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Experimental Evaluation of Interference in 2.4 GHz Wireless Network

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ABSTRACT

To attain automation across different applications, nuclear power plants are beginning to leverage advancements in wireless communication technologies. A "one-size-fits-all" solution cannot be applied since wireless technologies are selected according to application needs, quality of service requirements, and economic restrictions. To balance the trade-off between technical and economic requirements, a multi-band heterogeneous wireless network architecture is needed. Numerous wireless technologies including Wi-Fi, ZigBee, and Bluetooth® share the 2.4 GHz industrial, scientific, and medical band. However, due to different channel access mechanisms and transmit power levels, and very importantly, uncoordinated use, coexistence of these devices in the same vicinity can cause interference and degradation in performance.

This report provides the technical basis for understanding the coexistence of these wireless technologies through an experimental evaluation of their performance. This report investigates interactions encompassing variables such as transmission power level, distance between the devices, data rates, and the utilization of co-channel or adjacent channels. The results show that the operation of both ZigBee and Bluetooth. ZigBee is severely compromised when coexisting with Wi-Fi within the same frequency spectrum. On the other hand, the performance of Bluetooth is not impaired by ZigBee and vice versa unless there exists any external interference from Wi-Fi.

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ACRONYMS

AFH	adaptive frequency hopping
AP	access point
BLE	Bluetooth Low Energy
BS	base station
BT	Bluetooth
CA	Collison Avoidance
CS	Carrier Sense
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CTS	Clear to Send
ED	energy detection
FER	frame error rate
FHHS	Frequency Hopping Spread Spectrum
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
ISM	Industrial Scientific and Medical
LSSB	Licensed Spectrum Slot Boundary
LTE	Long-Term Evolution
LTE-LAA	LTE License Assisted Access
LTE-U	LTE in unlicensed spectrum
MA	Medium access
MAC	Medium access control
MIMO	Multiple Input Multiple Output
NPP	Nuclear power plant
NR-U	New Radio-Unlicensed
PER	packet error rate
PHY	Physical
QoS	quality of service
RSSI	received signal strength indicator
RTS	Request to Send
UDP	User datagram protocol
USB	Universal Serial Bus
Wi-Fi	Wireless-Fidelity
XCTU	XBee Configuration and Test Utility

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Experimental Evaluation of Interference in 2.4 GHz Wireless Network

1. INTRODUCTION

The nuclear industry is moving toward implementing advanced technologies to automate monitoring, inspection, security, and other tasks to enhance their operating efficiency and effectiveness without compromising on safety and reliability. Wired solutions enable reliable data transmission but their deployment costs are extremely high. Industrial automation is becoming a reality with the emergence of 5G technology, along with several advanced low-power Internet of Things (IoT) technologies [1]. Most wireless technologies available today, such as wireless local area network, [2] Bluetooth (BT), ZigBee, and radio frequency identification, use the 2.4 GHz and industrial, scientific, and medical (ISM) band. The Long-Term Evolution (LTE)-based solutions, such as Narrow Band–IoT, Category-1 (Cat-1), and Category-M (Cat-M) are also evolving as low-energy and low-bit-rate solutions for IoT applications. Most of the wireless communication deployment in nuclear power plants (NPPs) are on the secondary side of the plant. Smith et al. [3] proposed three-tier communication strategy to support wireless transmission in NPPs.

With a diversity of wireless technologies available today, it is not possible to develop a “one-size-fits-all” solution that would enable industrial automation. Different types of data are transmitted over a wireless network with different quality of service (QoS), latency, and bandwidth requirements [4]. Hence, to satisfy industrial automation and communication needs, coexisting wireless systems that result in a heterogeneous network are highly desired. To deploy multiple wireless technologies, signal degradation at different levels and interference between technologies should be considered. This helps to identify the required number of antennae or access points (APs) to be placed at different locations of the industrial environment for improved coverage and capacity. Specifically, the 2.4 GHz ISM band has gained immense popularity due to its global availability and lack of licensing requirements. As a result, many wireless technologies, such as Wireless-Fidelity (Wi-Fi), ZigBee, and Bluetooth, have stacked their claim within this limited spectrum. These technologies can coexist in critical industrial environments to achieve system automation, optimize maintenance by gathering data from sensor modules, and transmit real-time data to enhance productivity and improve efficiency. However, the growing number of devices competing for a part of this spectrum has raised concerns about potential interference and congestion, producing the need for innovative solutions to ensure harmonious coexistence and optimal performance of these wireless technologies.

This report provides the technical basis to understand the wireless protocols that occupy the 2.4 GHz band with experimental analysis to evaluate their performance when they coexist and operate simultaneously in close vicinity. The report is organized as follows: Section 2 provides a brief overview of different 2.4 GHz wireless protocols. Section 3 provides a brief literature review discussing some of the efforts addressing coexistence of wireless technologies. Section 4 presents a discussion on different hardware used in the experimentation, along with device configuration for Wi-Fi, ZigBee, and BLE. Section 5 summarizes the results and discussion for different experimental setups. Section 6 discusses some of the open topic of research that needs further attention as different wireless technologies are becoming available and can be potentially used in the nuclear industry. Section 7 summaries the report and describes the path forward.

2. 2.4 GHz Wireless Protocols Overview

This section provides an overview of three prominent wireless technologies—Wi-Fi, ZigBee, and Bluetooth—that operate within the 2.4 GHz ISM band with a total bandwidth of 100 MHz. The Institute of Electrical and Electronics Engineers (IEEE) defines the Physical (PHY) and Medium Access Control (MAC) layers in its standard for each of these protocols [5],[6],[7]. However, separate alliances of companies collaborated to develop specifications for the upper layers of the protocol stack. As these materials are extensively documented in the literature, this report offers a concise presentation of the essential information required to understand the topic comprehensively.

2.1 Wi-Fi

Wi-Fi is a widely used wireless communication technology for high-speed internet connectivity. The IEEE 802.11 family of standards defines Wi-Fi, which includes various versions such as 802.11 (a, b, g, n, ac) and 802.11ax (Wi-Fi 6). It operates in both the 2.4 GHz (version b, g, n, ax) and 5 GHz (a, n, ac, ax) frequency bands, providing data transfer rates ranging from a few megabits per second (Mbps) to gigabits per second (Gbps). Within the 2.4 GHz ISM band, a total bandwidth of 100 MHz is available, divided into 11 channels (numbered from 1 to 11), each 20 MHz wide. However, it is essential to note that channels other than 1, 6, and 11 overlap with adjacent channels, as depicted at the bottom of Figure 1 (above). Consequently, to minimize interference, it is essential for multiple Wi-Fi networks operating in close vicinity to use non-overlapping channels (i.e., 1, 6, or 11 or channels whose number differs by 5) to avoid mutual interference and ensure optimal performance. The 802.11 (n and onward) allows for the optional use of a 40 MHz channel by bonding two adjacent channels. Therefore, strategically selecting non-overlapping channels of either 20 or 40 MHz is critical to Wi-Fi deployment in environments with high wireless network activity.

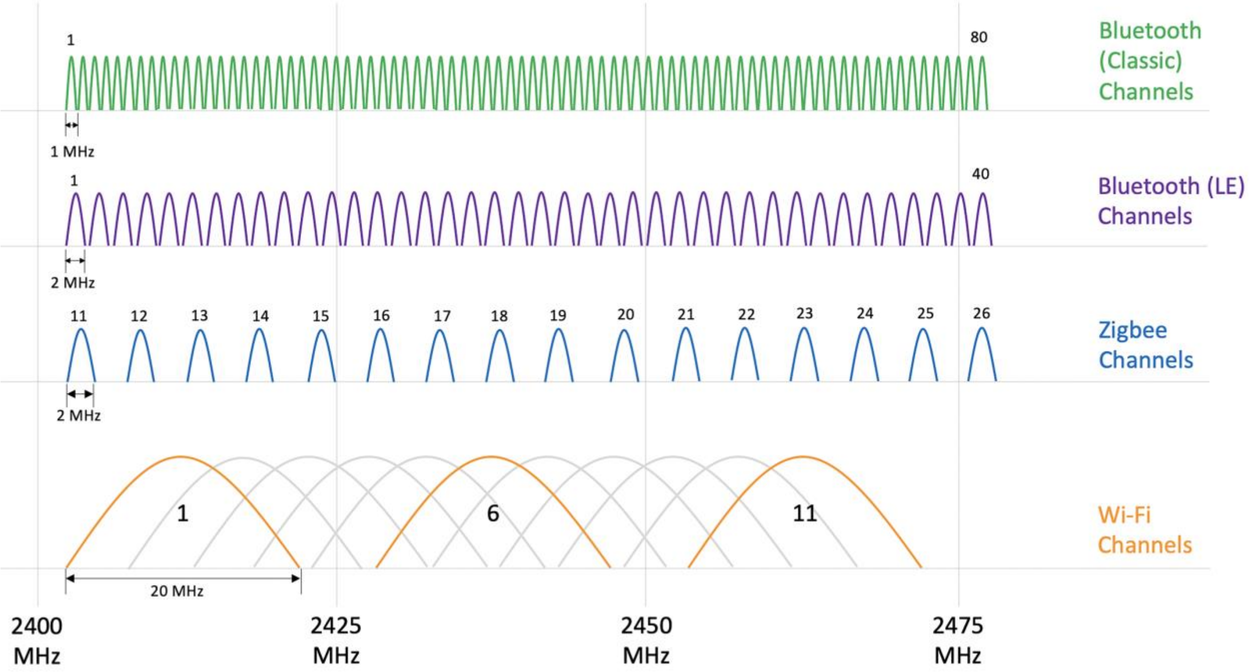


Figure 1. Wi-Fi, ZigBee, and Bluetooth channel distributions in 2.4 GHz ISM band.

Current Wi-Fi networks rely on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) mechanism to manage how Wi-Fi devices access the wireless medium and transmit data. In a Wi-Fi network, multiple devices like laptops and smartphones share the same wireless channel to communicate with the Access Point (AP) or the router. Without proper coordination, simultaneous transmission from multiple devices could lead to collisions, resulting in data loss and decreased throughput. CSMA/CA is a process designed to avoid collision by the following steps:

- Carrier Sense (CS): Before attempting to transmit, a device listens to the wireless channel to check if it is idle (no other devices are transmitting). If the channel is found busy, the device waits for a certain period for the channel to become accessible again.

- Multiple Access (MA): The device initiates transmission once the channel is free. However, due to the nature of wireless communication, it might be the case that two devices sensed the channel to be idle at the same time and started transmitting simultaneously. To address this issue, CSMA/CA incorporates a random back-off time mechanism to introduce a slight delay for each device before attempting to transmit. This randomization helps reduce the chances of simultaneous transmission and further collision.
- Collision Avoidance (CA): A collision might still occur if two devices start their transmission simultaneously despite the random back-off. Such a scenario may arise due to a hidden node problem (when two devices are within the range of the AP but out of range of each other, making them unaware of each other's transmission). To avoid such a scenario, Wi-Fi uses Request to Send / Clear to Send (RTS/CTS) to detect ongoing transmission during their back-off period. The RTS/CTS mechanism addresses the hidden node problem in the following way:
  - RTS: The device that wants to transmit sends an RTS frame to the AP, indicating its intention to send data.
    - CTS: If AP is ready to receive data, it responds with a CTS frame. The CTS acts as a signal to other devices within the range of the AP, informing them about an upcoming transmission. This CTS frame reserves the channel for a specific duration of time.
    - Data Transmission: After receiving the CTS, the transmitting device can send its data without worrying about a collision with other devices within the APs range.

