Src ID:0007,    Dst ID: 0255,   LQI:113,        RSS:-40.50,     Dist Est:0.37m
^C
```

Figure 33. Example execution of Z-Ranger rangefinding a RZUSBstick indoors.

```
root@kali:~/Desktop/ZR Test/build# ./z-ranger -c 26 -f ranger -d 9 -r
Will you be targeting indoor (i) or outdoor (o)?
o
Documented A and P parameters:
Outdoor:
        Itron smart meter:      A=-36.4 & P=2.3
        NI USRP-2921:           A=-16.0 & P=2.7
        Default:                A=-26.20 & P=2.5
Enter a reference RSS (A) to use:
-16
Enter an environment path-loss constant(P) to use:
2.7
DEBUG: debug level 9
calling libusb_init() to initialize libusb
calling libusb_open_device_with_vid_pid() to open USB device handle to ZENA
calling libusb_claim_interface(0)
ZENA successfully located and claimed
zena_set_channel(), 802.15.4 channel = 26
calling libusb_transfer() to selected_profile->ep_control
ZENA is now set to 802.15.4 channel 26
Packet Count:0, Src ID:0007,    Dst ID: 0255,   LQI:106,        RSS:-38.00,     Dist Est:6.53m
Packet Count:1, Src ID:0007,    Dst ID: 0255,   LQI:111,        RSS:-37.66,     Dist Est:6.34m
Packet Count:2, Src ID:0007,    Dst ID: 0255,   LQI:115,        RSS:-37.00,     Dist Est:5.99m
Packet Count:3, Src ID:0007,    Dst ID: 0255,   LQI:110,        RSS:-39.66,     Dist Est:7.52m
^C
root@kali:~/Desktop/ZR Test/build#
```

Figure 34. Example execution of Z-Ranger rangefinding a NI USRP-2921 outdoors.

5.5 Production Tool Set Comparison

The final version of Z-Ranger is available with open source code [Sei16] and is presented at the 2016 International Conference on Cyber Warfare and Security (ICCWS) [SRMR16]. As such, a comparison of Zbfind to Z-Ranger using only default settings provides insight as to what a novice user would encounter while rangefinding select target devices. Figure 35 depicts Z-Ranger and Zbfind rangefinding the indoor target devices using their respective default log-distance path loss parameters of $A = -38.93$ and $P = 2.75$ for Z-Ranger and $A = -58.0$ and $P = 3.0$ for Zbfind. Z-Ranger is found to significantly decrease MAPE in three of the four rangefinding estimates (Hue, S2, and MC13213 target devices). Only the RZUBstick ($M = 58.63\%, SD = 41.95\%$) shows no significant reduction in MAPE, as compared to Zbfind for the RZUSBstick ($M = 58.62\%, SD = 16.59\%$), $p \geq .01$. This accuracy improvement is also supported when examining average MAPE across all four targets by both SUT. The average MAPE produced by Zbfind is $M = 70.21\%$ and Z-Ranger produces $M = 44.56\%$, a reduction of 36.5%.

In an outdoor rangefinding scenario, Z-Ranger is calibrated with outdoor log-distance path loss default parameters of $A = -26.2$ and $P = 2.5$, and Zbfind is using the original values of $A = -58.0$ and $P = 3.0$. Figure 36 identifies a significant decrease in MAPE when rangefinding the NI USRP-2921 by Z-Ranger. The CENTRON ($M = 81.08, SD = 90.45\%$) shows no significant reduction in MAPE, as compared to Zbfind for the CENTRON ($M = 87.34\%, SD = 7.30\%$), $p \geq .01$.

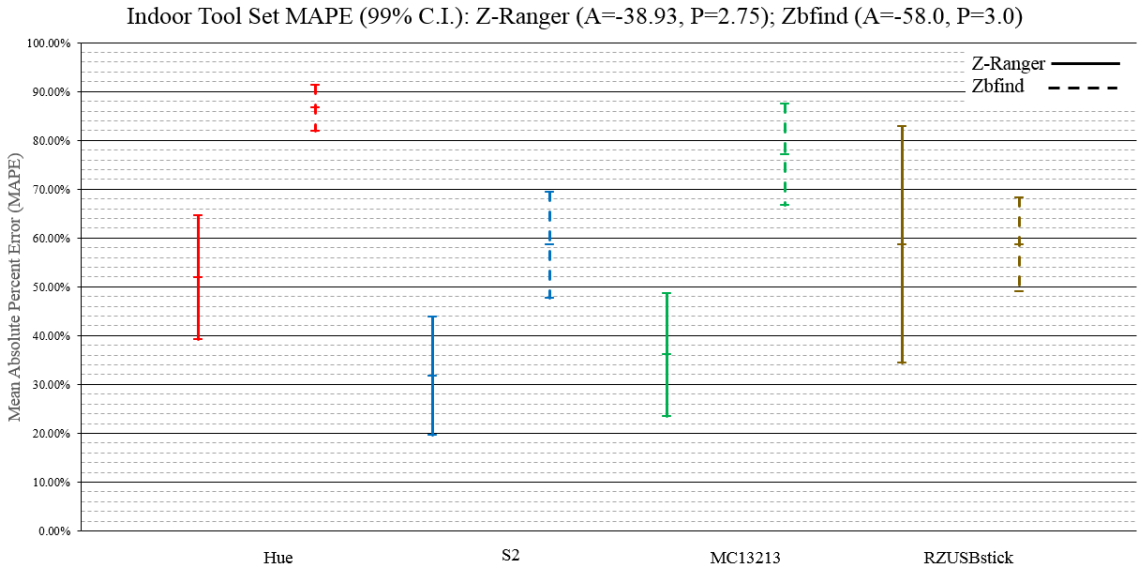


Figure 35. This figure depicts how the production tool sets compare in an indoor rangefinding scenario. Each tool set is configured to use default parameters for rangefinding select devices.

