Spring 2019

Assessing Coexistence of IEEE 802.15.4 Networks and IEEE 802.11b/g/n Networks - A Study of Interference Effects

Resy Verma

Recommended Citation

Verma, Resy, "Assessing Coexistence of IEEE 802.15.4 Networks and IEEE 802.11b/g/n Networks - A Study of Interference Effects" (2019). *Creative Components*. 274.
https://lib.dr.iastate.edu/creativecomponents/274

Assessing Coexistence of IEEE 802.15.4 Networks and IEEE 802.11b/g/n Networks - A Study of Interference Effects

by

Resy Verma

A Creative Component submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Computer Engineering (Computing and Networking Systems)

Program of Study Committee:
Joseph Zambreno, Major Professor

Iowa State University

Ames, Iowa

2019

DEDICATION

To my parents Reena and Alok Verma and my sister, Yashika for taking care of me even being thousands of miles away. Thanks for instilling in me the courage and confidence to forge my own paths, and for making me believe in love, simplicity and the power of an indomitable spirit.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my advisor, Dr. Joseph Zambreno for giving me the opportunity to work under his guidance. His constant support and encouragement helped me navigate through the tough roads on this journey. I have learned a great deal about paying attention to details from him and I thank him for always being approachable to discuss the trivial to the most critical matters. His invaluable feedback from time to time has played a vital role in completion of this work. I would also like to thank Dr. Daji Qiao for lending his sensor nodes for my experimental work. I thank the Department of Electrical and Computer Engineering and Iowa State University for being my home for two years.

I also thank my not-so-local guardian, Abhay Negi for inspiring and motivating me to move to the United States for my master's degree, and for always being there through my thick and thin. Last, but not the least, I thank all my friends here with whom I learned, laughed and lived.

ABSTRACT

The study of the coexistence capabilities of networks based on the IEEE 802.11 and IEEE 802.15.4 standards has long been of interest to researchers owing to the individual success of these two technologies in various applications of Internet of Things (IoT). Operating in the same Industrial-Scientific-Medical (ISM) band, their coexistence does not always yield satisfactory results. The performance of a network based on IEEE 802.15.4 standard has been shown to be significantly lowered in the presence of a strong IEEE 802.11 based network (Wireless LAN) to the extent that communication based on the IEEE 802.15.4 standard can be rendered impossible in certain scenarios. This work is an effort towards analyzing interference caused by the three non-overlapping channels 1, 6 and 11 of IEEE 802.11b/g/n on the usable 2.4GHz spectrum of IEEE 802.15.4 standard. Recommendations of plausible scenarios for successful coexistence of these two networking technologies have been made. Assessment of the performance of an IEEE 802.15.4 standard based network through the Packet Delivery Ratio (PDR) on various channels of operation has yielded valuable insights. The experiments carried out in real-world environment stand as a datapoint in predicting and understanding the interference behavior in real-life applications.

CHAPTER 1. Introduction

The growing power of the Internet of Things(IoT) is such that every other object has turned into a sensing, analyzing or a communicating device. Coexisting communication technologies have made smart systems more robust and smarter. Wireless Sensor Networks (WSN) are used in energy and time critical applications and are the backbone of smart devices such as the ones used in the medical devices sector. They make possible fast and reliable transfer of information. With fast growing applicability of WSNs in IoT, it is hard to isolate one communication network from the other. In many scenarios, different wireless devices and standards operate in the same frequency range and in close physical proximity. The 2.4GHz unlicensed Industrial-Scientific-Medical (ISM) frequency bands are generally open bands which are accepted worldwide for wireless operations. Originally, the ISM band was to be used for non-communication purposes only. But with the increased congestion in the radio spectrum, and the attraction towards the unlicensed band led to the communication systems becoming the biggest users of this band. There has been rapid growth of the ISM band in low-power, low cost, short range communication platforms. Medical devices, military equipment, microwave ovens, Bluetooth devices, WiFi devices etc. are just some of its uses. The IEEE 802.11 wireless communication protocols use the ISM band and so do Bluetooth, ZigBee and near field communication devices. Often times, these communication technologies are found in the same environment and are said to co-exist. Coexisting communication networks are not without challenges. Performance degradation of one because of another coexisting communication system is often reported. Packet losses, poor Signal to Interference Ratio (SIR) and Received Signal Strength (RSSI), poor link quality are some of the adversely impacted communication parameters.

Coexistence among wireless devices depends on three main factors: time, space and frequency. Understanding these three factors will help to separate radios and will allow for reliable and robust coexistence. Considering the temporal factors, employing Time Division Multiplexing (TDM) could result in improved coexistence conditions. In the frequency domain, operating on non-overlapping frequencies and allowing for separation of channels can help mitigate the problems that arise during coexistence of different wireless devices. In the spatial domain, trying to keep the radios and their antennas as far apart can increase the probability of coexistence. The focus should be on increasing the SIR of the intended received signal.

Like IEEE 802.11 standards, the IEEE 802.15.4 standard based networks too use the 2.4GHz ISM band for operation. These two protocols find applications in similar domains and can often be found in the close proximity of each other, therefore it becomes important to study their coexistence and analyze the network performance in terms of Packet Delivery Ratio (PDR) and the impacts on different channels of operation. There have been studies such as in [1] and [2] that show that IEEE 802.11 standard based transmissions are relatively less impacted due to colocated IEEE 802.15.4 signals However, heavy interference effects are observed on IEEE 802.15.4 due to IEEE 802.11b signals. Considering a scenario where a IEEE 802.15.4 standard based sensor network is to be deployed in a hospital setting, a closely located IEEE 802.11 standard based network might interfere with IEEE 802.15.4 signals and could result in critical data loss. In cases where network isolation is not feasible, a study of their coexistence becomes necessary.

The main issue that this work analyzes is the interference effects of IEEE 802.11 standard based signals on IEEE 802.15.4 standard based transmissions. A number of experiments have been done to assess this problem. In this work, three modes of IEEE 802.11

standard have been implemented: IEEE 802.11b, IEEE 802.11g and IEEE 802.11n. All three standards have been implemented at the three non over lapping frequencies 1, 6 and 11 of the IEEE 802.11 spectrum individually to provide for a wide variety of cases of operations. Fig. 1.1 gives an overview of the channel occupancies and overlaps between IEEE 802.11 and IEEE 802.15.4 standards. The impacts of these modes operating at three chosen channels on entire spectrum of IEEE 802.15.4 at 2.4GHz have been reported. This work aims to provide recommendations on the best and worst IEEE 802.15.4 operational channels during coexistence with IEEE 802.11b/g/n standard based networks.

The remainder of the report is organized as follows: Overviews on the different IEEE standards used throughout this report are discussed in Chapter 2. Chapter 3 deals with previous works done in this domain. The experimental set-up, various components used in carrying out the experiments and the implementation methodology are presented in Chapter 4. Description of test runs and their results are reported in Chapter 5. Chapter 6 concludes the report with briefly discussing future work.

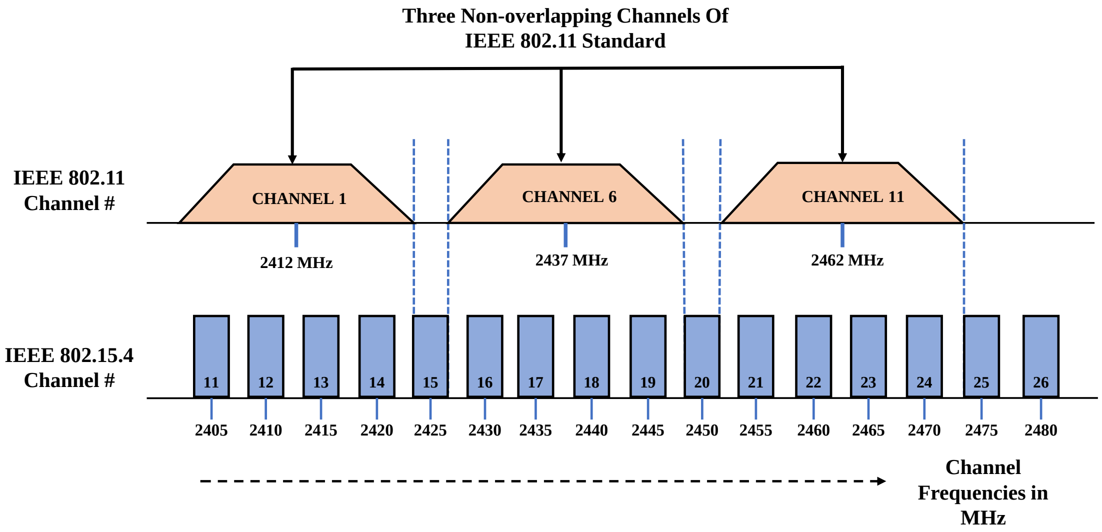


Figure 1.1 Channel occupancy of IEEE 802.11 standard and IEEE 802.15.4 standard

CHAPTER 2. Background

The IEEE 802.15.4 standard was developed to offer fundamental lower network layers of a Wireless Personal Area Network (WPAN). The focus of this technology is on low cost, low power, short range communication between devices. This standard is the basis for ZigBee, WirelessHART, etc. applications. Another common wireless technology-WLAN stems from the IEEE 802.11 based specifications. The family consists of IEEE 802.11a, IEEE 802.11b, IEEE 802.11g, IEEE 802.11n and IEEE 802.11ac standards. They are the most widely used networking standards. Previous works on studying the coexistence of IEEE 802.11 and IEEE 802.15.4 based networks have shown that it is the latter that gets severely impacted in the presence of the former such as in [2]. IEEE 802.15.4 based devices use channels that overlap with signals from IEEE 802.11 standard based devices and will face interference because of them. In some coexistence scenarios, it is observed that the IEEE 802.15.4 standard based transmission has to wait until the channel is free which results in delays, packet losses and lower throughput. The transmission power devices using IEEE 802.11 standard is much higher, almost as high as thirty times the transmission power of IEEE 802.15.4 standard based devices [3]. When these two networks are operate in the same environment and there are a number of devices running at high transmission rates, adverse interference effects can worsen [4]. By studying the operational channels and corresponding center frequencies of IEEE 802.11 standard and IEEE 802.15.4 standard at 2.4GHz as shown in Table 2.1 and Table 2.2, it can be seen that the three non-overlapping channels 1, 6 and 11 of IEEE 802.11 overlap with IEEE 802.15.4 channels 11-22. When the center frequencies of the IEEE 8021.15.4 channels do not directly overlap with the center frequencies of IEEE

802.11 spectrum, they can still be caught in the side lobes of the IEEE 802.11 spectrum as shown in Fig. 1.1. It is important to note here that IEEE 802.11 and IEEE 802.15.4 standards use different modulation techniques, different types of packet headers and packet formats and communication between these two standards is not possible without making significant hardware or protocol changes.