The flow graph for clear channel assessment is presented in Figure 2. However, in the CSMA/CA protocol, the sensed signal is first demodulated to verify whether the signal modulation and frame structure comply with the characteristic 802.11 PHY layer. If it is compliant, the device will consider the channel busy regardless of the signal energy level. Otherwise, it does not differ in transmission even when other protocols are transmitting (for example, ZigBee) because Wi-Fi transmitters cannot demodulate or verify signals from other protocol standards.

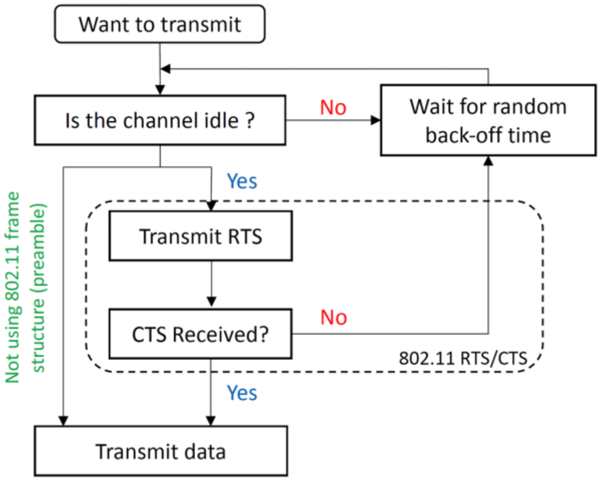


Figure 2. Clear channel assessment flow graph.

2.2 Bluetooth

Bluetooth (BT) is a short-range wireless communication protocol commonly used to connect personal devices such as smartphones, laptops, headphones, and smartwatches and share data between them. BT technology is divided into two categories: classic and Low Energy (LE). Both categories use BT protocol but are designed for different purposes with different characteristics.

- Classic BT: Designed for high-bandwidth applications such as streaming audio and video and supports devices with higher power requirements. Classic BT uses the 2.4 GHz band and has a maximum data rate of up to 3 Mbps with a range of 100 meters.
- Bluetooth Low Energy (BLE): The newer version of BT technology is designed for low-power applications such as fitness trackers, smart watches, smart home appliances, and sensing devices. It also operates in the 2.4 GHz band but has lower power consumption and a range of up to 50 meters with a maximum data rate of 1 Mbps.

The IEEE 802.15.1 standard specifies Bluetooth. The classic BT divides the band into 80 channels, each 1 MHz wide, while BLE divides the band into 40 channels, each 2 MHz wide, as depicted in Figure 1. Bluetooth uses Frequency Hopping Spread Spectrum (FHSS) to minimize interference. It rapidly switches (hops) between channels 1600 times/sec in a pseudo-random sequence [8]. Each BT device pair uses its own pseudo-random frequency hopping pattern; therefore, interference from other BT devices is small. BT (80MHz spectrum) is still prone to interference on 27% of its channel from Wi-Fi (using 20 MHz bandwidth).

A BT Special Interest Group has defined Adaptive Frequency Hopping (AFH) to address this issue. The algorithm allows the BT transmitter or receiver to monitor the quality and classify the channels as good or bad. A bad channel is removed from the hop set for a certain period and brought back to be utilized after a reassessment [9]. Currently, there are three prevailing methods for performing channel assessment with AFH: Received Signal Strength Indicator (RSSI), Packet Error Rate (PER), and Signal to Noise Ratio. The BT Special Interest Group specification does not mandate the method of channel assessment. Instead, the implementation is left up to the chipset vendor to define and optimize. To meet the regulation, the minimum number of channels to be used by BT must be greater or equal to 20 [10]. Therefore, if a Wi-Fi channel has a bandwidth of 40 MHz or two Wi-Fi networks operating on two 20 MHz channels nearby, BLE devices (37 data channels) will not be able to recover from interference quickly.

2.3 ZigBee

ZigBee is a low-power, short-range wireless sensor network protocol offering data rates up to 250 Kbps. It is important to note that the IEEE 802.15.4 standard defines the PHY and MAC layer specifications, while ZigBee is built on top of the 802.15.4 standard and defines the networking and application layer specifications making it a complete end-to-end solution for IoT networks. Though the terms (ZigBee and 802.15.4) are used interchangeably, in this report, we consider only the PHY and MAC layer of the ZigBee standard. ZigBee operates in the 2.4 GHz, 900 MHz, and 868 MHz frequency bands (2.4 GHz being the most common) [11]. ZigBee uses mesh networking, enabling devices to form self-organizing networks, making it ideal for intelligent home automation, industrial monitoring, and sensor networks. The 2.4 GHz band is divided into 16 channels (numbered from 11 to 26), each 2 MHz wide and does not overlap. Therefore, 16 ZigBee devices can operate simultaneously in close vicinity, as depicted in Figure 1. ZigBee does not change its channel frequently like Bluetooth, and rather uses CSMA/CA mechanism like Wi-Fi.

Instead of using RTS/CTS for clear channel assessment, ZigBee uses energy detection (ED) functionality to determine the activity of other systems and thus decide the operating channel. When a ZigBee device wants to transmit, it first goes into receive mode to detect and estimate the signal energy level in the desired channel, called ED. In ED mode, the receiver does not try to decode the signal; only its energy level is estimated. If there is a signal already in the band of interest, ED does not determine whether or not this is an 802.15.4 signal; rather, it backs off and retries after some time.

A summary of the three-protocol discussed above are provided in Table 1. The values (e.g., communication range or maximum data rate) are based on ideal conditions which could differ in real-world settings.

Table 1. Summary of protocols operating in 2.4 GHz ISM band.

Standard	Wi-Fi	Bluetooth (LE)	ZigBee
IEEE Spec.	802.11n	802.15.1	802.15.4
Frequency band	2.4 GHz, 5 GHz	2.4 GHz	2.4 GHz, 868/915 MHz
Max. data rate	600 Mbps	1 Mbps	250 Kbps
Comm. range	100 meters	50 meters	10-100 meters
Transmit power	(20 to 30) dBm	(0 to10) dBm	(-5 to 0) dBm
Channel BW	20 MHz / 40 MHz	2 MHz	2 MHz
No. of channels	11	40 (3 advertising channel)	16
Modulation	Quadratic Phase Shifting Keying	GFSK	Quadratic Phase Shifting Keying
Channel Access	CSMA/CA	FHSS/ Time Division Multiple Access	CSMA/CA

2.4 Coexistence Challenges of Wi-Fi, Bluetooth, and ZigBee

The coexistence of Wi-Fi, Bluetooth, and ZigBee in the same environment can present several challenges due to the shared 2.4 GHz frequency band. These challenges can lead to interference and degradation in performance and reliability. Some of the main challenges of coexistence for these protocols are:

- Interference and frame collision: Due to the overlapping spectrum, when the transceivers using these protocols coexist in close vicinity, their signals can interfere, or frames can collide, resulting in degraded performance and reliability.
- Channel overlap: Though all the protocols have the option to use different channels in the 2.4 GHz spectrum, there is some overlap in the frequency band they use, as depicted in Figure 1. For example, Wi-Fi channel 1 overlaps with four ZigBee channels (11, 12, 13, and 14) and Bluetooth (LE) channels (1–10). If multiple devices using these technologies transmit simultaneously, it can result in interference and degradation in performance.
- Power levels: Wi-Fi devices transmit their signal with power between 20 to 30 dBm, 30 times higher than ZigBee (0 dBm) and 10 times higher than Bluetooth LE (10 dBm). Wi-Fi signals can easily overpower ZigBee and Bluetooth signals, causing interference and reducing the effective throughput and transmission range.
- Coexistence mechanism: Although all of these technologies have implemented coexistence mechanisms to mitigate interference, they might not be entirely effective. For example, Wi-Fi uses CSMA/CA with RTS/CTS that requires the frame format or preamble to match the Wi-Fi protocol, whereas ZigBee uses CSMA/CA based on ED of signal to sense the channel and avoid interference. Therefore, if Wi-Fi is active, ZigBee will not be able to maintain its performance.
- Quality of Service: The interference caused by the coexistence can lead to variations in latency and throughput. Applications that require reliable and consistent data transfer, such as real-time video streaming or emergency sensing and alarm systems, might not provide the required QoS.

3. LITERATURE REVIEW

The coexistence of multiple wireless communication technologies in the 2.4 GHz band has been the subject of extensive research and investigation due to the widespread adoption of Wi-Fi, Bluetooth, and ZigBee in various applications. Numerous theoretical and experimental studies have been performed to address these challenges. In this section, we present an overview of the existing literature and research efforts on the coexistence of these wireless technologies.

Garroppo et al. [12] empirically investigated the coexistence of Wi-Fi, ZigBee, and Bluetooth technologies in an indoor laboratory environment. The study assessed performance using throughput and frame error rate (FER) measurements. The results revealed that Wi-Fi performance remained unaffected in terms of throughput when either ZigBee or Bluetooth was active. However, the performance of ZigBee was notably degraded, with a drop in FER ranging from 45 to 73% when Wi-Fi was active. Similarly, Bluetooth's throughput suffered degradation from 1.12 to 0.59 Mbps in the presence of Wi-Fi. The paper also revealed that the position of the nodes and the interferer significantly affect the performance. It is important to note that the study did not report the performance of Wi-Fi or Bluetooth in terms of FER. In addition, as the experiment was performed in a laboratory environment, external interference on the 2.4 GHz band was present.

Biswajit et al. [13] conducted an experimental investigation focusing on the performance evaluation of a ZigBee network in the presence of a Wi-Fi interference network in an indoor-apartment environment. The analysis of the performance of the ZigBee network was based in terms of RSSI, packet drop rate, and throughput. Various networking parameters were also considered, such as operating channels, the distances between ZigBee and Wi-Fi devices, transmit interval of ZigBee packets, and the transmit power of ZigBee devices to study the network performance. Results show that Wi-Fi interference from neighboring homes would not be an important factor in deploying ZigBee networks in a home. However, serious consideration may be needed when these devices operate inside the same home. The paper does not discuss the performance of the ZigBee network in the presence of other 2.4 GHz band networks (e.g., Bluetooth). Additionally, the experiments were conducted in a single apartment-based environment, which may not represent all indoor environments. Therefore, the results may not be generalized to other environments.

Research by B. Polepalli et al. [14] demonstrated that the traffic load of Wi-Fi networks can affect ZigBee network performance. The evaluation involved two scenarios: (1) ZigBee channel overlapping with the Wi-Fi extension channel, where the Wi-Fi bandwidth (e.g., 20 MHz of 802.11n) is increased to 40 MHz using channel bonding, with the primary channel for management signals and the extension channel for payload, and (2) ZigBee channel overlapping with Wi-Fi control channel. The overlap with the Wi-Fi extension channel results in a significant decline in ZigBee's successful packet delivery. Although the impact on ZigBee's packet loss rate is substantial, it is less severe than when overlapping with the Wi-Fi control channel. The degradation of ZigBee's performance worsens with a higher Wi-Fi traffic load, depending upon the actual usage of the extension channel.