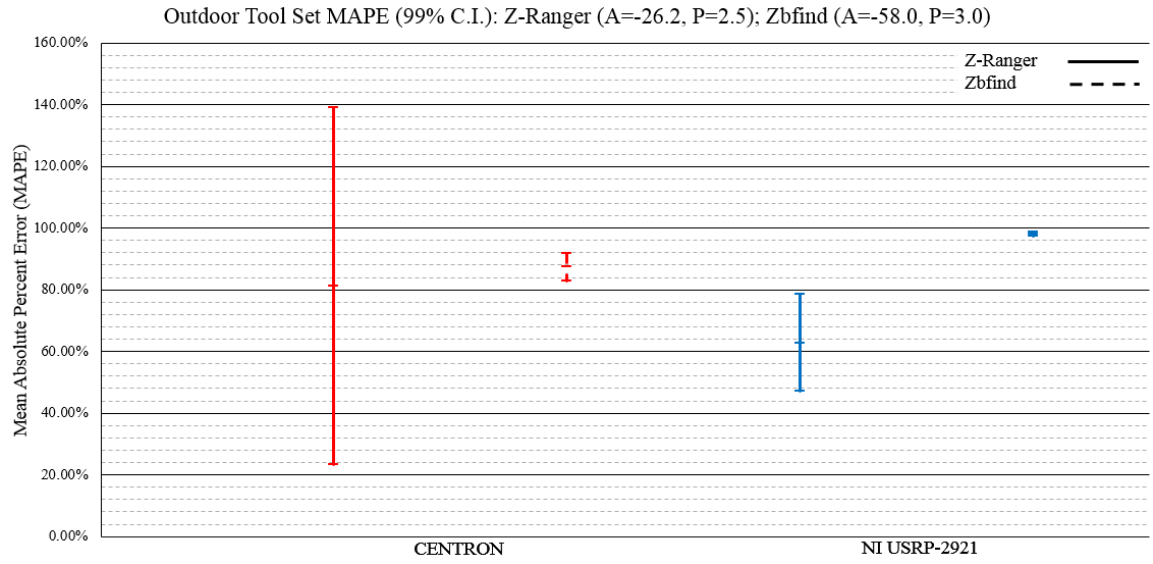


Figure 36. This figure depicts how the production tool sets compare in an outdoor rangefinding scenario. Each tool set is configured to use default parameters for rangefinding select devices.

5.6 Conclusion

Calibrating the A parameter using the cross-validation method for Z-Ranger is found to produce inconclusive results. Z-Ranger produces significantly lower MAPE values in two of the four (50%) indoor rangefinding experiments and both of the outdoor experiments (100%). The inconstancy in MAPE reduction does not support the hypothesis that a calibrated A parameter will reduce MAPE during rangefinding.

Using the best fit method to calibrate both the A and P parameters for both tool sets, it is found that Z-Ranger does not consistently reduce MAPE during either indoor or outdoor rangefinding experiments. During the indoor experiment, the best fit method does not produce a significantly higher or lower MAPE value for any of the four targets. The outdoor experiment produces a significant reduction in MAPE against only the CENTRON target device. The lack of consistency in MAPE reduction does not support the hypothesis that calibrated A and P parameters, along with an increase in RSSI resolution, contributes to a reduction in MAPE.

The results of the RSS windowing simulation are not conclusive, and no significant reductions in MAPE are found.

The final open source version of Z-Ranger does perform with error indistinguishable from the default Zbfind tool set. Comparing default rangefinding scenarios between the two tool sets, it is found that Z-Ranger operates at least as well in both an indoor and outdoor environment. During the indoor experiment, Z-Ranger is found to significantly reduce MAPE against three of the four select targets. Outdoor results show a significant reduction in MAPE against one of the two select targets. These findings conclude that Z-Ranger operates at least as well as Zbfind and directly supports research goal #3.

5.7 Summary

This chapter provides the results and analysis for the indoor and outdoor rangefinding experiments. Measured RSS samples from both the Z-Ranger and Zbfind tool sets are examined and compared. Initial A and P parameters for Z-Ranger are discovered using the K-fold cross-validation method for both environments. Further analysis using the best fit method are explored and ultimately implemented into the final release of Z-Ranger. An alternative method for accuracy improvement called windowing is also presented.

VI. Conclusion and Recommendations

6.1 Conclusions of Research

For the experimentation conducted in this thesis, the new Z-Ranger tool set is not found to consistently reduce MAPE as compared to the Zbfind tool set.

6.1.1 Goal 1: Determine if an increase in RSSI resolution reduces mean distance estimation error.

The mean results from both the indoor and outdoor experiments do not differ by a statistically significant margin. Therefore, no direct reduction in MAPE can be contributed to the increase in RSSI resolution. Inconsistency in MAPE reduction for both environments does not support the hypothesis that an increase in RSSI resolution necessarily contributes to a better rangefinding tool set.

6.1.2 Goal 2: Determine if a configurable reference RSS parameter decreases mean distance estimation error.

Results suggest that no consistent reduction in MAPE is observed while rangefinding in both indoor and outdoor environments. These results do not support the hypothesis that a configurable reference RSS parameter directly contributes to a reduction in rangefinding MAPE.

6.1.3 Goal 3: Develop a new low-rate wireless device rangefinding tool set that is at least as accurate as the existing Zbfind tool set.

Indoor rangefinding results show that Z-Ranger produces statistically lower MAPE values when rangefinding three of the four target devices. Similar results are experienced during outdoor rangefinding with Z-Ranger reducing significantly reducing

MAPE while rangefinding against one of the two select target devices. Results suggest that the final version of Z-Ranger performs at least as well as the Zbfind tool set. Z-Ranger version 1.0 is available for download [Sei16].

6.2 Research Contributions

This research provides a new open source tool set for rangefinding LR-WPAN sensors. The Z-Ranger tool set has been demonstrated through experimentation to perform at least as well as the Zbfind tool set when rangefinding select wireless sensor devices in both an indoor office corridor and an outdoor free space environment. Along with performance of the Z-Ranger tool set, the Zena offers a more rugged exterior housing that surrounds the internal components. This protective enclosure deters wind, water, and sand, thus the effective operating environment is larger than that of the RZUSBstick. This evaluation of the two tool sets contributes to the advancement of wireless security for LR-WPAN sensors.

