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Vivek Agarwal, Imtiaz Nasim, Amitabh Mishra

Idaho National Laboratory

Syed Ayaz Mahmud, Sneha K. Kasera, Mingyue Ji

University of Utah





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Co-existence of Heterogeneous Wireless Networks in 2.4 GHz and 5 GHz Spectrum

SYED AYAZ MAHMUD, SNEHA K. KASERA, MINGYUE JI UNIVERSITY OF UTAH

VIVEK AGARWAL, IMTIAZ NASIM, AMITABH MISHRA IDAHO NATIONAL LAB

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Idaho National Laboratory Idaho Falls, Idaho 83415

http://www.inl.gov

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ABSTRACT

To achieve automation across different applications, next-generation nuclear power plants are beginning to leverage advanced wireless technologies. The deployment of these wireless technologies is a salient need for modernizing the existing nuclear plants. A "one-size-fits-all" solution cannot be adopted since wireless technologies are selected according to specific application needs, quality of service, and economic restrictions. To balance the trade-off between technical and economic requirements, a multi-band heterogeneous wireless network architecture is needed. However, the co-existence of these multi-band wireless technologies poses numerous challenges. Due to factors including dissimilarity in channel access mechanisms, transmit power levels, distance between nodes, and interference among co-existing solutions, performance can be seriously degraded, leading to very low signal-to-noise ratio.

This report builds on our previous study, "Experimental Evaluation of Interference in 2.4 GHz Wireless Network," which analyzed the performance of wireless communication technologies such as Wi-Fi, Zigbee, and Bluetooth co-existing within the 2.4 GHz band. We now extend this study by developing a new upper-layer approach that uses rate control to create temporary opportunities for signal transmission while using the shared band. Unlike existing work in the literature, our approach does not require modifications at the link or physical layers of the network. Further, we extend our work to explore the co-existence of Wi-Fi and fifth-generation (5G) in the 5 GHz unlicensed spectrum, using both experiments and simulations. This report provides a technical foundation for understanding the operational designs of Wi-Fi and 5G in the unlicensed band and evaluates their performance when these networks co-exist. Our findings show that the performance of 5G can be improved by controlling the Wi-Fi's packet rate at the upper layer.

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ACRONYMS

AP access point

ACK acknowledgement

CSMA/CA carrier sensed multiple access with collision avoidance

CAPC channel access priority class

DIFS DCF inter frame space

DCF distributed coordination function

ED energy detection
5G fifth generation
FR frequency ranges
Gbps gigabits per second

ISM industrial, scientific, and medical

IoT Internet of Things

LTE-LAA licensed assisted access

LBT listen before talk

LTE-U long-term evolution-unlicensed

Mbps megabits per second NPP nuclear power plant

gNB next-generation node B

OAI open-air interface
PER packet error rate

POWDER Platform for Open Wireless Data-driven Experimental Research

PD preamble detection

QAM quadrature amplitude modulation

QoS quality of service
RF radio frequency
RS reservation signal

SINR Signal to Interference and Noise Ratio

SNR Signal to Noise Ratio

SSB synchronization signal block

TG Task Group

3GPP third-generation partnership project

TBF token bucket filter

TCP Transmission Control Protocol

USB universal serial bus

UNII Unlicensed National Information Infrastructure

UE user equipment

XCTU Xbee configuration and test utility

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1. INTRODUCTION

The existing nuclear industry and advanced reactor technologies are exploring multiple wireless solutions to achieve real-time data transmission for various applications. This exploration will benefit from utilizing wireless connectivity provided by various wireless communication technologies such as Wi-Fi, Zigbee, fifth generation (5G), and beyond. Using wireless connectivity, plant operators can send and receive data from sensors mounted on components to a monitoring location. Generally, in a nuclear power plant (NPP) setup, comprehensive radio frequency (RF) coverage planning is performed prior to the deployment of wireless systems. However, to meet the demand, a multi-band heterogeneous architecture is needed. Such a multi-band wireless network is required to streamline data from different NPP applications, automate control, or optimize maintenance, irrespective of reactor technology [1]. In this report, we research three types of wireless technology, their co-existence, and strategies to optimize their performance to ensure improved coverage and connectivity.