Table 2.1 US/Canada IEEE 802.11b/g Channel Frequencies

Channel	**Center Frequency(MHz)**	**Minimum(Hz)**	**Maximum(Hz)**
1	2412	2401	2423
2	2417	2406	2428
3	2422	2411	2433
4	2427	2416	2438
5	2432	2421	2443
6	2437	2426	2448
7	2442	2431	2453
8	2447	2436	2458
9	2452	2441	2463
10	2457	2446	2468
11	2462	2451	2473

2.1 Overview of IEEE 802.15.4

The IEEE 802.15.4 standard [5] specifies the physical and media access layer of Low-Rate Wireless Personal Area Networks (LR-WPANs). The IEEE 802.15.4 standard provides specifications for the Media Access Control (MAC) and Physical (PHY) layers, leaving the specification of the upper layers to specific higher standards such as ZigBee, 6LoWPAN and others. The PHY defines the frequency, power, modulation and other related characteristics of the link. The MAC defines the format of data handling. The initial release of the standard provided for two different PHY layers: 868 and 915 MHz low bands and the 2.4GHz high band. Both of these configurations are based on Direct Sequence Spread Spectrum (DSSS). In the 2.4Gz band, there are 16 channels available as presented in Table 2.2. This high band is the focus of the work presented in this report. The IEEE 802.15.4 standard is used

Table 2.2 IEEE 802.15.4 Channel Frequencies

Channel	**Center Frequency(MHz)**
11	2405
12	2410
13	2415
14	2420
15	2425
16	2430
17	2435
18	2440
19	2445
20	2450
21	2455
22	2460
23	2465
24	2470
25	2475
26	2480

in devices that require low power, low cost and a short transmission range. These features make the IEEE 802.15.4 standard a popular choice in wireless sensor networks. Networks can be built in star or peer-to-peer topologies. Owing to the short range, when deployed in a big field, the sensors equipped with IEEE 802.15.4 standard employ multi-hopping to relay messages from the source to the sink. The sensors usually work in the master-slave mode where the transmission between the master and slave takes place at 250kbps using one of the 16 channels of the ISM 2.4 GHz band. Theses channels are 5 MHz apart and each channel is 2 MHz wide. In the PHY layer, for the 2.4GHz band (high band), Quadrature Phase shift keying (QPSK) is used. In the MAC layer for media access control, Carrier Sense Multiple Access/Collision Avoidance (CSMA/CA) is used to sense the channel. The CSMA uses randomized back-off procedures to limit failed transmission attempts by nodes attempting to gain access to the channel at the same time. Every time a master wishes to send a message, it must do a Clear Channel Assessment (CCA). Before sending a packet, it waits for a back-off period. After the back-off period is completed, a clear channel assessment is performed. If the channel is found to be free, data can be sent. If the channel is not free, the back-off period is doubled.

2.2 Overview of IEEE 802.11 standard

The IEEE 802.11 specifies the PHY and MAC layer standards for Wireless Local Area Networks (WLANs). This standard is the basis for WiFi and is used to carry the internet traffic. The IEEE 802.11 standard is a family of sub-standards that use the same basic protocol with different modulation techniques, different data transmission rates, changes in technology and varied user applications. The family includes the most widely used IEEE 802.11 a/b/g/n/ac sub-standards. The IEEE 802.11 standard uses the ISM 2.4GHz spectrum with 11 channels, each 22 MHz wide. A WiFi network or a WLAN is made of some computers and an access point which communicate with each other using the frequency band allocated for their operation. The IEEE 802.11 standard employs the CSMA/CA mechanism at the MAC layer. This work focuses on the most commonly found IEEE 802.11b/g/n standards described below.

2.2.1 IEEE 802.11b standard

Released in 1999, the IEEE 802.11b standard was a ratification to the original IEEE 802.11 standard and become the definitive Wireless LAN technology allowing wireless functionality comparable to the ethernet. This standard provides a data transmission rate of 11 Mbps in the 2.4 GHz spectrum and uses DSSS at the PHY layer and the same media access control method as the original protocol. IEEE 802.11b standard based devices are cheap but have the slowest maximum speed of all IEEE 802.11 standards.

2.2.2 IEEE 802.11g standard

The IEEE 802.11g standard is backward compatible with IEEE 802.11b standard and uses Orthogonal Frequency Division Multiplexing (OFDM) at the PHY layer. Theoretically, it offers a bit rate of 54Mbps, higher than IEEE 802.11b standard. Most devices these days support IEEE 802.11b/g in a single mobile adaptor card or access point. As per [4], an IEEE 802.11g standard based network is susceptible to poor performance when a device operating on the IEEE 802.11b standard is signed on to the same network. The activity of the IEEE 802.11b network will reduce the data rate of the IEEE 802.11g network.

2.2.3 IEEE 802.11n standard

The IEEE 802.11n standard has added Multiple Input Multiple Output antennas (MIMO) where multiple transmitters and receivers operate simultaneously in the link. A network using IEEE 802.11n standard operates both on 2.4GHz and 5GHz frequency bands. It can use two 20 MHz channels in place of a single 20MHz channels and can offer speed over 100 Mbps. It provides increased range by using spatial multiplexing and exploits spatial diversity using special coding schemes.

CHAPTER 3. Related Work

The study of coexistence of homogeneous and heterogeneous wireless technologies has long been the interest of researchers working in the wireless communications field. Several works such as in [6, 7, 8, 9] have discussed interference models and coexistence scenarios of wireless systems. One of the early experiments designed for analyzing coexistence of ZigBee based WSN and WLAN was carried out in [10], where the experiments conducted indicated that WiFi networks and IEEE 802.15.4 WSNs may coexist but with reduced performance in terms of packet loss ratio. A potential coexistence scenario in Smart Grid-Home Area Network has been modeled and an analysis of performance with unslotted CSMA-CA has been done in [11], which indicated significant performance degradation for devices in close vicinity with interfering sources. A review of wireless coexistence test methodologies has been presented in [12], where the authors presented basic tests for reinforcing confidence in the coexistence of various wireless technologies. An experimental study of cross technology interference in In-vehicle wireless sensor networks has been done in [13], employing an enhanced version of Time Slotted Channel Hopping (TSCH) protocol for channel white-listing.

There are several reports on the interference caused by WLAN devices on IEEE 802.15.4 standard based devices such as in [1]. An investigation of WPANs for use in medical applications where scalability and back-off parameters in CSMA/CA mechanism has been discussed by the authors in [14]. It has been pointed out that IEEE 802.15.4 standard based ZigBee networks suffer from interference caused by networks operating on the IEEE 802.11 standard owing to the latters high transmission power - up to 30 times of ZigBee [3]. A study on IEEE 802.15.4 based networks as an interference to networks based on IEEE 802.11 standard has been done by [2], and concluded that IEEE 802.15.4 standard based devices do not pose a big threat to transmissions in networks operating on IEEE 802.11 standards. Successful coexistence is seen as a critical between frequency, space and time. There needs to be adequate frequency separation, low channel occupancy and sufficient separation between networks for coexistence to work. The density of devices in the networks is also an important consideration.

A focus on determining the interference power at which at which packet retransmission will be required is laid in [15]. A co-existence model consisting of power and timing aspects is presented in [16]. The authors in this work have introduced the concept of coexistence ranges which are determined based on the path loss model. An indoor probabilistic path loss model has been presented in [17], that accounts for path loss resulting from wall penetration, refection, scattering, and diffraction effects. A Non Line Of Sight (NLOS) setup in an anechoic chamber was used to test the coexistence of IEEE 802.15.4 standard based networks with other wireless technologies in [3], which can be used to determine the distance at which a medical device telemetry system can coexist with other wireless technologies. Several models such as in [18, 19], have been proposed that mathematically analyze coexistence . Signal to Noise Ratio (SINR) has been used to obtain the Bit Error rate (BER) in [20], to carry out calculations for determining the packet collision times for coexisting ZigBee, WLAN and Bluetooth networks. Similarly, works such as [20, 21], describe analytical models for evaluating PER, BER, and related parameters under IEEE 802.11 standard based interference.