Low-rate wireless sensors present a serious security risk to national critical infrastructure. Malicious foreign state actors are actively seeking and testing exploits, malware, and physical compromise of IEEE 802.15.4 sensors around the globe. Without effective and efficient tools for accurately identifying vulnerabilities quickly, the national defense is potentially weakened. This research contributes to the strengthening and advancement of a broader knowledge base for the Department of Defense.

6.3 Recommendations For Future Work

6.3.1 Exploring SDR Rangefinding.

Alternative devices for RSSI-based localization to be considered for future work are SDRs. Coluccia and Ricciato present a developed framework using a USRP for RSS experimentation [CR12] that may produce a more accurate distance estimation

tool. An SDR is considerably more sophisticated than a standard wireless transceiver, offering a variety of features and attributes for a developer to manipulate. Once a user is accustomed to the hardware and software environment, it may offer a more precise and accurate tool set for locating LR-WPANs and devices.

6.3.2 Rangefinding on an iOS Device.

As mentioned in Chapter II, the WiPry Pro bundle monitors the 2.4 GHz range, displaying local ZigBee devices on a spectrum analyzer. As configured, the WiPry application identifies channel and RSSI of a target device, however, Oscium Inc. boasts an open API for controlling their accessory. Configuring a rangefinding function using this new technology is worthy of exploration as it may represent the next step in RSSI-based localization of ZigBee devices. Allowing an attacker to covertly locate ZigBee devices using the common iPhone platform presents another avenue of attack on physical security of wireless sensors and requires further research.

6.3.3 Selective RSSI-based Distance Estimation Technique.

RSSI-based localization is found to be inconsistent at times due to confounding spectral dynamics. Inhibited low quality signals can be identified by the associated LQI and thus not used for distance estimation. Raju et al. present a successful adaptation of using LQI to filter RSSI measurements prior to calculating a distance estimate [ROA12]. In order to calculate a distance estimate, Raju et al. set a LQI threshold that must be met first. RSSI that does not meet the minimum threshold are filtered out and not used for distance calculation.

This RSSI validation technique could be implemented into Z-Ranger, potentially increasing rangefinding accuracy. A comparison analysis study of distance estimation models could then be undertaken and presented as an extension of this research.

Appendix A. Source Files

A.1 Z-Ranger

The steps below outline the process necessary to download, compile, and execute the Z-Ranger tool set. In this thesis, Z-Ranger is executed from the Kali Linux (Version 1.0) OS [Sec15], however, Z-Ranger is designed to run on most Linux distributions.

1. Download the Z-Ranger source code from AFITWiSec.
2. Unzip the Z-Ranger package.
3. Ensure GCC version 4.3.3 (or higher) and `libusb-1.0` is installed on the target computer.
4. In the same directory as `z-ranger.c`, execute the command `make`. This will use the `Makefile` file to create a new build directory where the latest compiled version of `z-ranger` will be held. After execution of `make`, the Z-Ranger application is available for execution.

A.2 RZUSBstick

Modification for the Zbfind application included adding the Python print statements depicted in Figure 37 starting at line number 955.

```
950
951             dist = zbpoll.zb_distance(rssi) # Distance to Tx device
952             rss = packetlist[2] # Receive Signal Strength [1-28] from register 13 on RZUSBSTICK
953             ms = datetime.datetime.now().strftime("%Y-%m-%d %H:%M:%S:%f")
954
955             """Print DATE,TIME, RSSI, DISTANCE"""
956             pdata = rxcount, ms, channel, rss, rssi, dist
957             data = "%d,%d,%d,%d\n" % (rxcount, channel, rssi, rss)
958
959             print ("Rxcount: %d, Time: %s, Channel: %d, RSSI: %d, RSS: %ddBm, Distance: %s" % pdata)
```

Figure 37. Zbfind source code modification.

A.3 NI USRP-2921

This section identifies the version and installation procedures necessary to replicate the IEEE 802.15.4 frame sent from the NI USRP-2921 used in this experiment.

A.3.1 GNU Radio Installation.

Download GNU Radio (version 3.7 or higher) from GNURadio. Follow the directions for the specific OS of the computer that will be connected to the NI-2921 USRP.

A.3.2 IEEE 802.15.4 Module.

Download the IEEE 802.15.4 GNU Radio modules from Github. At the time of this writing, 802.15.4 module is compatible with GNU Radio version 3.7. Follow the steps outlined by Bloessl for installing and compiling the blocks necessary for use.

Appendix B. Data Tables

B.1 RSSI-to-RSS Conversion Tables

B.1.1 Published MRF24J40 Converion Table.

Table 29. The MRF24J40 published RSS-to-RSSI values. Adapted from [Mic10].

RSS (dBm)	RSSI	RSS (dBm)	RSSI	RSS (dBm)	RSSI	RSS (dBm)	RSSI
-100	0	-80	37	-60	138	-40	239
-99	0	-79	43	-59	143	-39	245
-98	0	-78	48	-58	148	-38	250
-97	0	-77	53	-57	153	-37	253
-96	0	-76	58	-56	159	-36	254
-95	0	-75	63	-55	165	-35	255
-94	0	-74	68	-54	170	-34	255
-93	0	-73	73	-53	176	-33	255
-92	0	-72	78	-52	183	-32	255
-91	0	-71	83	-51	188	-31	255
-90	0	-70	89	-50	193	-30	255
-89	1	-69	95	-49	198	-29	255
-88	2	-68	100	-48	203	-28	255
-87	5	-67	107	-47	207	-27	255
-86	9	-66	111	-46	212	-26	255
-85	13	-65	117	-45	216	-25	255
-84	18	-64	121	-44	221	-24	255
-83	23	-63	125	-43	225	-23	255
-82	27	-62	129	-42	228	-22	255
-81	32	-61	133	-41	233	-21	255
						-20	255

B.1.2 Extended MRF24J40 Conversion Table.