Nickolas et al. [15] studied adjacent channel interference alongside co-channel interference between ZigBee and Wi-Fi networks. Adjacent channel interference is caused by extraneous power emission from an adjacent channel due to inadequate filtering or improper frequency tuning. The study found that ZigBee's PER increases as the frequency separation between the two protocols decreases, with the highest PER occurring when both networks converge to the same frequency band. The ZigBee transmitter was less affected by the sidelobes of the interfering network when nearby, as it sensed when the wireless channel was free to send packets. However, this was not the case when the transmitter was farther away from the interferer, leading to a false perception of a free channel.

4. EXPERIMENTAL SETUP

This section presents discussion on different hardware used in the experimentation, along with device configuration for Wi-Fi, ZigBee, and BLE.

4.1 Hardware and Device Configuration

4.1.1 Wi-Fi

To set up the Wi-Fi network, we utilized a commercially available NETGEAR Nighthawk (RAX45) router, which supports both 2.4 GHz and 5 GHz bands, encompassing all 802.11 versions (a/b/g/n/ac/ax). We specifically configured the router to operate at 2.4 GHz, 20 MHz bandwidth with the 802.11n protocol. The selection of version “n” was based on its support for Multiple Input Multiple Output (MIMO) antenna technology (which its predecessor did not support), enabling efficient data transmission and reception. Additionally, 802.11n offers backward compatibility with its predecessor standards and is widely used. In contrast, version “ac” operates solely in the 5 GHz bands, and version “ax,” despite its MIMO capabilities and operation in both 2.4 and 5 GHz bands, has yet to gain widespread adoption.

The router was configured as an Access Point (AP) and connected to two laptops: one laptop served as a server, establishing a connection to the AP via an Ethernet cable, while the other laptop acted as a client, connecting to the AP via a wireless channel as depicted in Figure 3. To generate network traffic over Wi-Fi, we employed iperf3, an open-source command-line tool extensively utilized for evaluating and measuring network performance. This tool provides periodic reports, offering valuable insights into data rate, packet loss, and jitter. The router’s transmit power was not modifiable, and as per the specification, it uses 22 dBm following the Federal Communications Commission (FCC) regulation which permits a maximum of 30 dBm.

Figure 3. Wi-Fi network setup.

4.1.2 ZigBee

To establish a ZigBee network, we utilized the XBee ZigBee mesh kit modules manufactured by Digi International, [16] which comply with the ZigBee standard. The initial attraction to the XBee modules stemmed from their cost-effectiveness and widespread adoption within research communities. These devices operate within the 2.4 GHz ISM band, which was also a requirement to test the coexistence with Wi-Fi and Bluetooth devices. The XBee devices can operate with transmit power ranging from −5 to 8 \dBm and have a 60-meter (200 feet) indoor range. For configuration and traffic generation between transmitter and receiver XBee modules, we used the XBee Configuration and Test Utility (XCTU), an application provided by Digi. Communication between the XBee modules and the XCTU software is via the XBee Universal Serial Bus (USB) interface, connected to a laptop using a USB cable, as depicted in Figure 4

Figure 4. ZigBee network setup.

4.1.3 Bluetooth Low Energy

For the third coexistence network, we implemented BLE. We opted for BLE over the BT classic for two main reasons. First, many devices commonly used today, such as fitness trackers, smartwatches, health monitors, and earbuds, use BLE due to their low-power consumption. These devices are often found near Wi-Fi routers, making BLE a relevant choice for our study. Second, most commercially available sniffing devices that analyze BT signals are more compatible with BLE. This makes BLE a practical and effective option for our experiment. Although most laptops and smartphones are equipped with BT classic and BLE protocols, they do not allow access to information from their PHY and link layer. The information accessible via network monitoring tools such as Wireshark or Linux pertains solely to the upper layers of the Bluetooth stack. Consequently, the information lacks insights into parameters like RSSI, PERs, and the count of re-transmission frames. Furthermore, using any sniffing tool or chip to eavesdrop on an ongoing transmission between BT commercial devices is only helpful if the communication is unencrypted.

To overcome this obstacle, we leveraged the capabilities of the XBee device by Digi to configure the module, enabling it to function as a BLE device. This module is set up as a BLE transmitter with a transmit power of 8 dBm. At the other end, an iPhone is utilized, incorporating an application (also provided by Digi) that serves as a receiver, facilitating connectivity with the transmitter through the BLE protocol, as shown in Figure 5. We developed a Python script that transmits BLE frames with a fixed payload size.

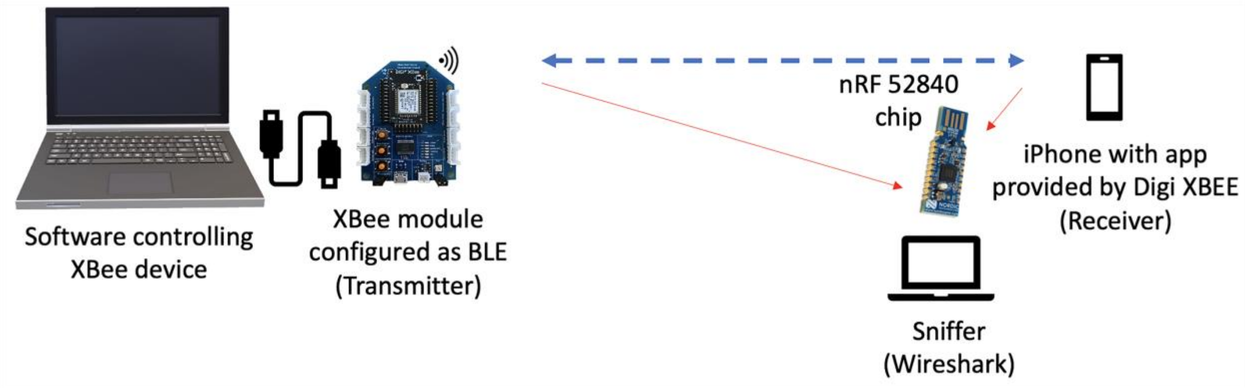


Figure 5. Bluetooth LE network setup.

We employed a sniffer chip developed by Nordic Semiconductor (nRF 52840) to capture the received or ACK frames. This chip captures all the BLE packets exchanged between the transceivers, which can be viewed in the Wireshark protocol analyzer in real time. As a result, we can extract information from both the PHY and link layers of the communication process. The sniffer chip is purposefully kept closer to the receiver to extract the RSSI value as accurately as possible.

4.2 Test Environment

We used the anechoic chamber facility at the University of Utah to carry out our experiment. The chamber's walls, ceiling, and floor are coated with high-loss microwave absorbers. This setup reduced external interferences that might otherwise undermine the integrity of our collected data. As a result, the reliability and accuracy of our research findings were assured. Figure 6 shows the inside of the anechoic chamber.

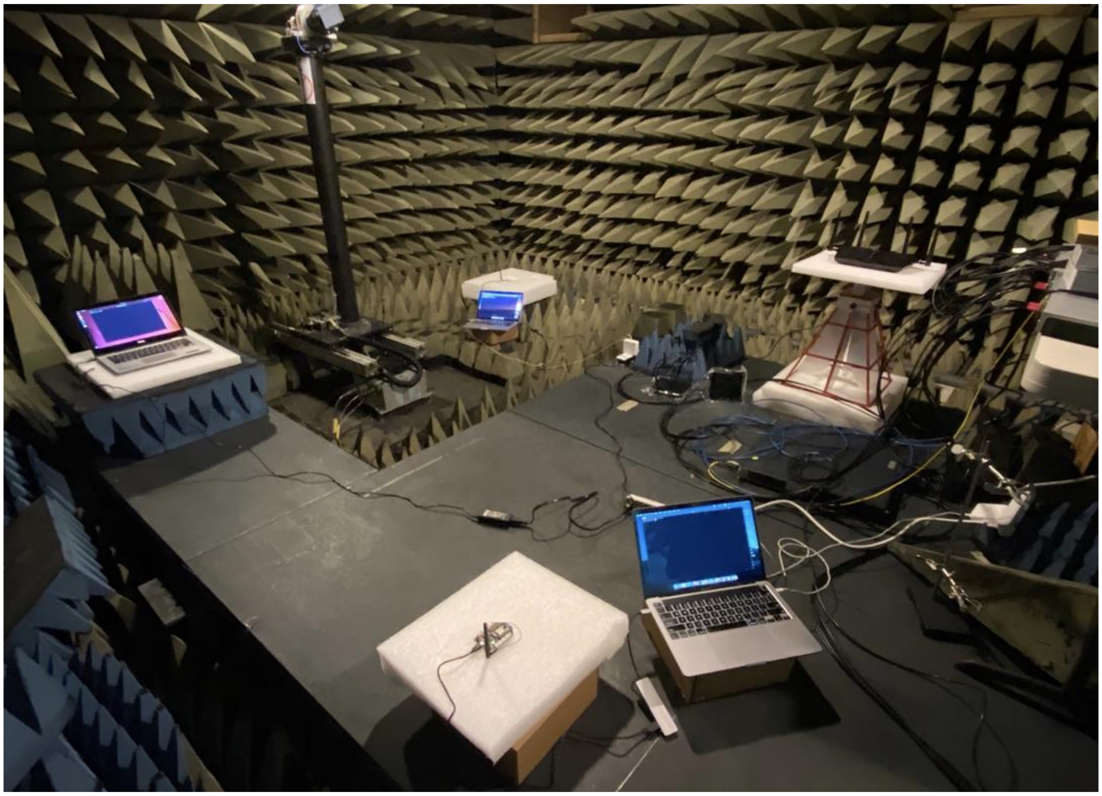


Figure 6. Experiment setup inside anechoic chamber.

5. RESULTS AND DISCUSSION

5.1 Baseline Performance Measurement

We start the experiment with a baseline evaluation of each protocol individually in an interference-free environment. These measurements are later compared with the same test when the transceivers using these protocols interfere.

5.1.1 Wi-Fi

For the Wi-Fi baseline test, we employ the iperf3 tool to generate a continuous transmission of UDP traffic with a frame size of 1470 bytes at a rate of 40 Mbps from the server to the client. The iperf3 output encompasses three QoS parameters for measurement: throughput, jitter, and the number of lost packets. For our analysis, we solely consider the throughput parameter, as the reported packet loss pertains to the network layer and not necessarily the link layer. In case of a packet loss or an error, the system automatically handles re-transmission at the link layer, effectively resolving the issue of packet error due to interference from other sources. We employ the “ethtool” utility on Linux systems to monitor and assess packet errors. This tool facilitates querying of link layer performance parameters, including the number of dropped packets and the count of re-transmissions, allowing us to gain insights into the link layer’s performance and potential network issues. To determine the link quality between the transceiver devices we also measure RSSI. To report the RSSI value continuously, we use the Linux tool “iwconfig” to collect data over 30 seconds and compute the mean. To measure the transmission range and to confirm the signal quality, the distance between the Wi-Fi router and the client was varied from 2 to 10 feet. Since the experiment was done inside the anechoic chamber, we were limited to a maximum of 10 feet. The Wi-Fi channel was fixed at number 1.