The detection of WiFi signals in wireless sensor networks has been shown in [22]. Here, the authors have built a signal attenuation model of WiFi signals to locate WiFi nodes. Their experiments achieve high accuracy in detecting nodes. It has been shown in [23], that interference effects are difficult to avoid in IEEE 802.11n networks when compared with IEEE 802.11g standard based networks. The impact of IEEE 802.11n traffic on the performance of an IEEE 802.15.4 networks is presented in [24], where overlap between IEEE 802.15.4 operational channels and IEEE 802.11n extension and control channels are used as evaluation scenarios. Various testing methodologies and tools and equipments have been used by researchers to study different aspects of interference caused by WLAN on IEEE 802.15.4 networks. It is indicated in [25] that a USRP device is equally capable of providing accurate DC measurements when compared with devices like VST and VSA. A practical measurement setup using a high precision spectrum analyzer and a medium precision USPRP2 software defined radio has been presented in [26]. The authors in this paper have compared the results based on duty cycles of occupancy in the measured bands.

Given the popularity and ubiquity of IEEE 802.11 and IEEE 802.15.4 based networks, researchers are developing solutions and algorithms to counter the interference problem. A metric- ReSIST for performing verification of frequency based interference avoidance mechanisms in IEEE 802.15.4 based networks has been proposed in [27]. ART proposed in [28] is an algorithm that exploits the frequency white space left out by WiFi and employs P-CSMA to tune the use of CSMA for leveraging the temporal white space of WiFi interference. Authors in [29] have proposed An adaptive scheme that uses multiple radio channels for the co-existence of 802.15.4 LR-WPAN and 802.11b WLAN is proposed in [29]. An algorithm that detects interference and adaptively and dynamically switches nodes to safe channel to avoid WLAN interference is discussed in [30], where the algorithm is found to enhance the ZigBee performance when coexisting with WiFi networks. A hybrid device in [4] is proposed that would coordinate messages and act as a mediator between IEEE 802.11 and IEEE 802.15.4 based signals. A center frequency and bandwidth estimation algorithm-Spatial Sample Clustering(SSC) proposed in [31] found maximum channel occupancy by IEEE 802.11b/g based WLAN systems using SRO and FBO calculations.

It has been shown in [32] that the proposed Adaptive Channel Access (ACA) algorithm for selection of communication channels in a ZigBee network improves PDR in a WLAN interference environment. A new Zigbee protocol-WISE has been proposed by [33] which can achieve desired trade-offs between link throughout and delivery ratio. For co-existence of Zigbee devices in WiFi environment, authors in [34] have proposed a real-time adaptive scheme (RAT) that adopts forward error correcting coding (FEC) on ZigBee devices. They have shown that sizes of WiFi frames follow power law distribution law model. With the model, corruption in ZigBee packets can be estimated to some extent, thus facilitating ZigBee device to choose a suitable FEC coding to maximize the throughput. Interference avoidance considering the intensity and denseness of networks in analyzed in [35], which also focuses on the locality of WiFi interference. The main contribution of the authors in this work was the proposal of MuZi: an interference avoiding approach, which employs three basic mechanisms, namely interference assessment, channel switch and connectivity maintenance. Their proposed interference assessing approach considers the degree of intensity and density and shows a relationship between WiFi interference and link quality.

For carrying out the experiments detailed in this report, a study of the Contiki OS and the Cooja simulator was done. Several articles were reasd to understand the scope of the simulator. The performance of different networks settings and evaluation of Contiki RPL environment is done in [36], where the study conducted is spanned across the whole life cycle of WSNs. Estimation of memory usage of applications and power consumption in WSNs was studied through simulations in Cooja in [37], where the authors suggest that Cooja can be used for educational purposes too.

With this work, we have run experiments to observe channel occupancy by WLAN devices and analyze the interference caused by networks using IEEE 802.11b/g/n standard on different channels of operation of the IEEE 802.15.4 standard based networks in the ISM band. Nine different interference scenarios have been studied in this work: IEEE

802.11b, IEEE 802.11g, and IEEE 802.11n operating on channels 1, 6 and 11 of the IEEE 802.11 2.4GHz spectrum. There is a need to make recommendation for channels that IEEE 802.15.4 standard based networks should prefer for operation when coexisting with IEEE 802.11 standard based devices. The recommendation will be based on comparing the Packet Delivery Ratio (PDR) parameter.

CHAPTER 4. Experimental Set-up

4.1 Components

4.1.1 The IEEE 802.15.4 standard based device

For carrying out the experiments presented in this report, IEEE 802.15.4 standard compliant Telos Rev B devices have been used [38]. It is a low power wireless module used in wireless sensor networks. It comes with a 250Kbps 2.4GHz IEEE 802.15.4 compliant CC2420 Chipcon wireless transceiver chip. It provides an integrated on-board antenna and a Texas Instruments 8MHz MSP microcontroller with 10k RAM and 48k flash. Programming and data collection capabilities are supported via USB. It also houses temperature, humidity and light sensors on board. An application may read from Telos by opening the COM port assigned to it. Telos communicates with the host PC through USART1 on the TI MSP430. The MSP430 BootStrap Loader programs the microcontroller's flash, connected to the host through the on-board USB connector. For communication and networking, it provides support for TinyOS and Contiki OS. All experiments reported in this report have been done on Contiki OS.

4.1.2 The 802.11b/g/n standard based network

For building a IEEE 802.11b/g/n standard based network, an access point and a client laptop have been used. The access point is a CISCO Linksys E1200 device. There is access to the GUI on the web based setup of the device which lets us see the wireless settings. The client is a HP laptop which has an Intel Dual Band Wireless AC-7265 network adapter.

4.1.3 Contiki OS

The Contiki is an open source operating system for the Internet of Things [39]. It is a toolbox that helps connect low power, low cost devices like the Telos B sensor modules to build complex networks. For this work, Instant Contiki version 3.0 has been used. The Contiki applications are written in C language. For these experiments, the Rime communication stack provided in Contiki has been used for wireless networking. Refer to Fig. 4.2 for a screenshot of the serial output while running one of the tests detailed in the next chapter. The image shows the serial output from the receiver side sensor node. The receiver is counting the number of packets being received successfully before hopping to the next channel.

The Contiki OS comes with a simulator called Cooja which allows emulation of networks before burning the code onto the hardware. The first step of all experimentation was testing the codes on the simulator and checking the behavior of the emulated sensor nodes in the simulated environment. The simulator has five windows that provide different functionalities. In the Network window, the location of the nodes, their ranges, node IDs and addresses can be seen. The Simulation Control window lets the user start, pause, reload or execute the steps of simulation. It also shows the time elapsed and the speed of the simulation. The outputs of the serial interfaces of the emulated nodes can be seen in the Motes Output window. The Timeline window shows channel changes, LED changes and radio on/off logs. Refer to Fig. 4.3 for a screenshot of a simulation run in the Cooja simulation environment for testing a piece of code that makes the four planted nodes to send out broadcast messages.

4.2 Implementation Procedure

The purpose of the experiments was to study the interference effects of IEEE 802.11 standard based signals on IEEE 802.15.4 standard compliant transmissions. The need for such a study is to make recommendations for the coexistence scenarios of these two communication technologies. The main focus of this work is on analyzing the effects on the IEEE 802.15.4 standard operational channels due to interference from IEEE 802.11b, IEEE 802.11g and IEEE 802.11n based WLAN traffic. In carrying out the experiments, we attempted to use realistic scenarios, as the motivation of this work is to generate recommendations for successful coexistence in everyday situations.