Table 30. Extended RSSI-to-RSS mapping for the Zena Wireless Adapter.

RSS (dBm)	RSSI	RSS (dBm)	RSSI	RSS (dBm)	RSSI	RSS (dBm)	RSSI	RSS (dBm)	RSSI
-90	0	-77.4	51	-67.71	102	-57	153	-47.75	204
-89	1	-77.2	52	-67.56	103	-56.83	154	-47.5	205
-88	2	-77	53	-67.42	104	-56.66	155	-47.25	206
-87.66	3	-76.8	54	-67.28	105	-56.5	156	-47	207
-87.33	4	-76.6	55	-67.14	106	-56.33	157	-46.8	208
-87	5	-76.4	56	-67	107	-56.17	158	-46.6	209
-87.75	6	-76.2	57	-66.75	108	-56	159	-46.4	210
-86.5	7	-76	58	-66.5	109	-55.83	160	-46.2	211
-86.25	8	-75.8	59	-66.25	110	-55.66	161	-46	212
-86	9	-75.6	60	-66	111	-55.5	162	-45.75	213
-85.75	10	-75.4	61	-65.83	112	-55.33	163	-45.5	214
-85.5	11	-75.2	62	-65.66	113	-55.17	164	-45.25	215
-85.25	12	-75	63	-65.5	114	-55	165	-45	216
-85	13	-74.8	64	-65.33	115	-54.8	166	-44.8	217
-84.8	14	-74.6	65	-65.17	116	-54.6	167	-44.6	218
-84.6	15	-74.4	66	-65	117	-54.4	168	-44.4	219
-84.4	16	-74.2	67	-64.75	118	-54.2	169	-44.2	220
-84.2	17	-74	68	-64.5	119	-54	170	-44	221
-84	18	-73.8	69	-64.25	120	-53.83	171	-43.75	222
-83.8	19	-73.6	70	-64	121	-53.66	172	-43.5	223
-83.6	20	-73.4	71	-63.75	122	-53.5	173	-43.25	224
-83.4	21	-73.2	72	-63.5	123	-53.33	174	-43	225
-83.2	22	-73	73	-63.25	124	-53.17	175	-42.66	226
-83	23	-72.8	74	-63	125	-53	176	-42.33	227
-82.75	24	-72.6	75	-62.75	126	-52.86	177	-42	228
-82.5	25	-72.4	76	-62.5	127	-52.71	178	-41.8	229
-82.25	26	-72.2	77	-62.25	128	-52.56	179	-41.6	230
-82	27	-72	78	-62	129	-52.42	180	-41.4	231
-81.8	28	-71.8	79	-61.75	130	-52.28	181	-41.2	232
-81.6	29	-71.6	80	-61.5	131	-52.14	182	-41	233
-81.4	30	-71.4	81	-61.25	132	-52	183	-40.83	234
-81.2	31	-71.2	82	-61	133	-51.8	184	-40.66	235
-81	32	-71	83	-60.8	134	-51.6	185	-40.5	236
-80.8	33	-70.83	84	-60.6	135	-51.4	186	-40.33	237
-80.6	34	-70.66	85	-60.4	136	-51.2	187	-40.17	238
-80.4	35	-70.5	86	-60.2	137	-51	188	-40	239
-80.2	36	-70.33	87	-60	138	-50.8	189	-39.83	240
-80	37	-70.17	88	-59.8	139	-50.6	190	-39.66	241
-79.83	38	-70	89	-59.6	140	-50.4	191	-39.5	242
-79.66	39	-69.83	90	-59.4	141	-50.2	192	-39.33	243
-79.5	40	-69.66	91	-59.2	142	-50	193	-39.17	244

Table 30. Extended RSSI-to-RSS mapping for Zena wireless adapter.

Continuation of Table 5

RSS (dBm)	**RSSI**	**RSS (dBm)**	**RSSI**	**RSS (dBm)**	**RSSI**	**RSS (dBm)**	**RSSI**	**RSS (dBm)**	**RSSI**
-79.33	41	-69.5	92	-59	143	-49.8	194	-39	245
-79.17	42	-69.33	93	-58.8	144	-49.6	195	-38.8	246
-79	43	-69.17	94	-58.6	145	-49.4	196	-38.6	247
-78.8	44	-69	95	-58.4	146	-49.2	197	-38.4	248
-78.6	45	-68.8	96	-58.2	147	-49	198	-38.2	249
-78.4	46	-68.6	97	-58	148	-48.8	199	-38	250
-78.2	47	-68.4	98	-57.8	149	-48.6	200	-37.66	251
-78	48	-68.2	99	-57.6	150	-48.4	201	-37.33	252
-77.8	49	-68	100	-57.4	151	-48.2	202	-37	253
-77.6	50	-67.86	101	-57.2	152	-48	203	-36	254
								-35	255

End of Table 5

B.2 Best fit Parameter Discovery Tables

B.2.1 Indoor Targets.