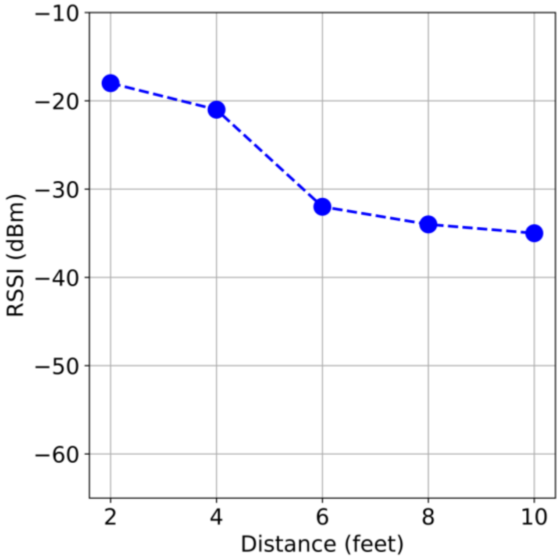


Figure 7. Wi-Fi RSSI vs. Distance (w/o external interference).

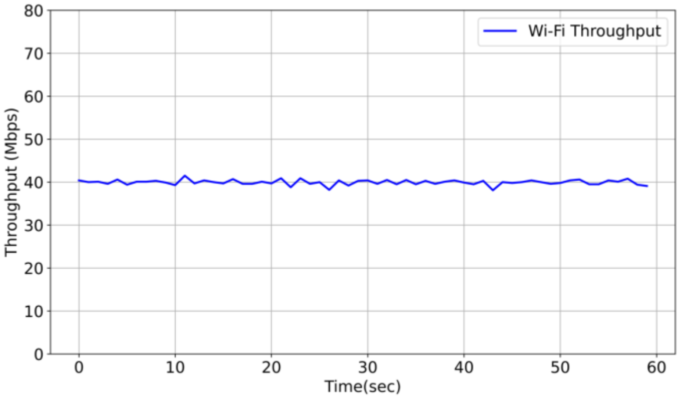


Figure 8. Wi-Fi Throughput vs. Time (w/o external interference).

Figure 7 illustrates the relationship between RSSI measurements and distance. It is observed that RSSI values are at their highest when the devices are close to each other. As the distance between the devices increases, the RSSI value also decreases. Figure 8 represents throughput versus time when the transceiver devices are separated by 10 feet. The figure reveals a consistent and stable throughput over the entire duration of 1 minute. In the absence of external interference, we did not observe any packet drops of Wi-Fi frames during the experiment.

5.1.2 ZigBee

In the context of ZigBee, the XCTU software is utilized to compute throughput, RSSI, and packet error rate. The RSSI values are measured over 30 seconds for each distance point. The mean RSSI values are then computed over the duration. Notably, the ZigBee device's transmit power was also controllable at specific values (−5, +2, and +8) dBm. Figure 9 depicts the RSSI values achieved while the transmit power was varied at each distance. As anticipated, the RSSI value is substantial, with high transmit power when devices operated in proximity. Conversely, reduced transmit power corresponds to attenuated RSSI. The figure also shows that RSSI drops fast for the first couple of feet and then decreases at a slower rate for a longer distance.

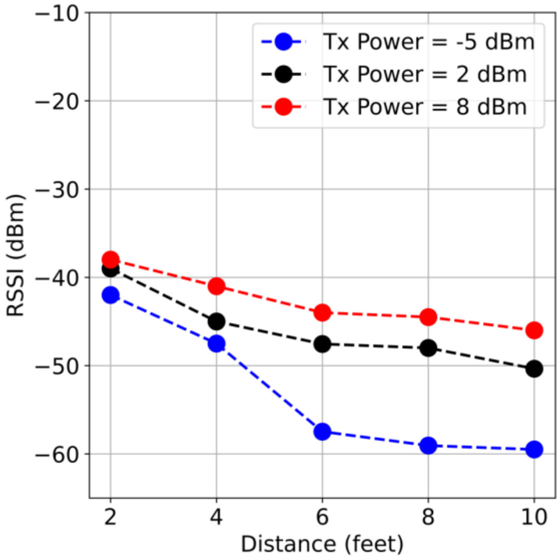


Figure 9. ZigBee RSSI vs. Distance (w/o external interference).

To measure throughput, we create frames with a payload size of 100 bytes, and 1327 frames are transmitted during a 1-minute duration. This transmission results in an average throughput of 15.16 Kbps, as illustrated in Figure 10. The throughput is computed from the ZigBee transmitter based on a specific frame's "delivery status" field. This field reports whether a frame is successfully delivered or not. If a frame is successfully delivered, we include the frame in throughput computation. Otherwise, we count the frame as an error. There are a number of error codes in the "delivery status" field reports, including no acknowledgment (NO ACK) from the receiver and clear channel assessment (CCA) failure. The transmitter retransmits the frame up to a maximum of four times. During the baseline measurement, we observed sharp drops and surges in the throughput, which was not due to any reported frame loss. The throughput drops are due to an increase in latency of few frames, which may occur due to retransmission and/or hardware limitations. Alternatively, the sudden throughput surges are observed as the result of the burst transmission. We have also confirmed that average throughput remains uniform, regardless of the distances (between 2–10 feet) and transmit power. For the duration of throughput measurement, the ZigBee channel was kept fixed at number 12.

5.1.3 Bluetooth

For the baseline test of BT, we conducted measurements of the RSSI across varying distances, ranging from 2 to 10 feet. The calculation of the mean RSSI was performed over 30 seconds. Similar to the observations made in the case of ZigBee, the recorded RSSI values of 8 dBm transmit power exhibited a range between −40 and −60 dBm, as illustrated in Figure 11. A series of BLE frames were transmitted to evaluate the throughput, each containing a payload of 100 bytes, approximately 15 times per second, for 1 minute. This resulted in a baseline throughput of 12.06 Kbps, as represented in Figure 12.

We observed an average packet loss of 1.63% during the 60 seconds, as shown in Figure 13, even when no other protocol was active inside the anechoic chamber. Moreover, the PER percentage was as high as 12% at random times. We utilized a Wi-Fi channel scanner software to investigate the issue to scan the channel for any external interference. We found that even inside the anechoic chamber, the external Wi-Fi network was detectable with power between –90 to −80 dBm (this is illustrated further in Figure 22).

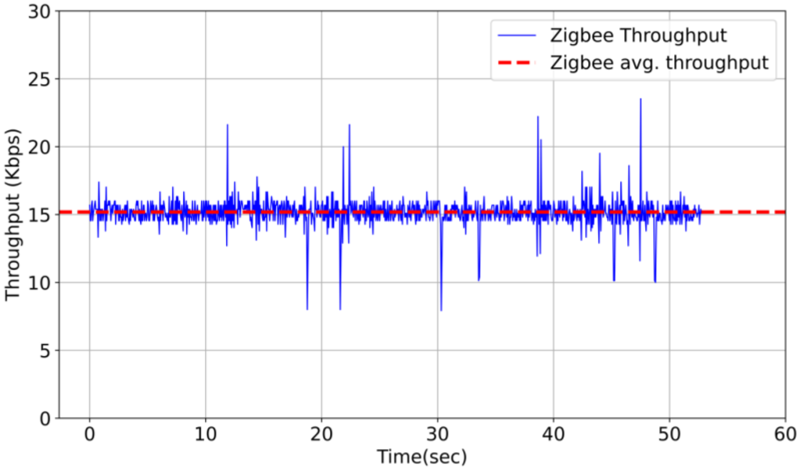


Figure 10. ZigBee Throughput vs. Time (w/o external interference) at a 10-feet separation between Tx-Rx with Tx power −5 dBm.

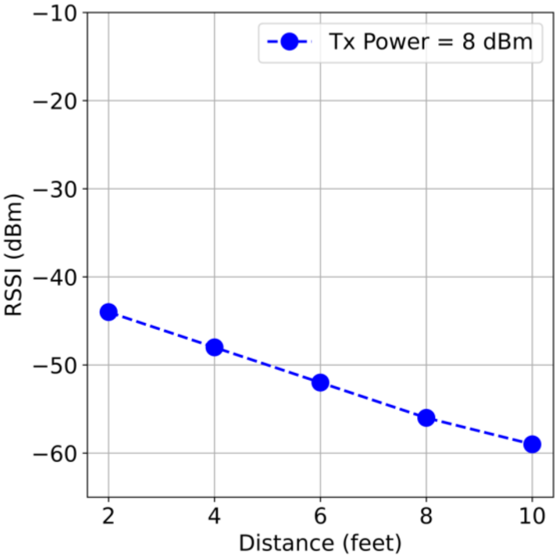


Figure 11. BT RSSI vs. Distance (w/o external interference).

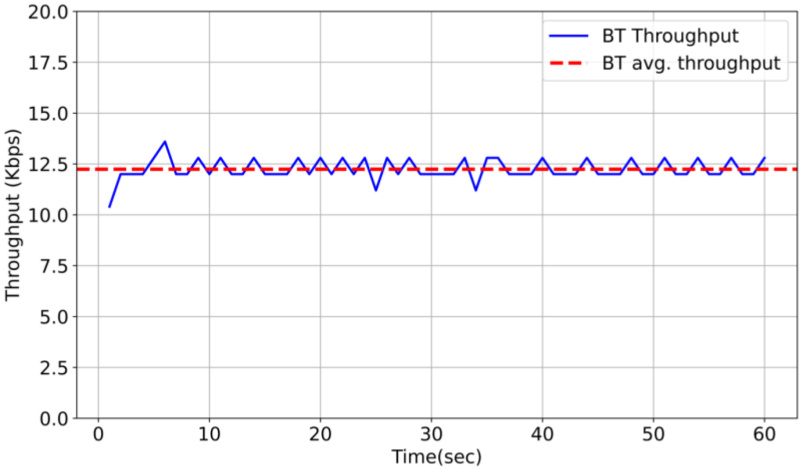


Figure 12. BT Throughput vs. Time (w/o external interference) at 10 feet separation between Tx-Rx with Tx power 8 dBm.

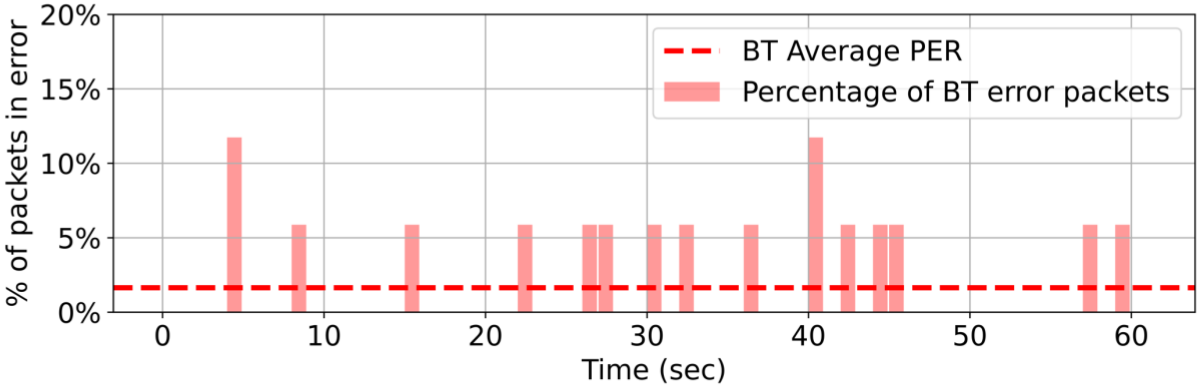


Figure 13. BT PER vs. Time (w/o external interference).