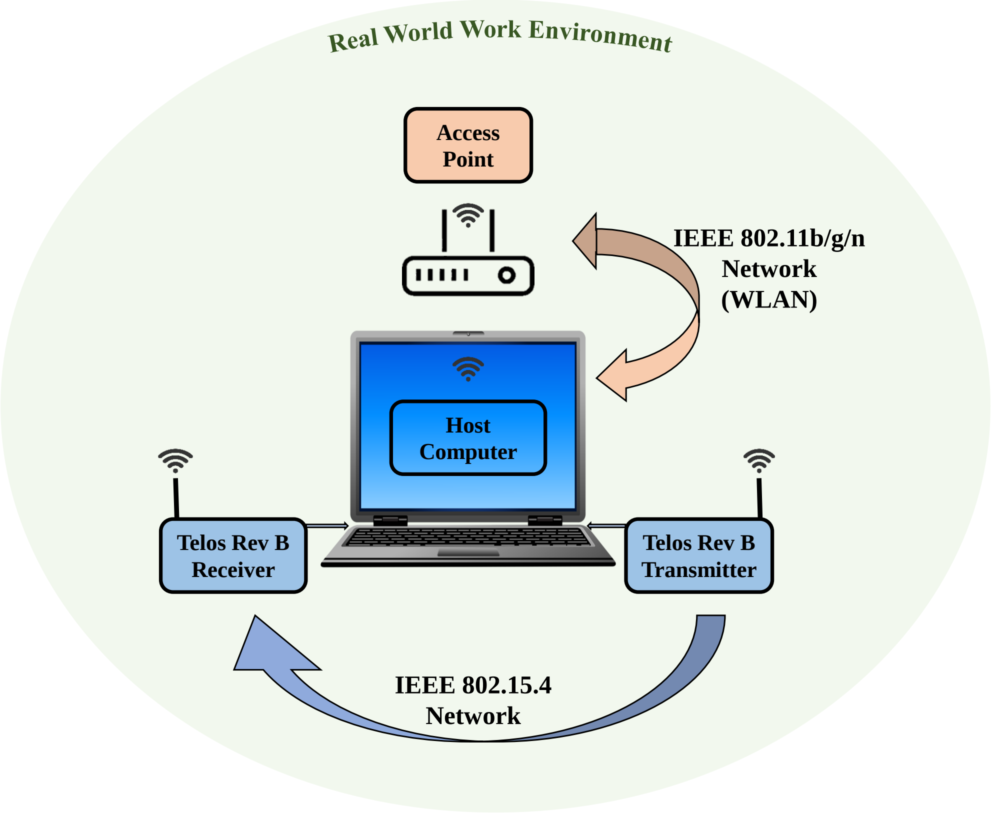
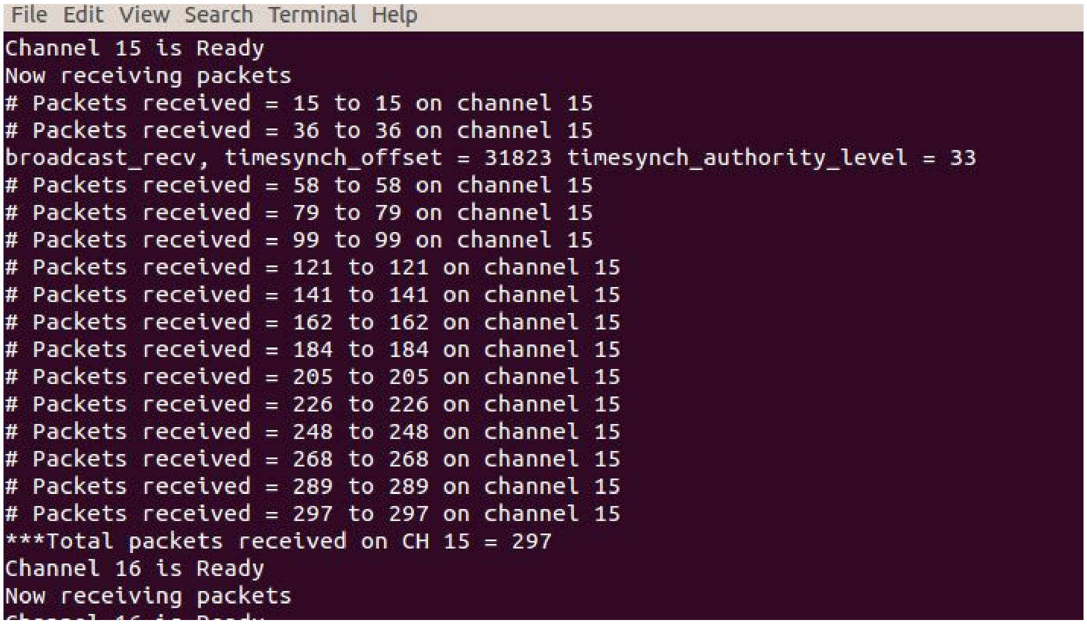


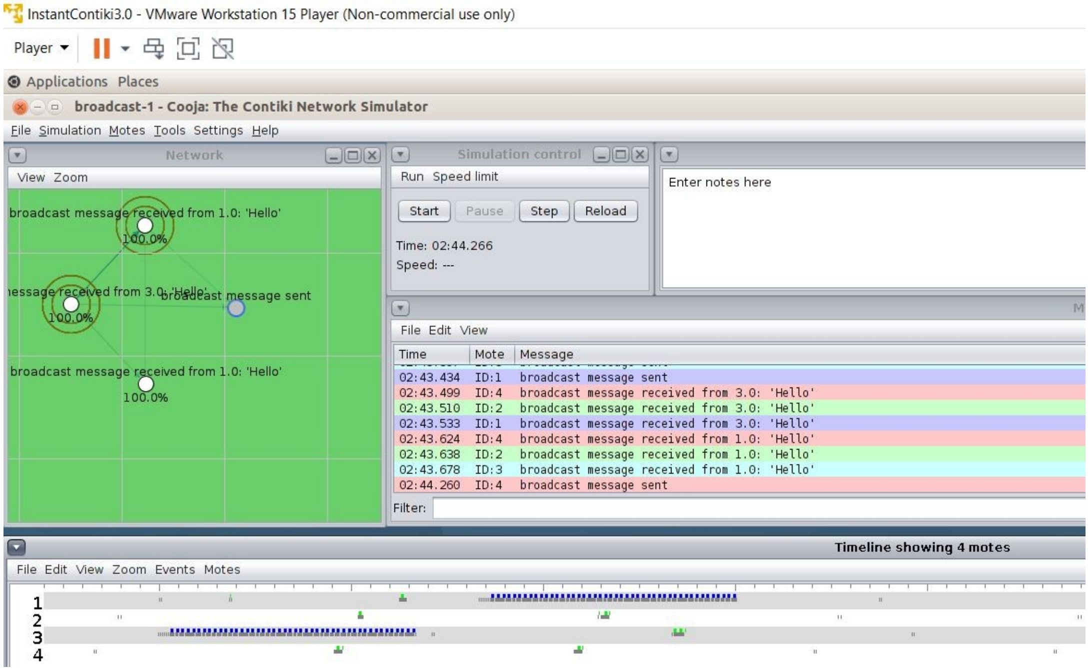
Figure 4.1 Experimental setup schematic

The experimental set up included the IEEE 802.11 standard compliant network formed of an access point and a client laptop and an IEEE 802.15.4 standard based network composed of two Telos Rev B sensor modules as shown in Fig. 4.1. For convenience, the set up was arranged on the ground. The access point and the laptop were placed close to each other, only one meter apart. The two sensor nodes used the same laptop as the host



```
Channel 15 is Ready
Now receiving packets
# Packets received = 15 to 15 on channel 15
# Packets received = 36 to 36 on channel 15
broadcast_recv, timesynch_offset = 31823 timesynch_authority_level = 33
# Packets received = 58 to 58 on channel 15
# Packets received = 79 to 79 on channel 15
# Packets received = 99 to 99 on channel 15
# Packets received = 121 to 121 on channel 15
# Packets received = 141 to 141 on channel 15
# Packets received = 162 to 162 on channel 15
# Packets received = 184 to 184 on channel 15
# Packets received = 205 to 205 on channel 15
# Packets received = 226 to 226 on channel 15
# Packets received = 248 to 248 on channel 15
# Packets received = 268 to 268 on channel 15
# Packets received = 289 to 289 on channel 15
# Packets received = 297 to 297 on channel 15
***Total packets received on CH 15 = 297
Channel 16 is Ready
Now receiving packets
```

Figure 4.2 Screenshot of a Contiki console serial output



```
Time       Mote  Message
02:43.434  ID:1  broadcast message sent
02:43.499  ID:4  broadcast message received from 3.0: 'Hello'
02:43.510  ID:2  broadcast message received from 3.0: 'Hello'
02:43.533  ID:1  broadcast message received from 3.0: 'Hello'
02:43.624  ID:4  broadcast message received from 1.0: 'Hello'
02:43.638  ID:2  broadcast message received from 1.0: 'Hello'
02:43.678  ID:3  broadcast message received from 1.0: 'Hello'
02:44.260  ID:4  broadcast message sent
```

Figure 4.3 Screenshot of a sample Cooja Simulator workspace computer. They were connected to the laptop via USB ports, on either sides of the laptop. In this manner, the WLAN link was in a way in between the network based on the IEEE 802.15.4 standard. This type of spatial arrangement was chosen to establish interference from the WLAN link to the sensor network.

To generate traffic on the IEEE 802.11 standard based link, a large file of 10GB size was being downloaded during the experiments. The time it took to download the file was sufficient for the tests to be completely run on the nodes. After running a set of tests for channels 1, 6 and 11 with one mode of IEEE 802.11 say IEEE 802.11b, the link was modified to operate on another mode, say IEEE 802.11g. Changing the mode of operation changed the data rate too as expected. A mobile application that reports the channel characteristics was used to further confirm that only the desired IEEE 802.11 mode and the selected channel were being implemented to form the link.

The parameter used to measure the performance of the sensor nodes under interference was the Packet Delivery Ratio (PDR). The PDR is the ratio of the number of packets successfully received by the receiver to the total number of packets sent by the transmitter. One of the nodes ran the transmitter program and the other one was programmed with the receiver side code. A total of 300 packets were periodically sent by the transmitter. The receiver side maintained a counter and would count the number of successfully received packets. A ratio of the successfully received packets to the total transmitted gives the PDR in each case. Even by looking at the crude number of packets successfully received, comments on interference effects can be made. The serial output on the transmitter side shows each packet form 1 through 300 being transmitted while at the receiver side the end result of the counter would reveal the number of successfully received packets. Both the transmitter and the receiver sides were programmed to continuously hop channels and cover all the IEEE 802.15.4 standard channels from 11 through 26. When the nodes would sequentially hop from one channel to the other, the transmission and counting of packets would repeat.

This type of multi-channel PDR measurement obtained through hopping of channels and the resultant coverage of the entire spectrum is valuable for making recommendations as to which channels faces least interference under each of the IEEE 802.11b, IEEE 802.11g, and IEEE 802.11n based interference scenarios when they operate at channels 1, 6 and 11 of the IEEE 802.11 spectrum. There are at least 8 iterations of each test so as to lower the spurious randomness in the readings taken.

CHAPTER 5. Measurements and Results

5.1 Test runs on IEEE 802.11b standard based WLAN traffic

Three major experiments have been carried out to observe the interference effects of IEEE 802.11b standards based WLAN traffic on IEEE 802.15.4 standard compliant communication between sensor nodes. Tests are done on the WLAN channels 1, 6 and 11 as these are the non-overlapping channels and are thus most commonly found in WLAN devices. The bandwidth used by IEEE 802.11b standard was 20 MHz. In the experiments, PDR has been used as the parameter to assess the performance of IEEE 802.15.4 complaint networks when coexisting with networks based on IEEE 802.11 standard. The graphs show the mean PDR over 8 iterations of the tests.