Table 31. Best fit values for P ∈ {1.6-4.0} for the Phillips Hue Bridge

	Z-Ranger		Zbfind	
P	**A (dBm)**	**MAPE(%)**	**A (dBm)**	**MAPE(%)**
1.6	-51.0	68.780	-48.0	43.780
1.7	-49.8	67.090	-46.6	39.548
1.8	-48.6	65.322	-45.6	36.810
1.9	-47.4	63.589	-44.3	35.978
2.0	-46.1	61.758	-43.0	35.460
2.1	-44.9	59.896	-41.7	35.029
2.2	-43.6	58.019	-40.4	34.675
2.3	-35.5	55.054	-39.1	34.413
2.4	-35.1	51.809	-37.8	34.214
2.5	-35.1	49.426	-36.5	34.064
2.6	-35.1	47.618	-35.3	33.935
2.7	-35.1	46.232	-33.9	33.894
2.8	-35.1	45.161	**-32.8**	**33.874**
2.9	-35.1	44.377	-32.0	34.191
3.0	-33.8	43.758	-31.1	34.464
3.1	-32.5	43.222	-30.1	34.842
3.2	-30.0	42.704	-28.7	35.368
3.3	-29.4	42.221	-27.8	36.149
3.4	-28.9	41.820	-27.4	37.018
3.5	**-27.7**	**41.128**	-26.9	37.801
3.6	-26.5	42.476	-26.1	38.744
3.7	-26.3	42.844	-25.2	39.628
3.8	-26.5	43.177	-24.4	40.486
3.9	-25.4	43.522	-23.6	41.301
4.0	-24.2	43.882	-22.7	42.333

Table 32. Best fit values for P ∈ {1.6-4.0} for the Awarepoint S2

	Z-Ranger		Zbfind	
P	**A (dBm)**	**MAPE(%)**	**A (dBm)**	**MAPE(%)**
1.6	-57.0	60.759	-63.3	42.197
1.7	-55.6	57.918	-62.1	38.455
1.8	-51.3	54.092	-60.9	34.817
1.9	-49.9	50.069	-59.9	31.487
2.0	-48.8	46.398	**-59.0**	**31.060**
2.1	-47.7	43.123	-57.8	31.306
2.2	-46.0	39.876	-56.5	31.640
2.3	-44.6	36.699	-55.2	32.054
2.4	-43.3	33.511	-53.9	32.529
2.5	-43.1	31.643	-52.7	33.064
2.6	-42.5	30.464	-51.5	33.716
2.7	-41.5	29.529	-50.4	34.385
2.8	**-40.4**	**29.133**	-49.2	35.042
2.9	-39.4	29.447	-48.0	35.727
3.0	-38.1	29.827	-46.8	36.472
3.1	-36.7	30.239	-45.4	37.313
3.2	-35.3	30.699	-44.0	38.173
3.3	-34.0	31.177	-42.6	39.049
3.4	-32.6	31.702	-41.2	39.937
3.5	-31.3	32.248	-40.2	40.888
3.6	-29.9	32.809	-39.5	41.818
3.7	-28.5	33.410	-38.7	42.785
3.8	-27.2	34.001	-38.0	43.986
3.9	-25.8	34.636	-37.3	45.098
4.0	-24.5	35.272	-36.6	46.131

Table 33. Best fit values for P ∈ {1.6-4.0} for the Freescale MC13213

	Z-Ranger		Zbfind	
P	**A (dBm)**	**MAPE(%)**	**A (dBm)**	**MAPE(%)**
1.6	-50.3	46.133	-53.1	43.014
1.7	-49.0	42.939	51.3	40.349
1.8	-46.1	39.005	50.3	38.817
1.9	-46.0	36.221	-48.8	38.355
2.0	-45.2	34.781	-47.8	37.966
2.1	-43.9	33.890	**-46.8**	**37.884**
2.2	-42.6	33.091	-45.9	38.046
2.3	-41.4	32.368	-44.7	38.687
2.4	-40.1	31.711	-43.7	39.464
2.5	-38.8	31.153	-42.6	40.227
2.6	**-38.0**	**31.134**	-41.7	40.995
2.7	-37.5	31.505	-40.6	41.729
2.8	-36.1	32.128	-39.7	42.465
2.9	-35.2	33.159	-39.9	43.143
3.0	-34.4	34.296	-39.1	43.756
3.1	-33.7	35.367	-38.2	44.357
3.2	-33.1	36.354	-37.7	45.169
3.3	-31.9	37.538	-36.6	46.121
3.4	-30.8	38.745	-35.7	47.476
3.5	-29.6	39.931	-34.9	48.747
3.6	-28.4	41.109	-34.0	49.971
3.7	-27.3	42.281	-33.2	51.092
3.8	-28.8	43.345	-32.4	52.186
3.9	-28.1	44.275	-31.5	52.207
4.0	-27.3	45.165	-30.7	54.182

Table 34. Best fit values for P ∈ {1.6-4.0} for the Atmel RZUSBstick

	Z-Ranger		Zbfind	
P	**A (dBm)**	**MAPE(%)**	**A (dBm)**	**MAPE(%)**
1.6	-53.6	55.025	-65.3	44.693
1.7	-53.1	51.609	-62.6	41.139
1.8	-52.6	48.899	61.2	37.141
1.9	-52.0	46.719	-61.0	34.521
2.0	-50.7	47.390	-59.6	33.413
2.1	**-49.6**	**46.174**	**-58.7**	**33.001**
2.2	-49.6	46.262	-58.2	33.114
2.3	-49.6	46.357	-57.2	33.547
2.4	-49.6	46.452	-56.0	34.037
2.5	-49.6	46.669	-54.8	34.588
2.6	-48.4	47.059	-53.4	35.293
2.7	-47.4	47.519	-52.1	36.027
2.8	-46.4	48.026	-50.7	36.795
2.9	-45.3	48.517	-49.3	37.591
3.0	-44.3	49.022	-47.9	38.413
3.1	-43.2	49.553	-46.5	39.255
3.2	-42.2	50.055	-45.1	40.116
3.3	-41.2	50.596	-43.7	40.990
3.4	-40.1	51.119	-42.3	41.877
3.5	-39.1	51.644	-40.9	42.773
3.6	-38.4	52.280	-41.4	43.582
3.7	-37.7	52.886	-40.2	44.378
3.8	-37.0	53.462	-38.9	45.166
3.9	-36.3	54.013	-37.7	45.938
4.0	-35.6	54.539	-36.5	46.699

B.2.2 Outdoor Targets.