5.2 Coexistence of Wi-Fi and ZigBee

We start our analysis by verifying the impact of Wi-Fi on an ongoing ZigBee transmission. The ZigBee network was set up to operate on channel 12, and the Wi-Fi network on channel 1. Thus both network coincides with the same spectrum (Wi-Fi channel 1 overlaps with ZigBee channel 11 to 14). Each device was kept at a distance of 10-feet apart inside the anechoic chamber. A schematic is shown in Figure 14.

Throughput of ZigBee and Wi-Fi (co-channel): Figure 15 shows the throughput of both Wi-Fi and ZigBee networks when coexisting. The ZigBee node was set to transmit continuously for 1 minute, while the Wi-Fi nodes were set to transmit for 20 seconds. We configured the Wi-Fi to start and end transmission between the 20th and 40th second to capture the interference effect.

Figure 15 shows that as soon as the Wi-Fi starts to transmit, the throughput of the ZigBee network drops from an average of 15.16 Kbps (baseline measurement) to an average of 5.23 Kbps (a decrease of 65.50%). Besides, a fluctuation is observed in ZigBee throughput even when Wi-Fi is not transmitting, which is due to the continuous beacon frames broadcast from the Wi-Fi router.

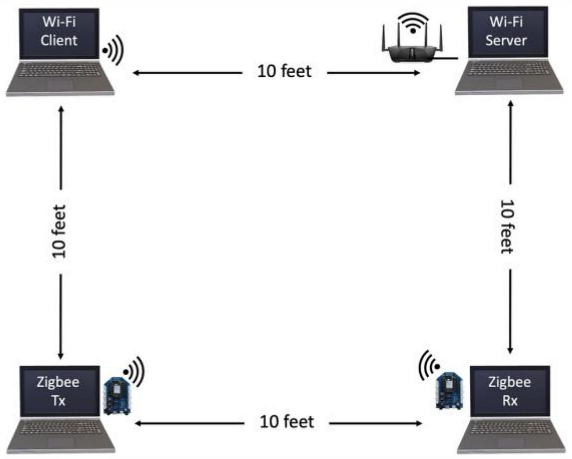


Figure 14. Schematic of Wi-Fi and ZigBee coexistence experimental setup.

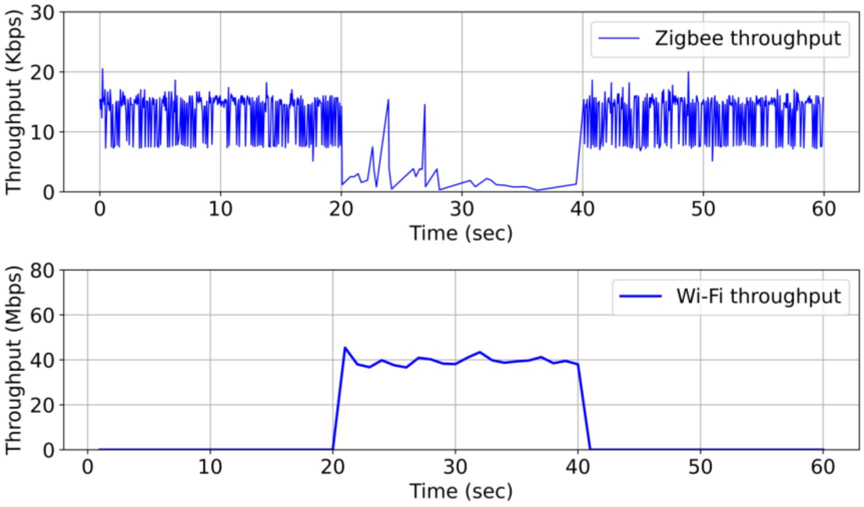


Figure 15. Throughput of ZigBee (top) and Wi-Fi (bottom) while coexisting.

PER of ZigBee and Wi-Fi: The ZigBee node transmitted 23 frames/sec (with a maximum payload of 100 bytes). Figure 16 shows that the ZigBee node has a packet error between 4.3% to 21.7% in the duration of the Wi-Fi transmission. On the other hand, PER of the Wi-Fi was found to be zero during the 20-second duration.

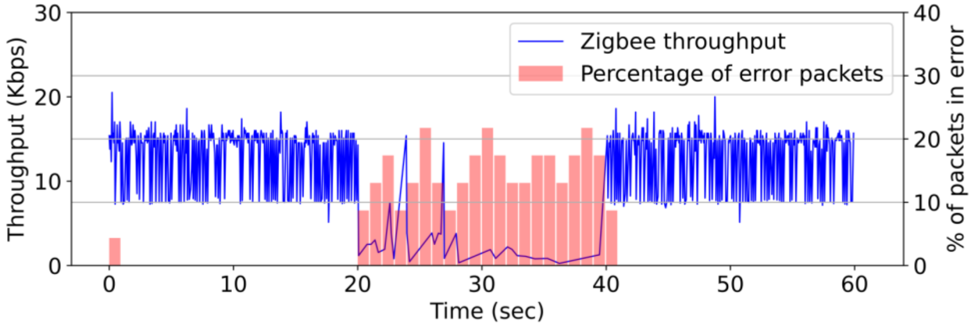


Figure 16. ZigBee Packet error percentage while Wi-Fi coexisting.

Throughput and PER of ZigBee and Wi-Fi (adjacent channel): To mitigate direct co-channel interference between networks, we investigated the effects of these networks functioning on adjacent channels. For instance, we examined the scenario where Wi-Fi operates on channel 11, and ZigBee operates on channel 12, resulting in frequency separation. As illustrated in Figure 17, the influence of adjacent channel operation is significantly reduced compared to co-channel operation. Although minor fluctuations persist, deep signal fading is not observed. The fluctuation observed is due to the interference from beacon frames from external Wi-Fi on Wi-Fi channel 1 that coincides with Zigbee channel 12. We have detected occasional low signal strength Wi-Fi even inside our Anechoic chamber as illustrated in Figure *24*. The average Zigbee throughput under this external Wi-Fi interference is 13.55 kbps which is a 10.6% reduction from the baseline value. Note that the baseline experiment was done during early morning hours and we suspect that no external Wi-Fi interference was present at that time in the chamber. The coexistence of Zigbee and Wi-Fi was evaluated during busy hours during higher network activity inside the building. We also note that Zigbee had only one packet in error during the whole duration. The Wi-Fi throughput and packet error remained unaffected.

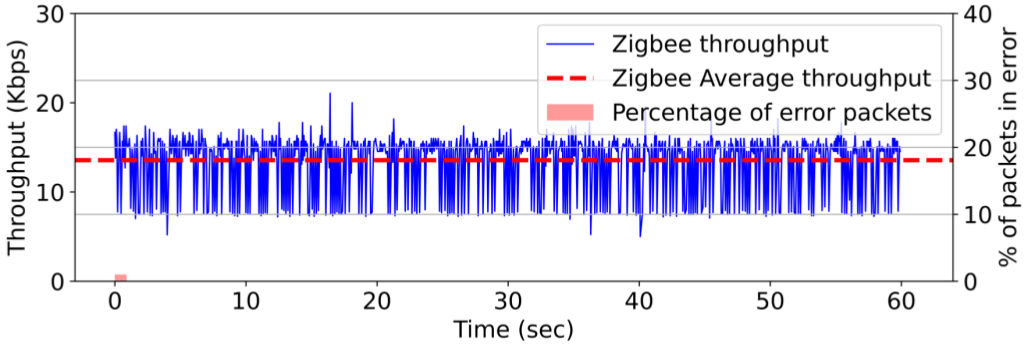
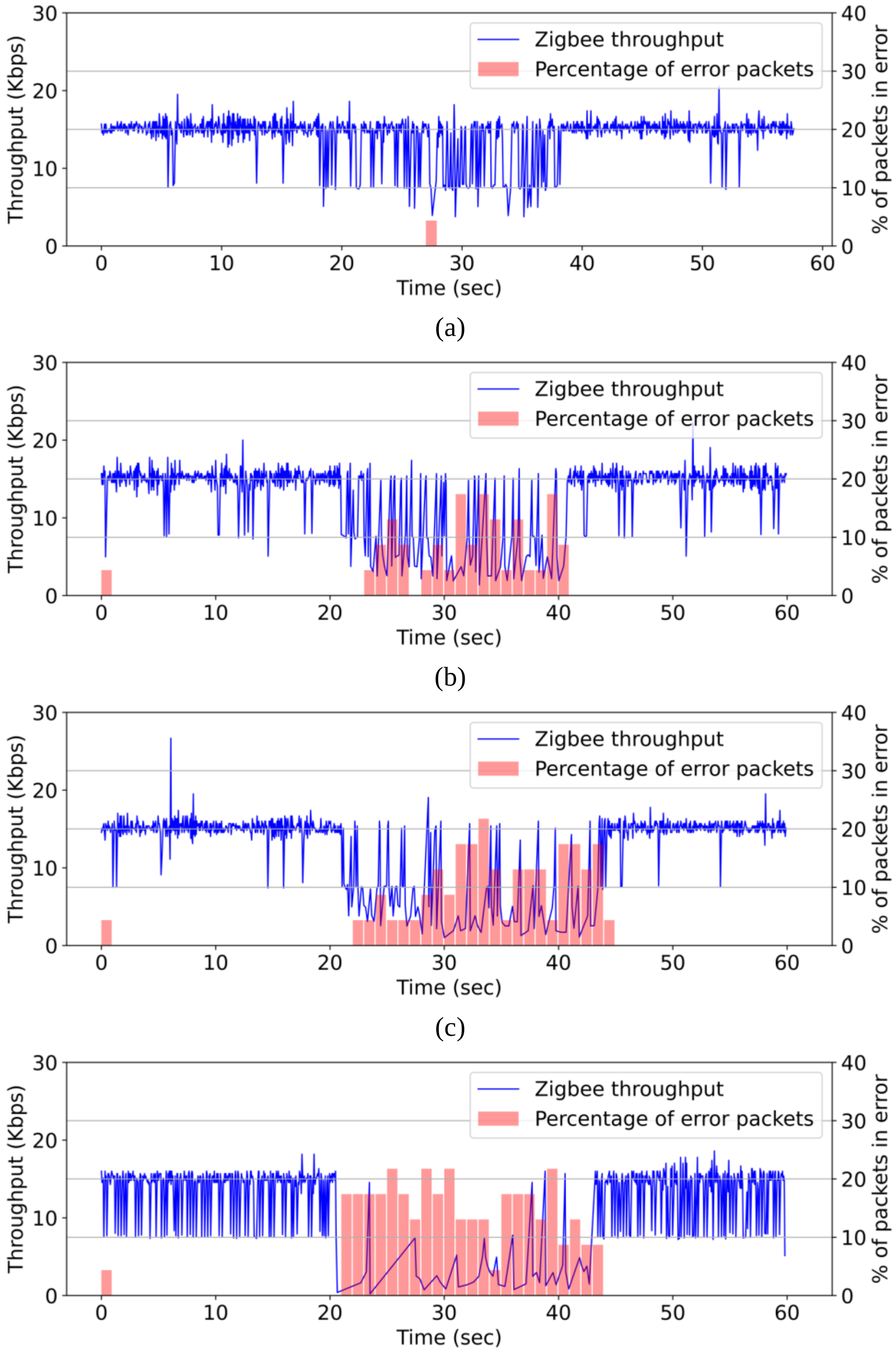


Figure 17. Throughput of ZigBee (channel 12) while Wi-Fi coexisting (channel 11).