1. Channel 1: Channel 1 with a centre frequency of 2412 MHz is one of the three non overlapping channel of WLAN in the 2.4GHz band. The observed effects of the interference caused due to WLAN traffic going over this channel on the IEEE 802.15.4 based traffic on channels 11-26 have been recorded and plotted.

   RESULT: The PDR corresponding to the channels 11-26 are plotted. The plot in Fig. 5.1 shows that channels 12 and 13 of the IEEE 802.15.4 standard spectrum have suffered the most. The lowest mean PDR recorded is around 0.15 which indicates that on an average only 15% of the transmitted packets were successfully received by the receiver. The max PDR reaches 1 and remains fairly constant from channel 15 through channel 26 of the IEEE 802.15.4 spectrum. This also shows that WLAN traffic on channel 11 does not affect the higher channels of the IEEE 802.15.4 standard

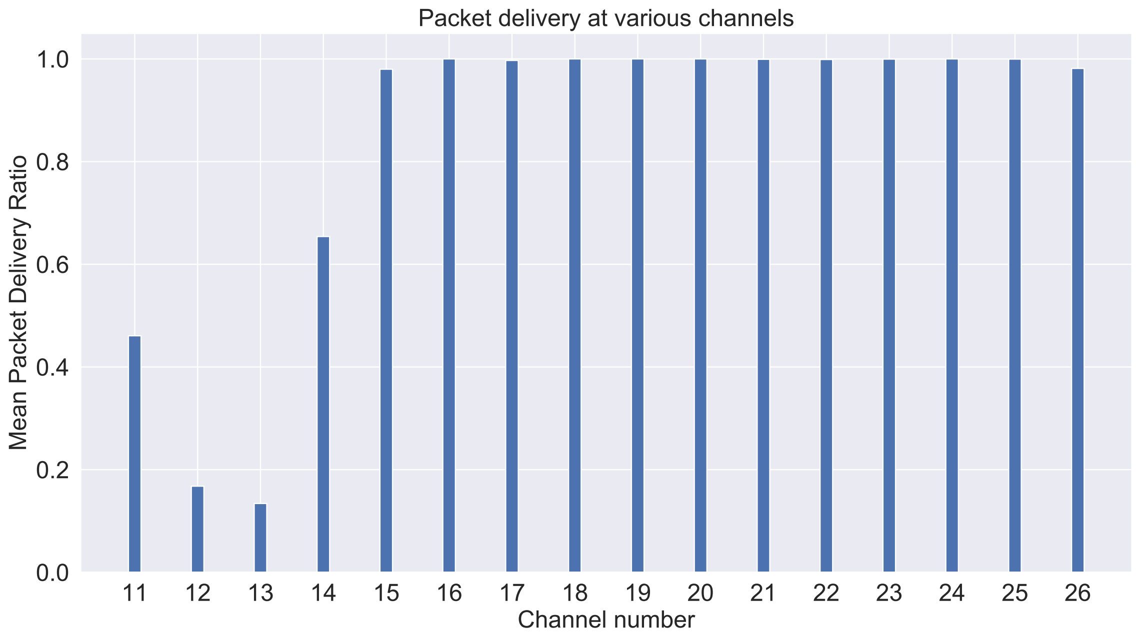


Figure 5.1 Mean PDR recorded under interference from IEEE 802.11b standard based traffic operating on channel 1

based frequency band.

2. Channel 6: Another set of 8 iterations were done for channel 6 of the WLAN. Channel 6 is centered at 2437 MHz.

   RESULT: Figure 5.2 shows that this time the middle channels-16 through 18 saw the worst impacts of WLAN traffic on channel 6. The mean PDR is close to 0.05. It is worth noting that channel 18 records lowest mean PDR even among channels 16,17 and 18. This result was expected given that channel 18's center frequency of 2440 MHz is closest to the centre frequency of WLAN channel 6.

3. Channel 11: Centre frequency of channel 11 is 2462 MHz.

   RESULT: The mean PDR plot for traffic on channel 11 as shown in Fig. 5.3 reveals that channels 22 and 23 of the IEEE 802.15.4 spectrum have the lowest mean PDR. The number of packets successfully received are only about 1% of the packets that were transmitted. The center frequency of WLAN channel 11 is close to the centre

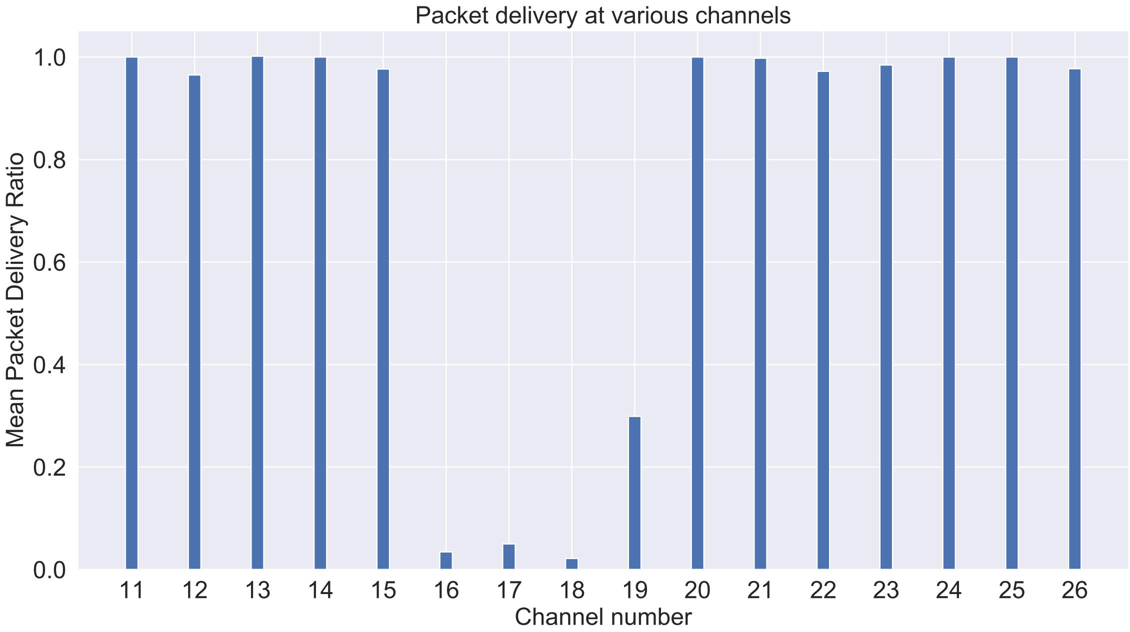


Figure 5.2 Mean PDR recorded under interference from IEEE 802.11b standard based traffic operating on channel 6

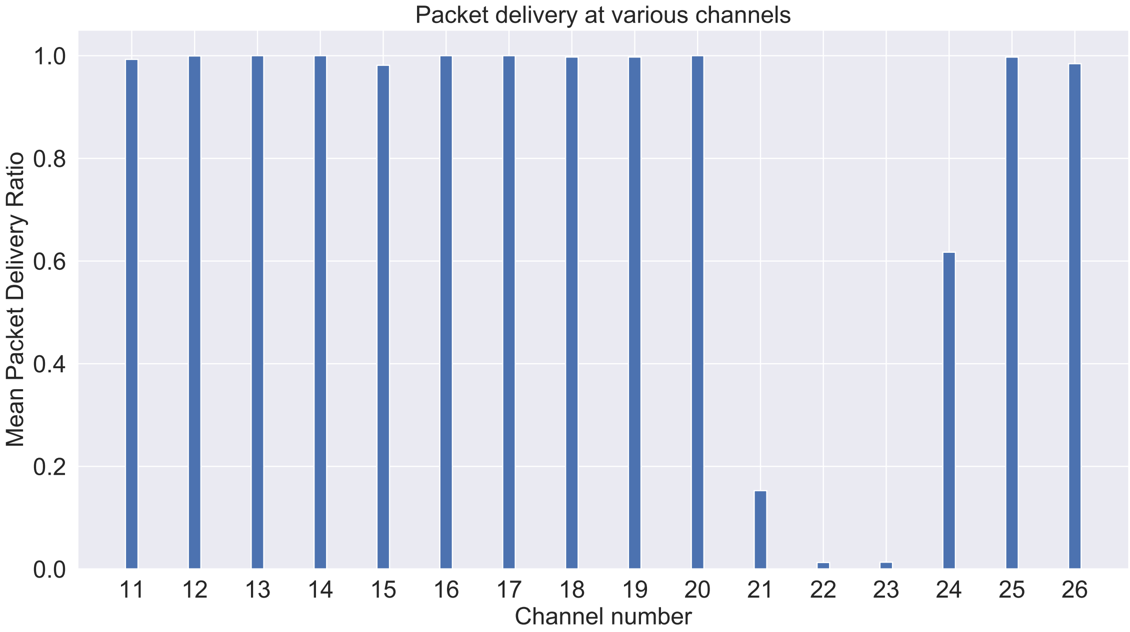


Figure 5.3 Mean PDR recorded under interference from IEEE 802.11b based traffic operating on channel 11

frequencies of IEEE 802.15.4 standard channels 22(2460 MHz) and 23(2465 MHz) and thus these two channels see maximum impact.

5.2 Test runs on IEEE 802.11g standard based WLAN traffic

Similar to the tests conducted for IEEE 802.11b standard based traffic, 8 iterations for each of the three non-overlapping channels 1, 6 and 11 were conducted. The bandwidth used by the signals was 20MHz.