Table 35. Best fit values for P ∈ {1.6-4.0} for the Openway CENTRON smart meter

	Z-Ranger		Zbfind	
P	**A (dBm)**	**MAPE(%)**	**A (dBm)**	**MAPE(%)**
1.6	-49.0	42.210	-53.1	26.431
1.7	-47.3	38.820	-51.2	24.060
1.8	-45.6	35.978	-49.3	21.686
1.9	-43.8	33.289	-47.3	19.095
2.0	-42.0	32.698	**-45.9**	**17.662**
2.1	-40.1	32.259	-44.2	18.190
2.2	-38.3	31.979	-42.3	19.308
2.3	**-36.4**	**31.823**	-40.7	20.669
2.4	-34.5	32.106	-39.7	22.214
2.5	-32.7	32.640	-37.9	24.398
2.6	-31.3	33.269	-36.1	26.715
2.7	-29.9	34.052	-34.5	29.098
2.8	-28.6	35.207	-33.0	31.500
2.9	-27.3	36.307	-33.6	33.754
3.0	-25.8	37.421	-32.3	35.649
3.1	-24.3	38.520	-31.0	37.460
3.2	-22.9	39.596	-29.7	39.208
3.3	-21.4	41.198	-28.1	41.034
3.4	-19.9	42.972	-26.7	42.864
3.5	-18.3	44.782	-25.7	44.595
3.6	-16.9	46.580	-24.4	46.258
3.7	-15.4	48.330	-23.1	47.873
3.8	-13.9	50.039	-21.8	49.429
3.9	-12.1	51.711	-20.5	50.930
4.0	-11.6	53.304	-19.2	52.381

Table 36. Best fit values for P ∈ {1.6-4.0} for the NI USRP-2921

	Z-Ranger		Zbfind	
P	**A (dBm)**	**MAPE(%)**	**A (dBm)**	**MAPE(%)**
1.6	-36.1	70.749	-33.6	55.948
1.7	-35.0	65.832	-31.7	52.714
1.8	-35.0	63.171	-30.0	49.702
1.9	-30.7	61.528	-27.6	45.933
2.0	-28.8	59.762	-25.1	42.412
2.1	-27.0	58.325	-23.2	38.639
2.2	-25.2	57.166	-21.2	34.910
2.3	-23.3	56.220	-19.6	32.149
2.4	-21.5	55.488	-18.1	30.116
2.5	-19.7	54.948	-16.2	29.442
2.6	-17.8	54.579	-14.3	28.916
2.7	**-16.0**	**54.338**	**-12.9**	**28.800**
2.8	-14.7	54.545	-11.0	29.255
2.9	-13.7	55.150	-9.2	29.817
3.0	-11.8	56.075	-7.3	30.489
3.1	-9.9	57.098	-5.4	31.269
3.2	-7.9	58.202	-3.6	32.299
3.3	-6.0	59.387	-2.2	33.792
3.4	-4.9	60.728	-0.3	35.325
3.5	-5.3	61.985	1.7	36.951
3.6	-3.3	63.140	3.7	38.662
3.7	-1.7	64.570	5.4	40.462
3.8	0.0	66.315	6.8	42.339
3.9	1.9	68.166	8.1	44.444
4.0	3.9	70.042	9.4	46.442

Appendix C. Windowing Table Results

C.1 Z-Ranger

C.1.1 Indoor RSS Sliding Window.

C.1.1.1 Z-Ranger.

Table 37. Indoor RSS sliding window MAPE comparison for Z-Ranger.

Method	Hue	S2	MC13213	RZUSBstick	MAPE	Improvement
Best fit	51.86%	31.67%	36.06%	58.64%	44.56%	-
2-Window	51.97%	26.29%	33.10%	59.39%	42.69%	4.2%
3-Window	52.03%	26.98%	33.09%	59.36%	42.87%	3.8%

C.1.1.2 Zbfind.

Table 38. Indoor RSS sliding window MAPE comparison for Zbfind.

Method	Hue	S2	MC13213	RZUSBstick	MAPE	Improvement
Best fit	65.48%	76.96%	47.05%	84.15%	68.41%	-
2-Window	64.45%	85.26%	49.03%	89.25%	72.00%	-5.2%
3-Window	64.62%	84.71%	48.95%	88.56%	71.71%	-4.8%

C.1.2 Outdoor RSS Sliding Window.

C.1.2.1 Z-Ranger.

Table 39. Outdoor RSS sliding window MAPE comparison for Z-Ranger.

Method	CENTRON	NI USRP-2921	MAPE	Improvement
Best fit	80.93%	62.78%	71.86%	-
2-Window	102.78%	71.67%	87.23%	-21.4%
3-Window	99.06%	71.80%	85.43%	-18.9%

C.1.2.2 Zbfind.

Table 40. Outdoor RSS sliding window MAPE comparison for Zbfind.

Method	CENTRON	NI USRP-2921	MAPE	Improvement
Best fit	190.94%	70.71%	130.83%	-
2-Window	220.18%	76.79%	148.49%	-13.5%
3-Window	220.12%	76.87%	148.50%	-13.5%

C.1.3 Indoor RSS Sequential Window.

C.1.3.1 Z-Ranger.

Table 41. Indoor RSS sequential window MAPE comparison for Z-Ranger.

Method	Hue	S2	MC13213	RZUSBstick	MAPE	Improvement
Best fit	51.86%	31.67%	36.06%	58.64%	44.56%	-
2-Window	52.02%	26.47%	35.84%	58.97%	43.33%	2.8%
3-Window	51.91%	26.90%	35.96%	58.52%	43.33%	2.8%

C.1.3.2 Zbfind.

Table 42. Indoor RSS sequential window MAPE comparison for Zbfind.

Method	Hue	S2	MC13213	RZUSBstick	MAPE	Improvement
Best fit	65.48%	76.96%	47.05%	84.15%	68.41%	-
2-Window	64.30%	84.82%	48.85%	88.66%	71.66%	-4.8%
3-Window	64.55%	82.63%	48.97%	87.29%	70.86%	-3.6%

C.1.4 Outdoor RSS Sequential Window.

C.1.4.1 Z-Ranger.

Table 43. Outdoor RSS sequential window MAPE comparison for Z-Ranger.