Throughput and PER of ZigBee with different Wi-Fi data rates: Figure 18 shows the effect on ZigBee throughput and PER while the Wi-Fi network data rate is varied (10, 20, 30, and 40) Mbps (Wi-Fi channel 1). The plot reveals that increasing Wi-Fi data rates have an adverse effect on ZigBee's throughput and PER. As the data rate of Wi-Fi increases, the duration of individual transmission becomes shorter, leading to more frequent channel access attempts by Wi-Fi transmitter. The increased contention for the channel reduces the available airtime for ZigBee devices, impacting their ability to transmit and receive data efficiently. Table 2 summarizes the impact of Wi-Fi over ZigBee (20-second interference period) when the data rate is varied:

Table 2. Performance of ZigBee while Wi-Fi data rate is varied.

	Wi-Fi Data Rate			
	10 Mbps	20 Mbps	30 Mbps	40 Mbps
ZigBee avg. throughput	13.17 Kbps	9 Kbps	7.33 Kbps	5.14 Kbps
ZigBee average PER	0.19%	7.31%	10.27%	15.61%



(a)

(b)

(c)

(d)

Figure 18. Throughput and PER of ZigBee while Wi-Fi coexisting with different data rates: (a) 10 Mbps, (b) 20 Mbps, (c) 30 Mbps, and (d) 40 Mbps.

Throughput and PER of ZigBee with varying distance between Wi-Fi and ZigBee devices: To explore the influence of Wi-Fi over ZigBee with respect to distance between the devices, we varied the placement of ZigBee transceiver nodes as illustrated in Figure 19 from 4 to 10 feet.

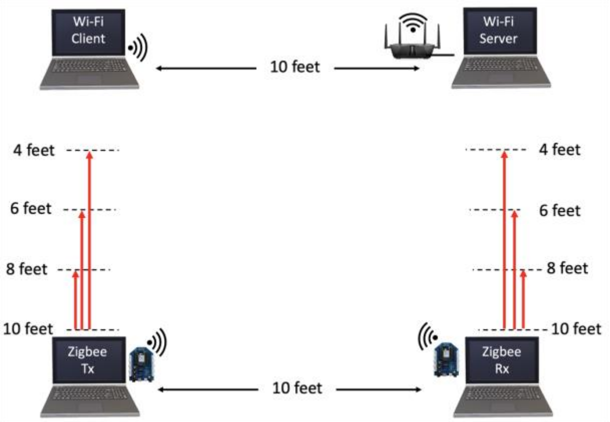


Figure 19. Schematic of ZigBee and Wi-Fi with varying distances.

Figure 20 reveals that varying the distance between ZigBee and Wi-Fi transceivers, spanning from 4 to 10 feet, does not yield any clear pattern in the throughput and PER performance of ZigBee. When the distance between the ZigBee and Wi-Fi transceivers is longer than some threshold, we would likely see improvement in ZigBee's performance as Wi-Fi signal strength would weaken. However, finding this threshold value will need further investigation. Since the experiment was performed inside the anechoic chamber, we were limited to a 10-foot separation between the devices. A summary of the performance is shown in Table 3.

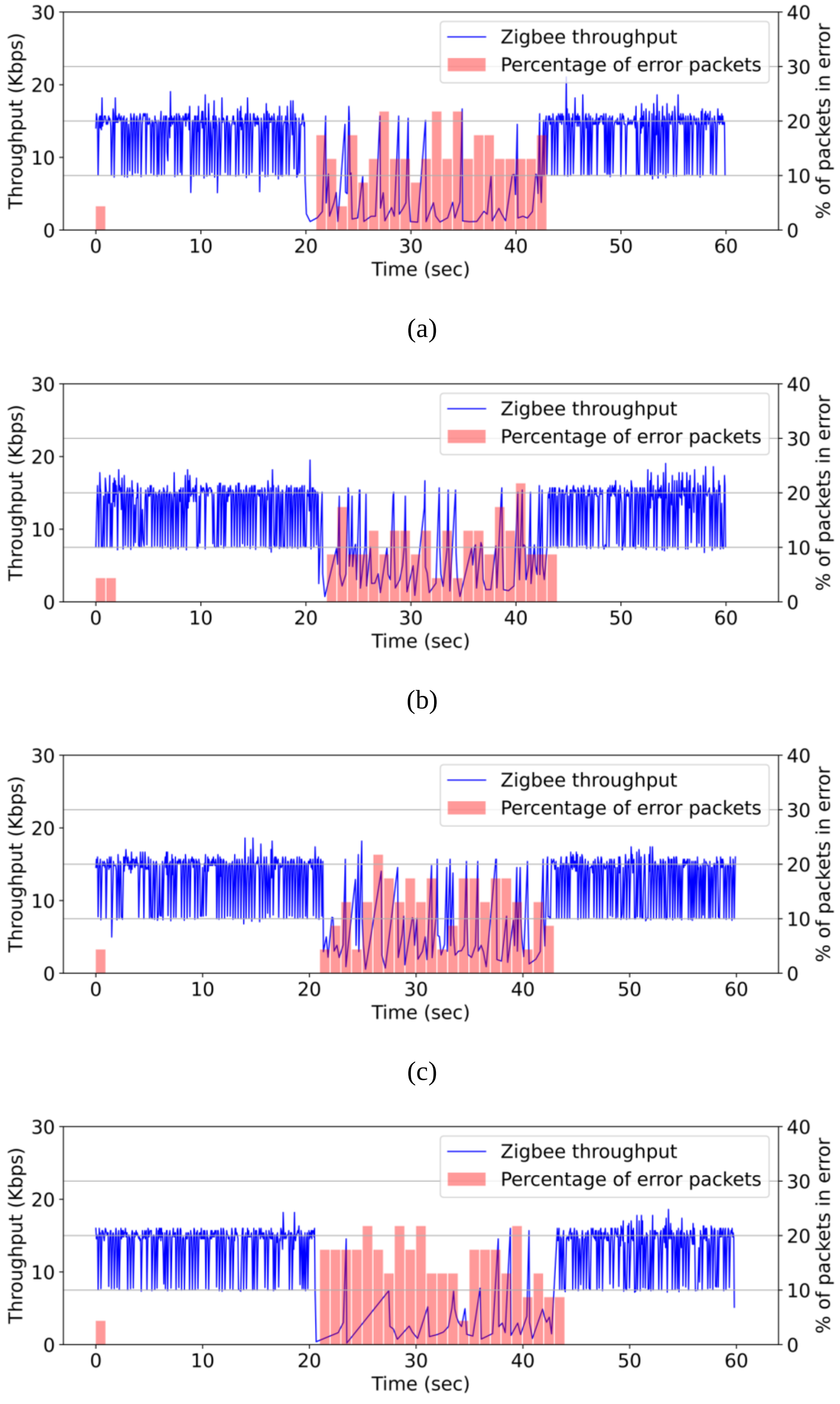
Table 3. Performance of ZigBee while distance from Wi-Fi is varied.

	Distance between Wi-Fi and ZigBee			
	4 feet	6 feet	8 feet	10 feet
ZigBee avg. throughput	5.37 Kbps	7.18 Kbps	6.86 Kbps	5.14 Kbps
ZigBee average PER	14.42 %	10.86 %	12.64 %	15.61 %

Throughput and PER of ZigBee with varying transmit power: To further analyze the performance of ZigBee in the presence of Wi-Fi, we increased the transmit power of ZigBee from −5 to 8 dBm as shown in Figure 21. If the Wi-Fi transceiver operates near ZigBee (within 10 feet), increasing the transmit power does not improve ZigBee's performance. Table 4 summarizes the average throughput between 6.10~6.15 Mbps with PER 14~15%.

Table 4. Performance of ZigBee while the transmit power is varied.

	ZigBee transmit power		
	−5 dBm	2 dBm	8 dBm
ZigBee avg. throughput	6.14 Mbps	6.10 Mbps	6.15 Mbps
ZigBee average PER	14.42%	14.82%	15.01%



(a)

(b)

(c)

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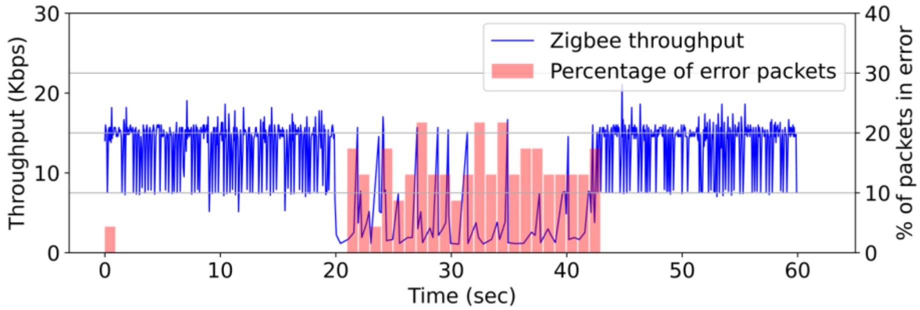
Figure 20. Throughput and PER of ZigBee while varying distance: (a) 4 feet, (b) 6 feet, (c) 8 feet, and (d) 10 feet between ZigBee and Wi-Fi devices.



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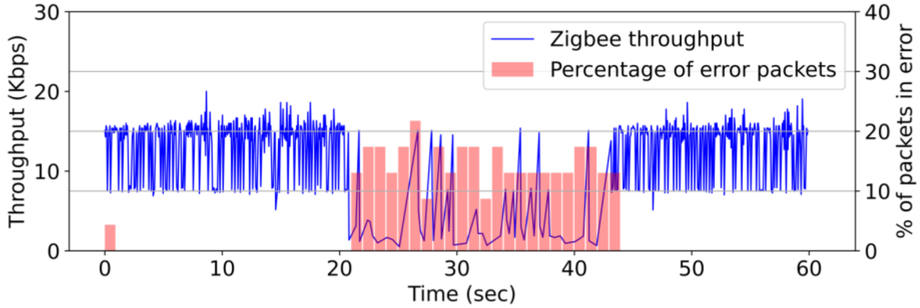

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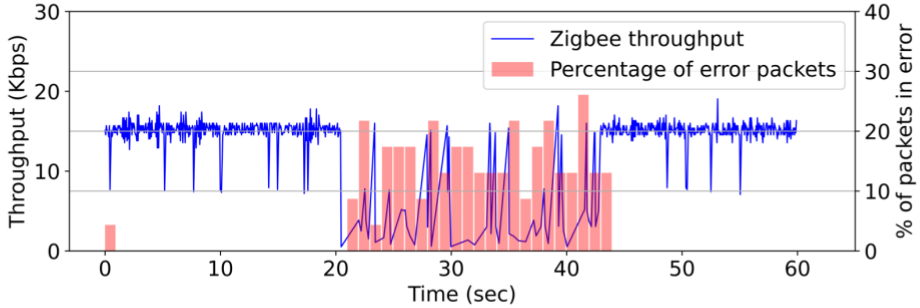


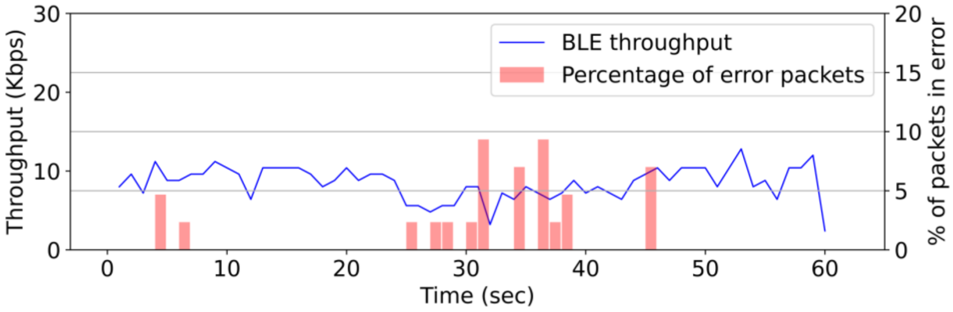
(c)

Figure 21. Throughput and PER of ZigBee while varying transmit power of ZigBee: (a) −5 dBm, (b) 2 dBm, and (c) 8 dBm.