1. Channel 1: Centre frequency is 2412 MHz.

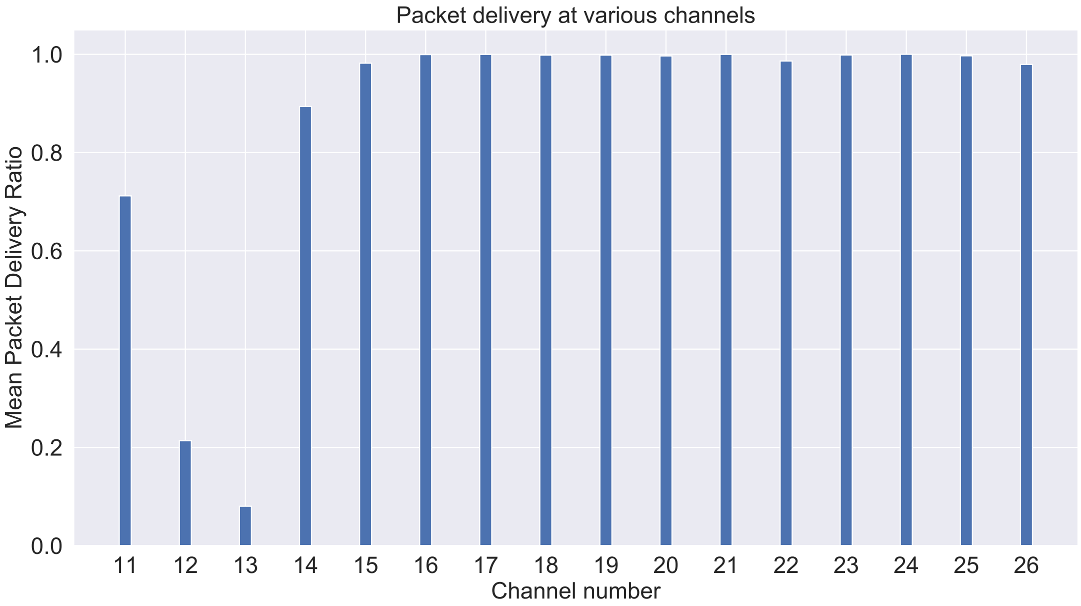


Figure 5.4 Mean PDR recorded under interference from IEEE 802.11g standard based traffic operating on channel 1

RESULT: As can be seen in Fig. 5.4, the worst effects are observed on channel 13 with centre frequency of 2415 MHz. However, this not the only channel affected. For channels 12-13, the mean PDR lies close to 0.825 and then rises and remains close to 1 for channels 16-20 and 25-26. A dip in the values is seen in channels 21-23 but it still lies between 0.95 and 0.975.

2. Channel 6: Center frequency is 2437 MHz.

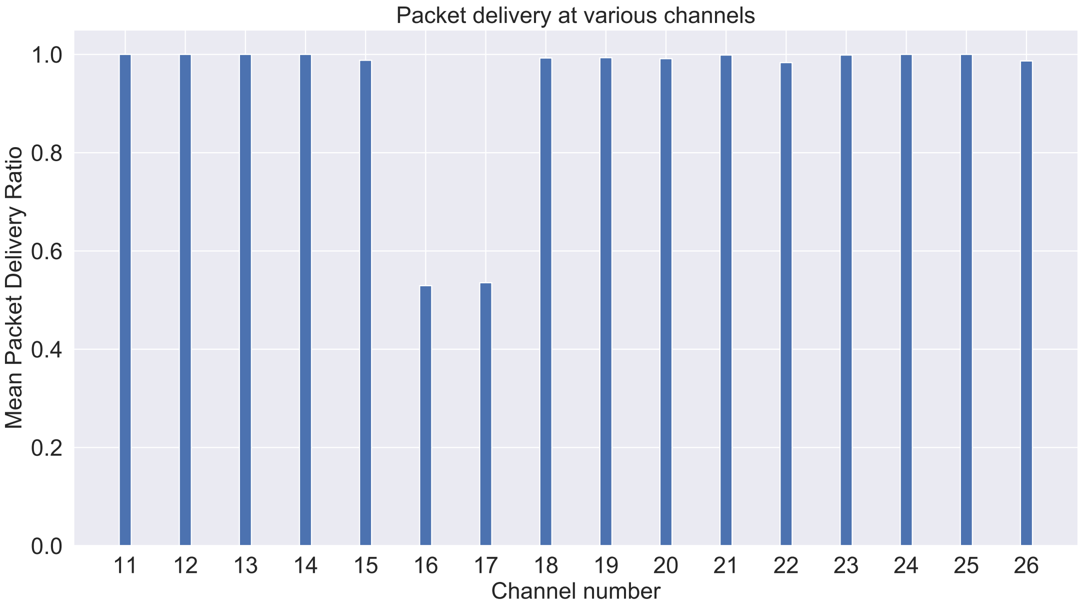


Figure 5.5 Mean PDR recorded under interference from IEEE 802.11g standard based traffic operating on channel 6

RESULT: As per Fig. 5.5, channel 18 has the lowest mean PDR among all channels. Channel 17 also has a low PDR clearly suggesting that these two channels have suffered the most. A mean PDR of 0.7 is not too bad but is poor in comparison to the values obtained at other channels. The maximum PDR values obtained reached the 1.0 mark suggesting that 100% success was achieved in receiving packets on lesser affected channels of the lower and the higher bands.

3. Channel 11: Center frequency is 2462 MHz.

   RESULT: Poorest packet reception has been observed on channel 22 with a mean PDR of 0.7 as shown in Fig. 5.6. WLAN channel 11 and 802.15.4 channel 22 have very closely located center frequencies and thus this result is not surprising. At other frequencies the plot looks smooth indicating good packet reception, reported to be 100% in many cases.

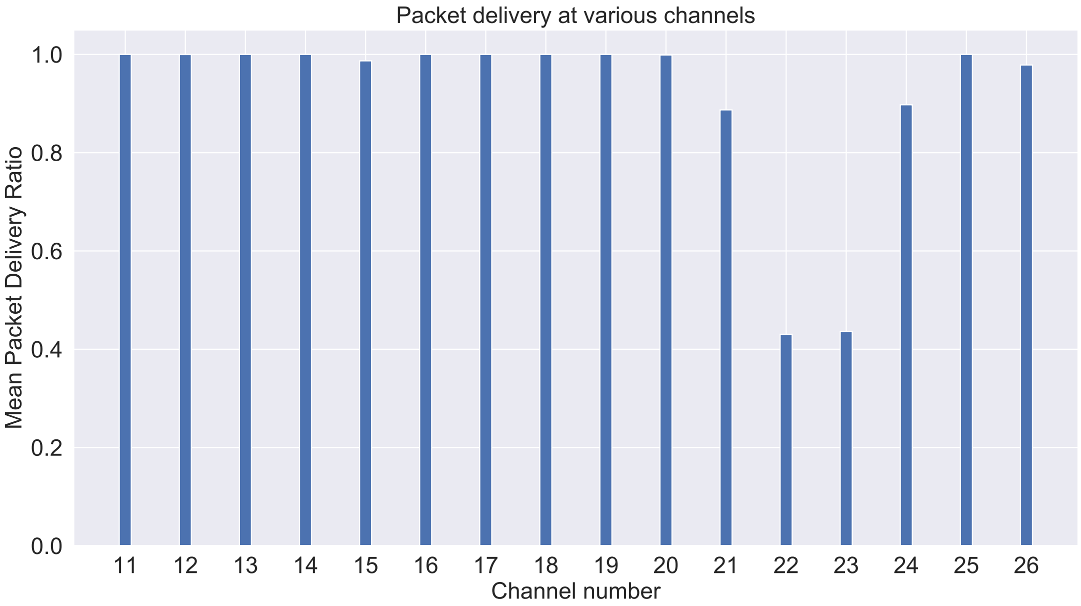


Figure 5.6 Mean PDR recorded under interference from IEEE 802.11g standard based traffic operating on channel 11

5.3 Test runs on IEEE 802.11n standard based WLAN traffic

The last set of tests were run for IEEE 802.11n standard based link. Since IEEE 802.11 standard can use a wider bandwidth, hence readings were taken when the IEEE 802.11n standard based link was utilizing a bandwidth of 40 MHz. Owing to a wider bandwidth, the IEEE 802.11n standard spectrum does not have any non-overlapping channels, contrary to IEEE 802.11b/g standard. Still, observations have been recorded on channels 1, 6 and 11. The experiments were run at least 8 times to address randomness.

1. Channel 1: Center frequency is 2412 MHz.

   RESULT: The plot in Fig. 5.7 clearly shows that the lower channels 11 through 14 are most affected by WLAN traffic on channel 1. The lowest mean PDR of less than 0.2 was found at channel 12. Channel 15 onwards the packet reception improved. The graph never maintains a constant mean PDR of 1, it reaches a peak at 1 for channel 20, dips a little and then records maximum again for channel 25.