Method	CENTRON	NI USRP-2921	MAPE	Improvement
Best fit	80.93%	62.78%	71.86%	-
2-Window	101.18%	71.67%	86.69%	-20.6%
3-Window	99.54%	71.91%	85.73%	-19.3%

C.1.4.2 Zbfind.

Table 44. Outdoor RSS sequential window MAPE comparison for Zbfind.

Method	CENTRON	NI USRP-2921	MAPE	Improvement
Best fit	190.94%	70.71%	130.86%	-
2-Window	220.81%	76.74%	148.78%	-13.7%
3-Window	219.74%	76.79%	148.27%	-13.3%

Bibliography

Ada06. J. Adams. An Introduction to IEEE STD 802.15.4. In *2006 IEEE Aerospace Conference*, page 8, 2006.

Atm09a. Atmel. Atmel AT86RF230 Data Sheet. `http://www.atmel.com/images/doc5131.pdf` [Accessed: 26 May 2015], February 2009.

Atm09b. Atmel. AVR2009: AT86RF230 Software Programming Model. Technical report, 2009.

Atm12. Atmel. Atmel AVR2016: RZRAVEN Hardware Users Guide. `http://www.atmel.com/Images/doc8117.pdf` [Accessed: 5 January 2016], 2012.

Bio03. P. Biondi. The Scapy Project. `http://www.secdev.org/projects/scapy/` [Accessed: 21 October 2015], 2003.

Blo12. B. Bloessl. IEEE 802.15.4 ZigBee Transceiver. `https://github.com/bastibl/gr-ieee802-15-4/tree/master/apps` [Accessed: 23 November 2015], 2012.

BPC+07. P. Baronti, P. Pillai, V. Chook, S. Chessa, A. Gotta, and Y. Fun Hu. Wireless Sensor Networks: A Survey on the State of the Art and the 802.15.4 and ZigBee Standards. In *Computer Communications*, volume 30, pages 1655–1695. Elsevier, 26 May 2007.

CR12. A. Coluccia and F. Ricciato. A Software-Defined Radio Tool for Experimenting with RSS Measurements in IEEE 802.15.4: Implementation and Applications. In *2012 21st International Conference on Computer Communications and Networks (ICCCN)*, pages 1–6, 2012.

Des11. J. Desbonnet. Using the Microchip ZENA ZigBee/802.15.4 Network Analyzer with Linux. `http://jdesbonnet.blogspot.com/2011/02/using-microchip-zena-zigbee802154.html` [Accessed: 27 August 2015], 2011.

EPR10. EPRI. An Investigation of Radiofrequency Fields Associated with the Itron Smart Meter. `http://smartgridcc.org/wp-content/uploads/2012/08/000000000001021126.pdf` [Accessed: 11 November 2015], 2010.

Fre09. Freescale. MC13211/212/213 ZigBee- Compliant Platform - 2.4 GHz Low Power Transceiver for the IEEE 802.15.4 Standard plus Microcontroller. `https://cache.freescale.com/files/rf_if/doc/data_sheet/MC1321x.pdf?pspll=1` [Accessed: 11 November 2015], 2009.

GBM+12. T. Goodspeed, S. Bratus, R. Melgares, R. Speers, and S. Smith. Api-do: Tools for Exploring the Wireless Attack Surface in Smart Meters. In *45th Hawaii International Conference on System Science (HICSS)*, pages 2133–2140, 2012.

GGH10. S. Gansemer, U. Grossmann, and S. Hakobyan. RSSI-based Euclidean Distance Algorithm for Indoor Positioning Adapted for the use in Dynamically Changing WLAN Environments and Multi-level Buildings. In *International Conference on Indoor Positioning and Indoor Navigation (IPIN)*, pages 1–6, 2010.

Goo09. T. Goodspeed. Extracting Keys from Second Generation ZigBee Chips. In *Chipcon, Black Hat USA*, 2009.

IEE03. IEEE. Standard for Local and Metropolitan Area Networks Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs), 2003.

IEE11. IEEE. Standard for Local and Metropolitan Area Networks Part 15.4: Low-Rate Wireless Personal Area Networks (LR-WPANs), 2011.

IEE15. IEEE. IEEE About Page. `http://www.ieee.org/about/ieee_history.html` [Accessed: 21 October 2015], 2015.

Jih11. C. Jihong. Patient Positioning System in Hospital Based on Zigbee. In *International Conference on Intelligent Computation and Bio-Medical Instrumentation (ICBMI)*, pages 159–162, 2011.

JL09. Z. Jianwu and Z. Lu. Research on Distance Measurement Based on RSSI of ZigBee. In *ISECS International Colloquium on Computing, Communication, Control, and Management (CCCM)*, volume 3, pages 210–212, August 2009.

Koh95. R. Kohavi. A Study of Cross-Validation and Bootstrap for Accuracy Estimation and Model Selection. In *International Joint Conference on Artificial Intelligence (IJCAI)*, 1995.

Mic10. Microchip. MRF24J40 Data Sheet: IEEE 802.15.4 2.4 GHz RF Transceiver. `http://ww1.microchip.com/downloads/en/DeviceDoc/39776C.pdf` [Accessed: 6 January 2016], 2010.

Mic11. Microchip. Zena Wireless Adapter. `https://www.microchip.com/DevelopmentTools/ProductDetails.aspx?PartNO=AC182015-1` [Accessed: 21 August 2015], 2011.

Mic12. Microchip. Wireless Development Studio. `https://www.microchip.com/stellent/idcplg?IdcService=SS_GET_PAGE&nodeId=2680&dDocName=en554472` [Accessed: 9 August 2015], 2012.

Mic16. Microsoft. USB Endpoints and their Pipes. https://msdn.microsoft.com/en-us/library/windows/hardware/dn303353(v=vs.85).aspx [Accessed: 26 January 2016], 2016.

MSB11. R. Melgares, R. Speers, and S. Bratus. Api-do: Tools for ZigBee and 802.15.4 Security Auditing. https://code.google.com/p/zigbee-security/ [Accessed: 20 October 2015], 2011.