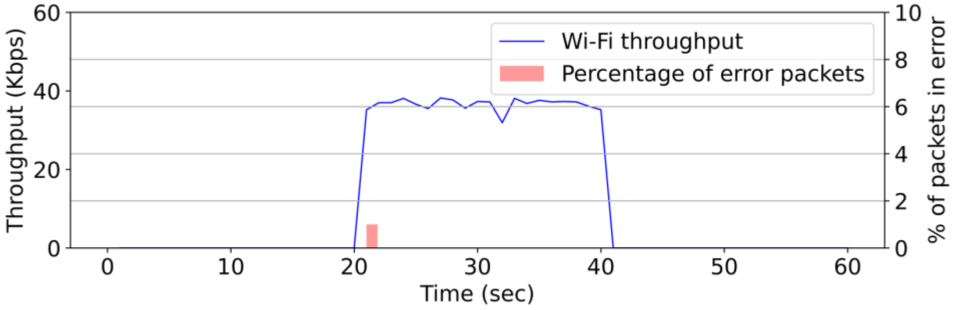
5.3 Coexistence of Wi-Fi and BLE

In order to assess the coexistence performance of Wi-Fi and BLE, we configured Wi-Fi to operate on channel 6. This channel selection aligns with the frequency range of BLE channels 11 to 20. The arrangement of the devices replicated the layout depicted in Figure 14, with the exception that BLE transceivers replaced the ZigBee nodes. While Wi-Fi occupies a bandwidth of 20 MHz, BLE is constrained to a mere 27 clean channels for transmission, excluding the three channels dedicated to advertising. The outcome is presented in Figure 22, which illustrates the impact on throughput and PER when BLE and Wi-Fi interfere. Observations reveal that the average throughput of BLE experiences a degradation, dropping from the baseline of 12.06 Kbps to 7.08 Kbps, constituting a significant decrease of 41.29%. This degradation occurs immediately upon the commencement of Wi-Fi operation within

20 to 40 seconds. Additionally, the PER of BLE fluctuates from 2 to 9%. Conversely, the Wi-Fi throughput remains consistent and robust, with a notably low PER.



(a)



(b)

Figure 22. Throughput and PER of (a) BLE and (b) Wi-Fi while coexisting.

To investigate the reason behind high PER and degradation in throughput for BLE even when AFH is operational, we extracted channel utilization percentage of BLE as depicted in Figure 23. It is observed that during the Wi-Fi interference, BLE channels 11 to 20 have zero utilization (37 to 39 are advertising channels) as expected.

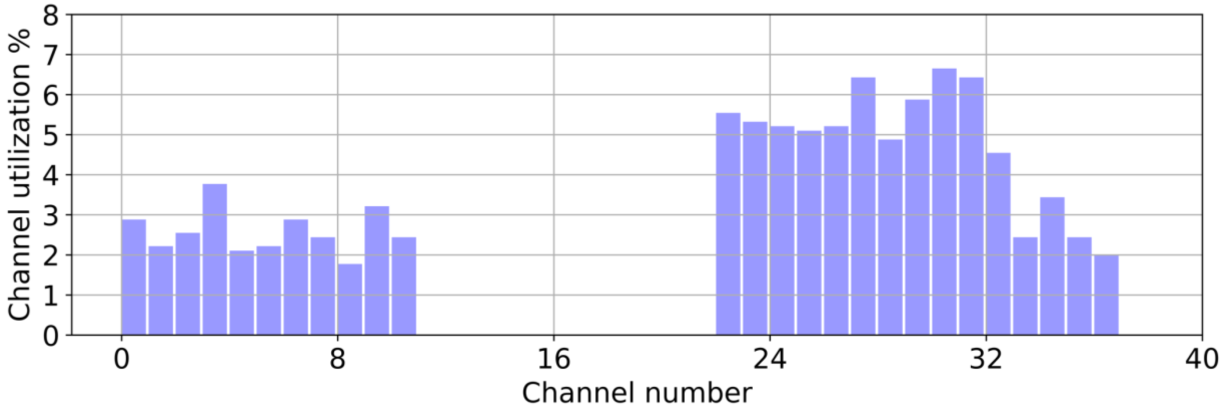


Figure 23. BLE channel utilization while Wi-Fi (channel 6) interfering.

Additionally, we made an observation using a Wi-Fi scanner application, revealing the persistence of external Wi-Fi interference from channels 1 and 11 inside the anechoic chamber as illustrated in Figure *24*. These channels coincide with BLE channels 0 to 9 and 23 to 32. Consequently, as the minimum number of channels mandated for BLE is 20, it employs the interfered channels, and experiences degraded performance.

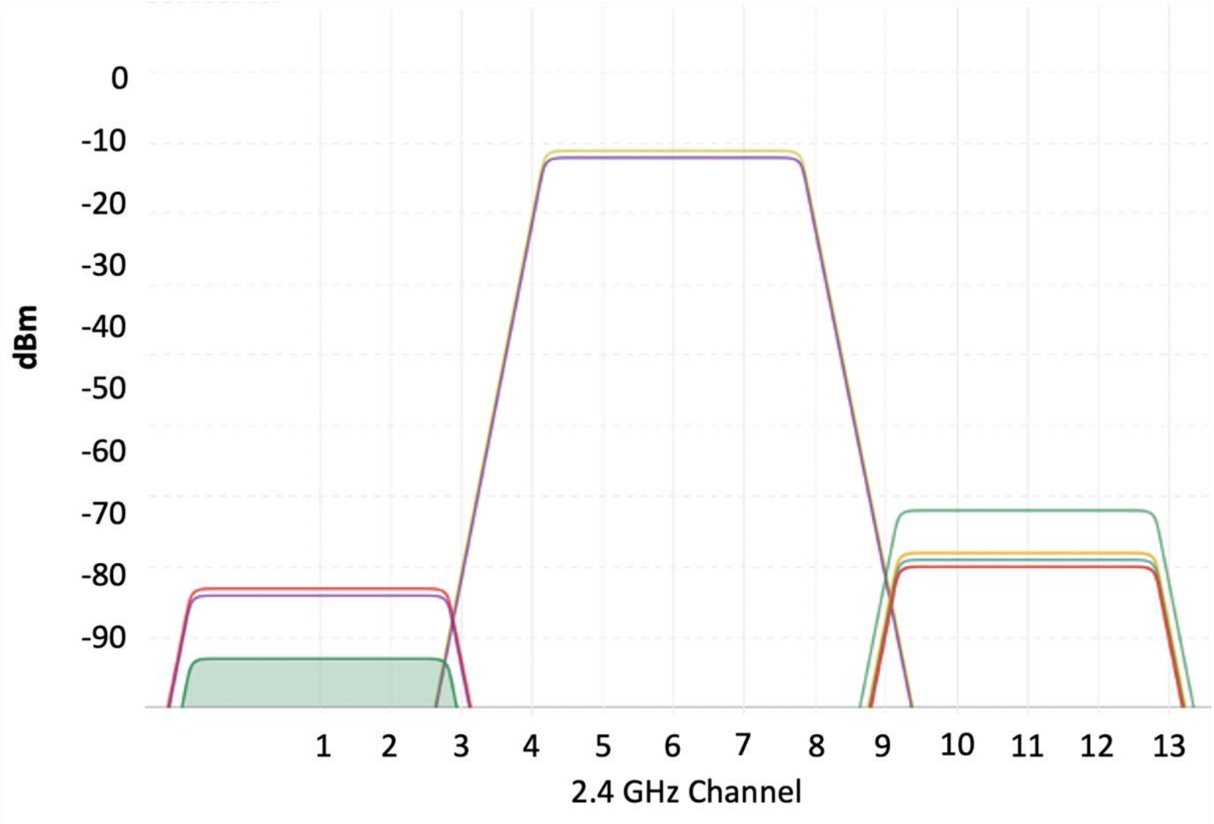
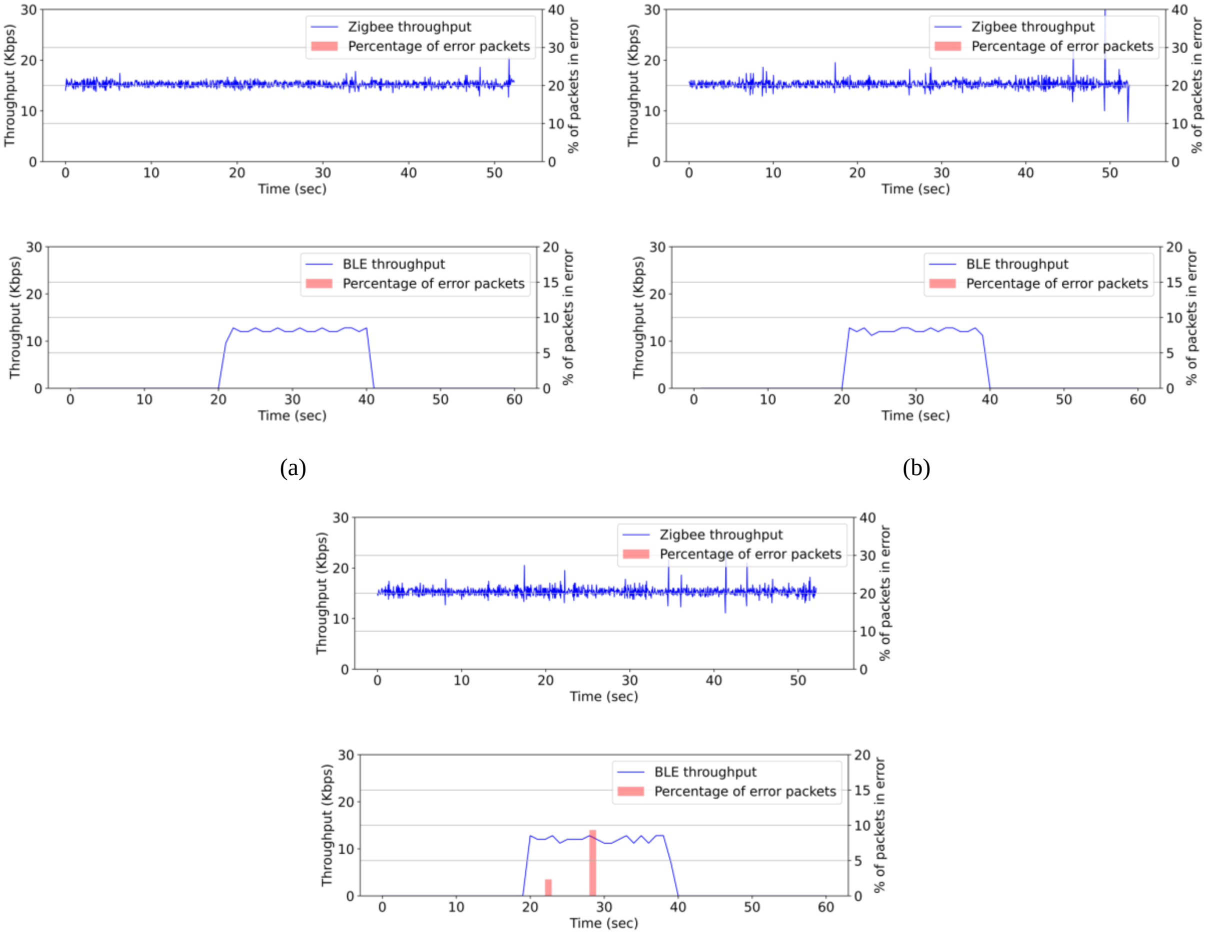


Figure 24. Wi-Fi channel scanner output.