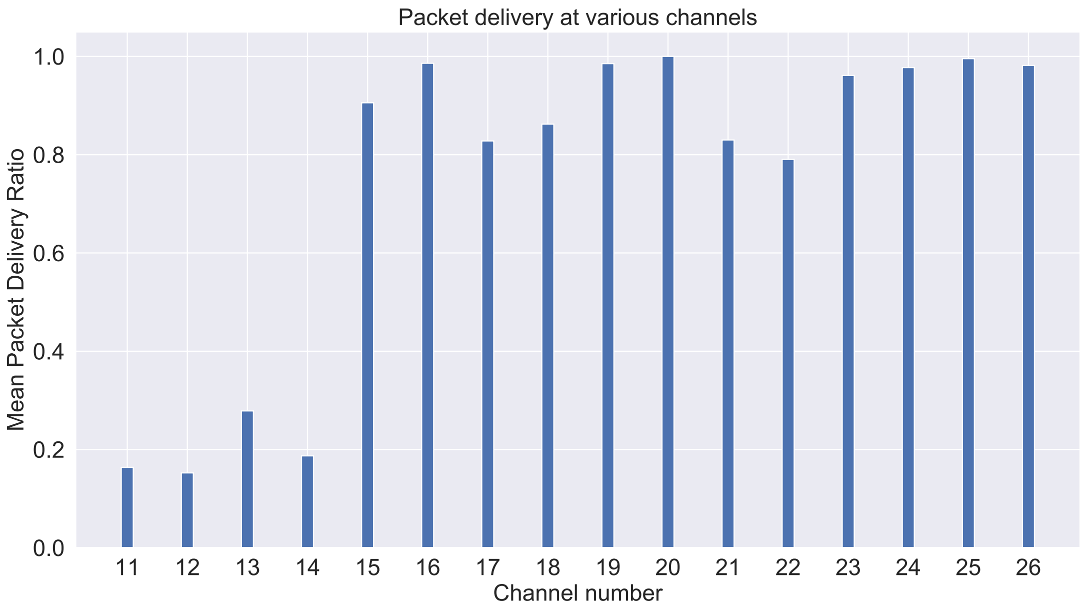


Figure 5.7 Mean PDR recorded under interference from IEEE 802.11n standard based traffic operating on channel 1

2. Channel 6 : Center frequency is 2437 MHz.

   RESULT: The mean PDR plotted in Fig. 5.8 shows worst interference impacts on the mid-band channels 16-19 than others. The lowest value recorded is close to 0 for channel 18. Packet reception at channels 12-15 hovers around 80%. Thus, it can be said that interference due to IEEE 802.11n based taraffic operating on channel 6 causes disturbances in a wider band of the IEEE 802.15.4 channels.

3. Channel 11: The center frequency is 2462 MHz

   RESULT: Channel 23 is the most severely impacted of all channels as per the plot in Fig. 5.9. The PDR is found to be around 0.95 which is not too bad. But, better packet reception is observed for the rest of the channels except channel 15. Channel 15 could be caught in the extended side lobe of WLAN channel 11 of IEEE 802.11n standard as it uses a wider bandwidth.

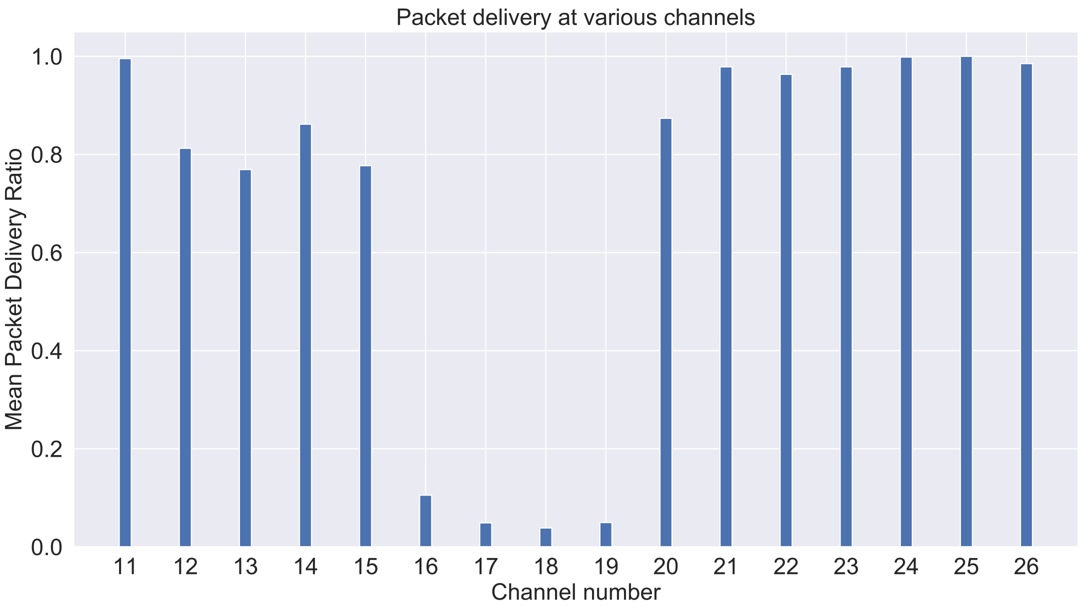


Figure 5.8 Mean PDR recorded under interference from IEEE 802.11n standard based traffic operating on channel 6

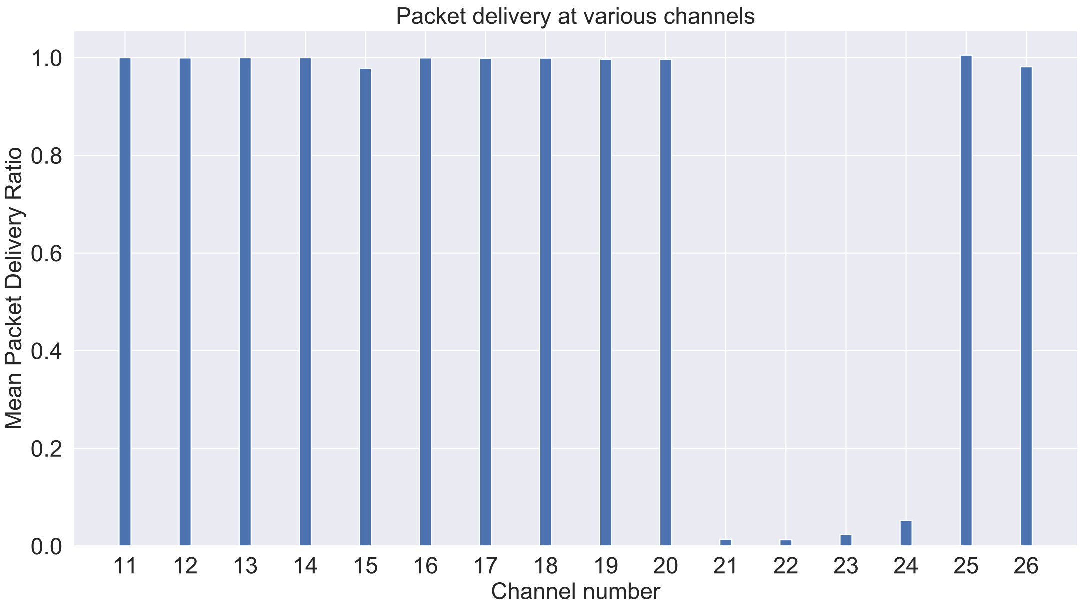


Figure 5.9 Mean PDR recorded under interference from IEEE 802.11n standard based traffic operating on channel 11

5.4 Inferences

Based on the experiments conducted in the real world environment chosen, the following inferences can be drawn:

1. As per the experiments carried out and the observations made, the IEEE 802.15.4 channels 15, 20, 25 and 26 had the best PDR values. These channels were found to be least affected by the interfering IEEE 802.11b/g/n signals. This inference is being attributed to the fact that the center frequencies of these 4 channels do not overlap with the center frequencies of any of 1, 6 or 11 WLAN channels used for experiments documented in this report. Refer Fig. 1.1 for center frequencies.

2. If the center frequency separation between selected WLAN channel and the IEEE 802.15.4 standard channel is greater than 12 MHz , then the mean packet reception recorded under IEEE 802.11b/g standard based traffic is around 85%-95%. The mean PDR increased as the frequency separation between IEEE 802.15.4 and IEEE 802.11 based networks increased. Thus, for successful coexistence, the recommended channel separation is greater than 12 Mhz as per this report. It should also be noted that interference becomes almost negligible whenever the center frequency separation is at least 20 MHz.

3. It was observed that whenever a channel overlap would take place, it resulted in increased latency in the IEEE 802.15.4 network. In presence of heavy WLAN traffic on the same frequency would lead to the channel being busy more often. The IEEE 802.15.4 standard based sensor nodes would back-off multiple times before being able to carry out their transmission. The dips in mean PDR values recorded for channels other than the ones overlapping directly with the WLAN channels can be attributed to the surrounding noise, or due to interference from other devices lying outside the test set-up. These dips were however much lower as they were farther away in space than the direct WLAN interference established for the above mentioned experiments.

CHAPTER 6. Conclusion

The objective of this work was to study the coexistence of two most popular wireless communication technologies, the one based on IEEE 802.11 standard commonly referred to as WLAN, and the other based on IEEE 802.15.4 standard. Both of these typically operate in the unlicensed 2.4GHz ISM band. An overlap between the channels used by the two networks adversely affects the network based on IEEE 802.15.4 standard. This could be due to the fact that the IEEE 802.15.4 standard uses a a smaller bandwidth and transmits at lower power in comparison to the transmission power and channel width used by IEEE 802.11 standard based networks. This work suggests that avoiding channel overlap can be thought of as a mechanism to improve performance of IEEE 802.15.4 standard compliant networks when coexisting with IEEE 802.11 standard based networks. In this report, several experiments that were conducted have been reported which assessed packet reception at the receiver side of a network operating on the IEEE 802.15.4 standard under heavy interference. A real world work environment was chosen to conduct the tests. The three modes of WLAN operation chosen were IEEE 802.11b, IEEE 802.11g and IEEE 802.11n as most of the devices found these days make use of one or all of these three. WLAN traffic was sent on three non-overlapping channels, namely 1, 6 and 11 and interference effects were observed on all 16 channels of the 2.4GHZ frequency spectrum used by the IEEE 802.15.4 standard. After studying the impacts on the mean packet delivery ratio, recommendations are being made for the channels that should be avoided under interference from WLAN traffic in various scenario.(Refer Table 6.1)

Table 6.1 Recommended IEEE 802.15.4 standard channels to avoid for successful co-existence with IEEE 802.11 standard based networks

WLAN mode	**WLAN Chan. 1**	**WLAN Chan. 6**	**WLAN Chan. 11**
802.11b	11-13	16-18	21-23
802.11g	12-13	17-18	22-23
802.11n	11-14	16-19	21-24

6.1 Future Work

A similar study of coexistence in various scenarios mentioned in this report can be carried out with packet latency as the barometer for assessing results. The two sensor nodes will need to be time synchronized to accurately measure packet latency. Experiments can be done in an isolated environment such as in an anechoic chamber to address spurious surrounding noise caught in real world work environment. Use of spectrum analyzers can be made to study the two signal patterns on the different channels.