Osc15. Oscium. WiPry Pro. https://www.oscium.com/spectrum-analyzers/wipry-pro-combo [Accessed: 12 November 2015), 2015.

Poo15. I. Poole. Radio Signal Path Loss. http://www.radio-electronics.com/info/propagation/path-loss/rf-signal-loss-tutorial.php [Accessed: 9 November 2015], 2015.

Rad15. GNU Radio. GNU Radio: The Free and Open Software Radio Ecosystem. https://gnuradio.org/redmine/projects/gnuradio [Accessed: 11 November 2015], 2015.

Ran15. Random. Random Team Generator. http://www.randomlists.com/team-generator[Accessed: 20 November 2015], 2015.

Rap96. T. Rappaport. *Wireless Communication Principles and Practice*, chapter 3, page 102. 1996.

RMLS14. B. Ramsey, B. Mullins, W. Lowder, and R. Speers. Sharpening the Stinger: Tuning KillerBee for Critical Infrastructure Warwalking. In *IEEE Military Communications Conference (MILCOM)*, pages 104–109, 2014.

RMW12. B. Ramsey, B. Mullins, and E. White. Improved Tools for Indoor ZigBee Warwalking. In *7th IEEE International Workshop on Practical Issues in Building Sensor Network Applications*, 2012.

ROA12. M. Raju, T. Oliveira, and D. Agrawal. A Practical Distance Estimator Through Distributed RSSI/LQI Processing-An Experimental Study. In *IEEE International Conference on Communications (ICC)*, pages 6575–6579, 2012.

Sch06. T. Schmid. GNU Radio 802.15.4 En- and Decoding. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.179.31&rep=rep1&type=pdf [Accessed: 23 Nov 2015], 2006.

Sec15. Offensive Security. Kali Linux 2.0. https://www.kali.org/[Accessed: 22 October 2015], 2015.

Sei16. A. Seitz. Z-Ranger. https://github.com/AFITWiSec/Z-Ranger [Accessed: 23 January 2016], 2016.

SKG12. F. Schuster, W. Kastner, and W. Granzer. Integrating Smart Cameras into ZigBee. In *9th IEEE International Workshop on Factory Communication Systems (WFCS)*, pages 67–70, 2012.

SRMR16. A. Seitz, B. Ramsey, B. Mullins, and M. Rice. Z-Ranger: An Improved Tool Set for ZigBee Warwalking. In *International Conference on Cyber Warfare and Security (ICCWS)*, 2016.

Ver13. E. Verschuur. ZenaNG Linux. `https://github.com/emericv/ZenaNG` [Accessed: 21 October 2015], 2013.

Whi07. T. Whittaker. Final Word. In *Control and Automation*, volume 18, page 48. 2007.

WSM10. J. Wright, R. Speers, and R. Melgares. KillerBee: Framework and Tools for Exploiting ZigBee and IEEE 802.15.4 Networks. `https://github.com/riverloopsec/killerbee` [Accessed: 15 October 2015], 2010.

XC11. Y. Xu and X. Chen. Node Localization in Wireless Sensor Network Using Dynamic Distance Prediction Algorithm. In *IEEE Instrumentation and Measurement Technology Conference (I2MTC)*, pages 1–4, 2011.

Zig12. ZigBee. ZigBee Specification. `www.zigbee.org/` [Accessed: 15 March 2015], 2012.

Zig15. ZigBee. ZigBee Alliance. `http://www.zigbee.org/zigbeealliance/` [Accessed: 20 October 2015], 2015.

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704–0188

1. REPORT DATE *(DD–MM–YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From — To)*
24–03–2016	Master's Thesis	May 2014 — Mar 2016

4. TITLE AND SUBTITLE

A Comparative Analysis of IEEE 802.15.4 Adapters for Wireless Rangefinding

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Seitz, Andrew P., MSgt, USAF

5d. PROJECT NUMBER

JON 16G129

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Institute of Technology
Graduate School of Engineering and Management (AFIT/EN)
2950 Hobson Way
WPAFB OH 45433-7765

8. PERFORMING ORGANIZATION REPORT NUMBER

AFIT-ENG-MS-16-M-045

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

AFRL Information Directorate
POC: Hiren Patel, Cyber ISR Program Manager
ATTN: Hiren Patel AFRL/RIGD
Mailstop: 525 Brooks Rd, Rome, NY, 13441
Email: hiren.patel@us.af.mil Phone: 315-330-4315

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL/RIGD

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A:
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED.

13. SUPPLEMENTARY NOTES

This work is declared a work of the U.S. Government and is not subject to copyright protection in the United States.

14. ABSTRACT

ZigBee offers low-cost mesh connectivity in hospitals, refineries, and critical infrastructure. This thesis explores two ZigBee Received Signal Strength Indicator (RSSI)-based rangefinding tool sets: Z-Ranger and Zbfind. Z-Ranger is a new tool set developed herein for the Zena Wireless Adapter that offers configurable distance estimating parameters and a RSSI resolution of 256 values. Zbfind is an application developed for the Atmel RZUSBstick with no configurable distance estimating parameters and a RSSI resolution of 29 values. The two tool sets are evaluated while rangefinding four wireless devices indoors and two devices outdoors. Mean error is calculated at each of the 35 collection points and a 99% confidence interval and $p - Test$ are used to identify statistical deviations between the two. After three rounds of evaluation, the results suggest that calibrated distance estimating parameters along with an increased RSSI resolution do not statistically reduce mean error when compared to non-calibrated parameters and lower RSSI resolution. The result of this research is that Z-Ranger is shown to be an alternative rangefinding tool set that performs as well as Zbfind.

15. SUBJECT TERMS

ZigBee, Warwalking, RSSI-based Distance Estimation, Low-rate sensor

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Dr. Benjamin Ramsey, AFIT/ENG
U	U	U	U	121	19b. TELEPHONE NUMBER *(include area code)* (937) 255-3636x4603; benjamin.ramsey@afit.edu