5.4 Coexistence of ZigBee and BLE

To complete the series of three-technology tests, we assessed the mutual interference of ZigBee and BLE. Since BLE spans the whole 2.4 GHz band (total 80 MHz of bandwidth), one ZigBee channel of 2 MHz, which is 2.5% of the BLE band, is scarcely affected. In addition, with the adoption of AFH, BLE avoids using the occupied channel of ZigBee as long as the number of BLE good channels is higher than 20. Figure 25 depicts the throughput of ZigBee at different transmit powers: (a) −5 dBm, (b) 2 dBm, and (c) 8 dBm, while BLE is interfering with 8 dBm transmit power. The ZigBee was set to operate on channel 12 (which coincides with BLE channel 3). The throughput of ZigBee though has minor fluctuations and no degradation is observed when the BLE transmission was active between the 20th and 40th second. Due to the AFH, BLE throughput was also not seen to be degraded. The plot also reveals zero PER for all cases, and 8% maximum PER for a 1-second duration when ZigBee transmit power was 8 dBm.



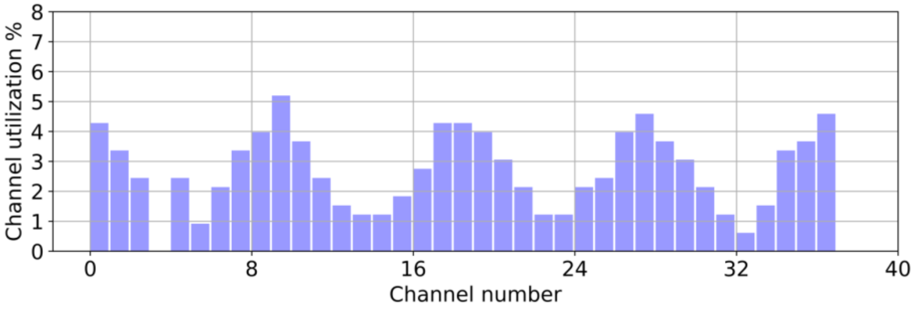
(a)

(b)

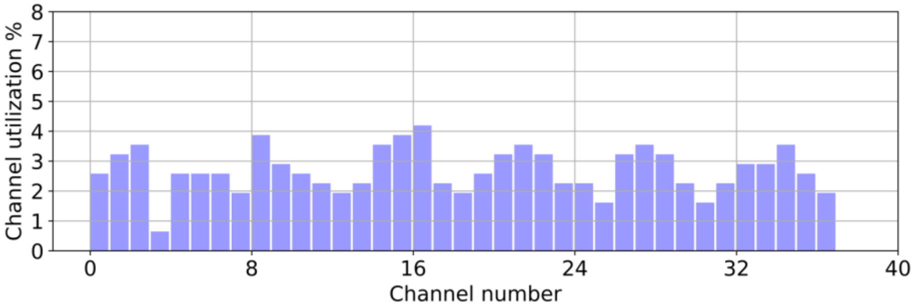
(c)

Figure 25. Zigbee Throughput and PER when BLE interfering (a) Tx power: −5 dBm, (b) Tx power: −2 dBm, and (c) Tx power: 8 dBm.

Figure 26 shows the utilization of BLE channels during the interference period. It is observed that at ZigBee transmit power of −5 dBm, BLE has zero utilization on channel 3 (no interference), and when ZigBee transmit power was increased to 2 and 8 dBm, BLE channel 3 has ~1% utilization, which is low compared to other channels. This suggests that BLE continues to avoid the operating channel of ZigBee (channel 3) as long as BLE has enough good channels for transmission. If there is any external interference (e.g., Wi-Fi as discussed in previous section), BLE is forced to use an interference channel, which causes packet error or performance degradation.



(a)



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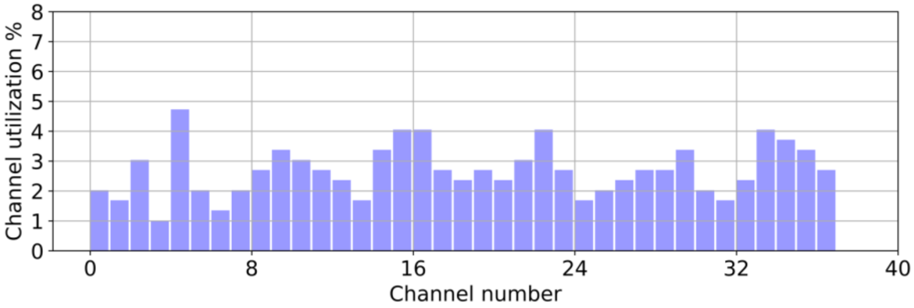

(c)

Figure 26. BLE channel utilization with ZigBee interference (a) Tx power: −5 dBm, (b) Tx power: −2 dBm, and (c) Tx power: 8 dBm.

6. DISCUSSION ON OPEN RESEARCH OPPORTUNITIES

With the intense use of wireless communication, mobile data traffic has experienced significant growth in recent years. To tackle this increasing high demand, mobile operators have adopted different solutions, one of which is using unlicensed spectrum since unlicensed bands are free from usage costs in terms of purchasing a license of operation. The extension of cellular technology into the unlicensed spectrum has commenced in the 5 GHz frequency band, an area currently utilized extensively by Wi-Fi networks (operating under IEEE 802.11 a, n, ac, and ax standards).

In our forthcoming research, we will investigate the association issue in the context where Wi-Fi and LTE-U/LTE-LAA coexist within the same channel. We will address queries such as: (1) How do the Wi-Fi client and AP associate when LTE-U/LTE-LAA base station (BS) are active with their maximum duty cycle? (2) To what extent does the presence of LTE-U/LTE-LAA impact the throughput and PER of the Wi-Fi connection? We will examine the channel access and transmission scheduling mechanism of 5G-NR-U when coexisting with Wi-Fi. Most of the research articles in this area are based on theoretical investigations due to their flexibility but miss out on realism. Though simulation models for some of the current standards exist, there is much ambiguity in many simulation parameters, making it difficult to obtain practical real-environment scenarios. For a thorough study of coexistence of different wireless technologies in real-environments, we will use software-defined radios (SDR) on the Platform for Open Wireless Data-driven Experimental Research testbed to build LTE / 5G-NR protocol stack and evaluate the performance together with Wi-Fi devices inside the anechoic chamber at University of Utah. We will extend our experiment to longer distances in both indoor and outdoor environments for a more comprehensive exploration.

Following our measurement study, we propose to develop coordinated mechanisms for minimizing interference and maximizing performance of wireless technologies that coexist in the same bands, especially for critical applications. Below, we provide details on the challenges related to coexistence of cellular technologies with Wi-Fi.

LTE-U vs. Wi-Fi: The LTE consortium made one of the first attempts to bring LTE to 5 GHz unlicensed band [17]. LTE in unlicensed spectrum (LTE-U) systems are specifically designed to operate under centralized control of network units based on non-contention MAC protocol to prevent packet collision among subscribers [18]. On the other hand, Wi-Fi users rely on CSMA/CA to reduce packet collision and use a contention-based MAC protocol to resolve packet collision through a random back-off mechanism. Consequently, the potential for Wi-Fi users to detect and identify clear channels suitable for transmission is notably constrained and a harmonious coexistence environment for both networks becomes a major challenge.

LTE-LAA vs. Wi-Fi: After the release of LTE-U, the Third Generation Partnership Project, referred as, 3GPP, consortium introduced License Assisted Access (LTE-LAA) technology. In contrast to LTE-U, LTE-LAA uses the Listen Before Talk (LBT) mechanism, where the BS listens for activity on the channel before initiating transmission. This helps prevent interference with other devices, such as Wi-Fi. However, the LAA specification maintains the LTE frame structure, which includes specific time intervals for transmitting data known as Licensed Spectrum Slot Boundary (LSSB) [19]. The waiting period in LBT might not always align perfectly with these boundaries, creating a situation where the BS may not transmit data strictly at an LSSB. The LAA specification does not provide specific guidelines for the BS’s behavior between the end of the waiting period and the next LSSB. If the BS decides to wait for the LSSB, Wi-Fi stations may occupy the channel, leading to poor LAA performance [20]. To overcome this problem, LAA uses a Reservation Signal (RS) to forbid other devices from occupying the channel [21]. The use of RS introduces additional overhead and notably reduces the throughput in Wi-Fi networks.

5G-NR-U vs. Wi-Fi: The successor of LTE-LAA is the 5G New Radio-Unlicensed (NR-U). NR-U partially solves the problem mentioned above through its scalable numerology (i.e., flexible Orthogonal Frequency Division Multiplexing symbol lengths, and scalable subcarrier spacing) [22]. This means that the granularity of the channel access scheduling can be varied, and with reduced overhead. Thus, RS is still needed. Although RS improves overall performance, it has a few disadvantages. RS does not carry any data, and RS may lead to asymmetric collision when Wi-Fi uses RTS/CTS. In the presence of such a collision, if the RS is longer than an RTS frame, the Wi-Fi transmitter that has sent the RTS detects the collision and increases its contention window, degrading its performance.

7. SUMMARY AND PATH FORWARD

This report extensively examines the coexistence of three wireless technologies, Wi-Fi, ZigBee, and BLE, operating within the 2.4 GHz ISM band. The study thoroughly investigates all potential interactions, encompassing variables such as transmission power, distances, data rates, and the utilization of co-channel or adjacent channels. In summary, the evaluation of performance metrics (specifically throughput and PER) for each of these technologies indicates that the operation of both ZigBee and BLE is noticeably compromised when coexisting with Wi-Fi within the same frequency spectrum. ZigBee registered a high throughput drop of 65.5% and PER between 4.3 and 27.1%, while BLE showed a throughput drop of 41.29% and PER between 2 and 9% in the presence of Wi-Fi. Though effective in an interference-free environment, the FHSS or AFH technique BLE uses is inefficient when multiple Wi-Fi channels coexist. As seen in our experiment, the performance of BLE was not impaired by ZigBee unless external interference from Wi-Fi existed, which is typical in home, office, or industrial spaces. Furthermore, when these transceivers operate on short distances, within 2 to 10 feet, there is a slight variation in performance. In addition, the presence of ZigBee and BLE has a negligible impact on the performance of Wi-Fi. Our intended future work will be to expand on the obtained results and conduct more test scenarios under different environments and provide a solution for the coexistence of all three technologies in the same vicinity.

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