BIBLIOGRAPHY

[1] J.-H. Hauer, V. Handziski, and A. Wolisz, “Experimental study of the impact of WLAN interference on IEEE 802.15. 4 body area networks,” in *European Conference on Wireless Sensor Networks*, Springer, 2009.

[2] S. Pollin, I. Tan, B. Hodge, C. Chun, and A. Bahai, “Harmful coexistence between 802.15. 4 and 802.11: A measurement-based study,” in *International Conference on Cognitive Radio Oriented Wireless Networks and Communications, 2008. (CrownCom 2008).*

[3] N. J. LaSorte, S. A. Rajab, and H. H. Refai, “Developing a reproducible non-line-of-sight experimental setup for testing wireless medical device coexistence utilizing ZigBee,” *IEEE Transactions on Biomedical Engineering*, 2012.

[4] J. Hou, B. Chang, D.-K. Cho, and M. Gerla, “Minimizing 802.11 interference on ZigBee medical sensors,” in *Proceedings of the Fourth International Conference on Body Area Networks*, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2009.

[5] “IEEE Standard for Telecommunications and Information Exchange Between Systems - LAN/MAN Specific Requirements: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPAN),” *IEEE Std 802.15.4-2003.*

[6] A. Iyer, C. Rosenberg, and A. Karnik, “What is the right model for wireless channel interference?,” *IEEE Transactions on Wireless Communications*, 2009.

[7] R. G. Garroppo, L. Gazzarrini, S. Giordano, and L. Tavanti, "Experimental assessment of the coexistence of Wi-Fi, ZigBee, and Bluetooth devices," in *IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks (WoWMoM), 2011.*

[8] S. Seidman and N. LaSorte, "An experimental method for evaluating wireless coexistence of a Bluetooth medical device," *IEEE Electromagnetic Compatibility Magazine*, 2014.

[9] G. H. Koepke, W. F. Young, J. M. Ladbury, and J. B. Coder, "Interference and coexistence of wireless systems in critical infrastructure," tech. rep., 2015.

[10] L. Angrisani, M. Bertocco, D. Fortin, and A. Sona, "Assessing coexistence problems of IEEE 802.11b and IEEE 802.15.4 wireless networks through cross-layer measurements," in *IEEE Instrumentation and Measurement Technology Conference Proceedings (IMTC), 2007.*

[11] M. A. Sarijari, A. Lo, M. S. Abdullah, S. H. De Groot, I. G. Niemegeers, and R. A. Rashid, "Coexistence of heterogeneous and homogeneous wireless technologies in smart grid-home area network," in *IEEE International Conference on Parallel and Distributed Systems (ICPADS), 2013.*

[12] W. F. Young, J. B. Coder, and L. A. Gonzalez, "A review of wireless coexistence test methodologies," in *IEEE Symposium on Electromagnetic Compatibility and Signal Integrity, 2015.*

[13] R. Tavakoli, M. Nabi, T. Basten, and K. Goossens, "An experimental study of cross-technology interference in in-vehicle wireless sensor networks," in *Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, 2016.

[14] N. Golmie, D. Cypher, and O. Rébala, “Performance analysis of low rate wireless technologies for medical applications,” *Computer Communications*, 2005.

[15] I. Howitt and A. Shukla, “Coexistence empirical study and analytical model for low-rate WPAN and IEEE 802.11b,” in *IEEE Wireless Communications and Networking Conference (WCNC), 2008.*

[16] W. Yuan, X. Wang, and J.-P. M. Linnartz, “A coexistence model of IEEE 802.15.4 and IEEE 802.11 b/g,” in *IEEE symposium on communications and vehicular technology in the Benelux*, 2007.

[17] A. El-Keyi, H. U. Sokun, T. N. Nguyen, Q. Ye, H. J. Zhu, and H. Yanikomeroglu, “A novel probabilistic path loss model for simulating coexistence between 802.11 and 802.15. 4 networks in smart home environments,” in *IEEE 28th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC), 2017.*

[18] D. Yang, Y. Xu, and M. Gidlund, “Wireless coexistence between IEEE 802.11 and IEEE 802.15. 4-based networks: A survey,” *International Journal of Distributed Sensor Networks*, 2011.

[19] J. W. Chong, H. Y. Hwang, C. Y. Jung, and D. K. Sung, “Analysis of throughput in a zigbee network under the presence of wlan interference,” in *IEEEInternational Symposium on Communications and Information Technologies, (ISCIT) 2007.*

[20] S. Y. Shin, H. S. Park, S. Choi, and W. H. Kwon, “Packet error rate analysis of ZigBee under WLAN and Bluetooth interferences,” *IEEE Transactions on Wireless Communications*, 2007.

[21] A. Lavric, V. Popa, I. Finis, A.-M. Gaitan, and A.-I. Petrariu, “Packet error rate analysis of IEEE 802.15.4 under IEEE 802.11g and bluetooth interferences,” in *IEEE International Conference on Communications (COMM), 2012.*

[22] Y. Lin, J. Li, and Y. Zhu, “Cross-platform interference: Locating wifi devices with zigbee sensor networks,” in *IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), 2015.*

[23] M. Petrova, L. Wu, P. Mahonen, and J. Riihijarvi, “Interference measurements on performance degradation between colocated IEEE 802.11g/n and IEEE 802.15. 4 networks,” in *IEEE International Conference on Networking (ICN), 2007.*

[24] B. Polepalli, W. Xie, D. Thangaraja, M. Goyal, H. Hosseini, and Y. Bashir, “Impact of IEEE 802.11n operation on IEEE 802.15.4 operation,” in *IEEE International Conference on Advanced Information Networking and Applications Workshops, 2009.*

[25] W. Balid, M. O. Al Kalaa, S. Rajab, H. Tafish, and H. H. Refai, “Development of measurement techniques and tools for coexistence testing of wireless medical devices,” in *IEEE Wireless Communications and Networking Conference (WCNC), 2016.*

[26] D. Denkovski, M. Pavloski, V. Atanasovski, and L. Gavrilovska, “Parameter settings for 2.4 GHz ISM spectrum measurements,” in *IEEE International Symposium on Applied Sciences in Biomedical and Communication Technologies (ISABEL), 2010.*

[27] L. Tytgat, O. Yaron, S. Pollin, I. Moerman, and P. Demeester, “Analysis and experimental verification of frequency-based interference avoidance mechanisms in IEEE 802.15.4,” *IEEE/ACM Transactions on Networking*, 2015.

[28] F. Li, J. Luo, G. Shi, and Y. He, “Art: Adaptive frequency-temporal co-existing of ZigBee and WiFi,” *IEEE Transactions on Mobile Computing*, 2017.

[29] C. Won, J. Youn, H. Ali, H. Sharif, and J. Deogun, “Adaptive radio channel allocation for supporting coexistence of 802.15.4 and 802.11b,” in *IEEE Vehicular Technology Conference*, IEEE, 2005.

[30] S. S. Wagh, A. More, and P. R. Kharote, “Performance evaluation of IEEE 802.15.4 protocol under coexistence of WiFi 802.11b,” *Procedia Computer Science*, 2015.

[31] M. H. Virk, R. Vuohtoniemi, M. Hämäläinen, J.-P. Mäkelä, and J. Iinatti, "Spectrum occupancy evaluations at 2.35-2.50 GHz ISM band in a hospital environment," in *Proceedings of the 9th International Conference on Body Area Networks*, ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2014.

[32] C.-H. Cheng and C.-C. Ho, "Implementation of multi-channel technology in ZigBee wireless sensor networks," *Computers & Electrical Engineering*, 2016.

[33] J. Huang, G. Xing, G. Zhou, and R. Zhou, "Beyond co-existence: Exploiting wifi white space for zigbee performance assurance," in *IEEE International Conference on Network Protocols (ICNP), 2010.*

[34] P. Guo, J. Cao, K. Zhang, and X. Liu, "Enhancing ZigBee throughput under WiFi interference using real-time adaptive coding," in *IEEE INFOCOM Proceedings, 2014.*

[35] R. Xu, G. Shi, J. Luo, Z. Zhao, and Y. Shu, "Muzi: Multi-channel zigbee networks for avoiding wifi interference," in *IEEE International Conference on Internet of Things, 2011 and 4th International Conference on Cyber, Physical and Social Computing,(iThings/CPSCom) 2011.*

[36] T. Zhang and X. Li, "Evaluating and analyzing the performance of rpl in contiki," in *Proceedings of the first international workshop on Mobile sensing, computing and communication*, ACM, 2014.

[37] A. Velinov and A. Mileva, "Running and testing applications for Contiki OS using Cooja simulator," 2016.

[38] Moteiv Corporation, *Telos (Rev B) Datasheet*, Dec. 2004.

[39] "The Contiki OS." http://www.contiki-os.org/, accessed Spring 2019.