Considering the diversity of wireless technologies available today, developing a 'one-size-fits-all' solution that would enable industrial automation is not feasible [2]. Different types of data are transmitted over a wireless network with varying quality of service (QoS), latency, and bandwidth requirements [3]. Hence, co-existing heterogeneous wireless networks are highly desirable for satisfying industrial automation and communication needs. When deploying multiple wireless technologies, signal degradation and interference between the signals should be considered. This requires identifying the location for the transmitters, the distance between the nodes, and their transmit power to improve coverage and capacity.

The 2.4 GHz industrial, scientific, and medical (ISM) band has gained immense popularity due to its global availability and lack of licensing requirements. As a result, many wireless technologies, such as Wi-Fi and Zigbee, have shown interest within this limited spectrum. Similarly, the demand for high throughput and low latency among mobile internet users continuous to increase each year [4]. With the advent of bandwidth-hungry applications such as video streaming, augmented reality, etc., it is challenging for mobile network operators to tackle such demand in the available licensed spectrum. The recent development of third-generation partnership projects (3GPP) has proposed extending 5G operations in the unlicensed spectrum in 5 GHz bands, [5] an area also utilized by Wi-Fi (operating under 802.11 a, n, ac, and ax standards). The growing number of devices in the unlicensed spectrum has raised concerns about high interference and congestion, requiring the need for innovative solutions to ensure harmonious co-existence and optimal performance of these wireless technologies.

This report provides the technical basis for understanding wireless protocols, specifically Zigbee, Wi-Fi, and 5G when they co-exist. More specifically, we evaluate the networks' performance while they coexist in 2.4 GHz band (Zigbee and Wi-Fi) and 5 GHz band (Wi-Fi and 5G) for simultaneous operation within a close vicinity. We also develop a rate control mechanism that creates an opportunity to utilize the available temporal channels to improve the overall performance of the network.

2. WIRELESS PROTOCOLS OVERVIEW

2.1. Wi-Fi

The Institute of Electrical and Electronic Engineers (IEEE) 802.11 family of standards defines Wi-Fi, which supports high-speed internet connectivity. Wi-Fi includes various versions, such as 802.11 (a, b, g,

n, ac) and 802.11ax (Wi-Fi 6). It can operate in multiple bands, including 2.4 GHz, 5 GHz, and 6 GHz frequency bands, providing data transfer rates ranging from a few megabits per second (Mbps) to gigabits per second (Gbps).

2.1.1. Wi-Fi Channel Allocation

Within the 2.4 GHz ISM band, a total bandwidth of 100 MHz is available, divided into 11 usable channels (numbered 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 in Figure 1. Consequently, to minimize mutual interference and ensure optimal performance, Wi-Fi networks operating in close vicinity must operate using non-overlapping channels (i.e., channel 1, 6, or 11 or channels whose number differs by 5). IEEE 802.11 (n and onwards) allows for the optional use of a 40 MHz channel by bonding two adjacent channels.

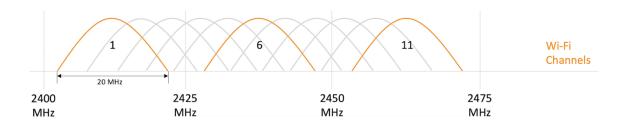


Figure 1. Channel allocation in Wi-Fi 2.4 GHz ISM band.

Figure 2 shows the channel allocation of the 5 GHz spectrum, ranging from 5170 to 5835 MHz. The spectrum is further divided into four sub-bands known as unlicensed national information infrastructure (UNII-1, 2, 2e, and 3), which have specific usage requirements. For example, UNII-1 (5150 to 5250) MHz and UNII-3 (5745 to 5825) MHz bands are permitted to be used both indoors and outdoors with a maximum transmit power of 1000 mW. The UNII-2 (5260 to 5725) MHz bands are used by weather radar systems [6]. Therefore, access points (APs) operating on UNII-2 channels are required to use dynamic frequency selection to avoid interfering with the weather radar signal. The UNII band is further sub-divided into smaller channels of 20, 40, 80, and 160 MHz wide. These channels can be bonded together to create wider band channels. For example, a 40 MHz channel is composed of two contiguous 20 MHz channels, and 160 MHz is composed of two 80 MHz contiguous channels, respectively. Each of the channels are numbered as depicted in Figure 2. Due to the wider spectrum in 5 GHz, there are 25 non-overlapping channels available, each 20 MHz wide. As a result, the likelihood of co-channel interference is reduced when compared to the 2.4 GHz Wi-Fi spectrum.

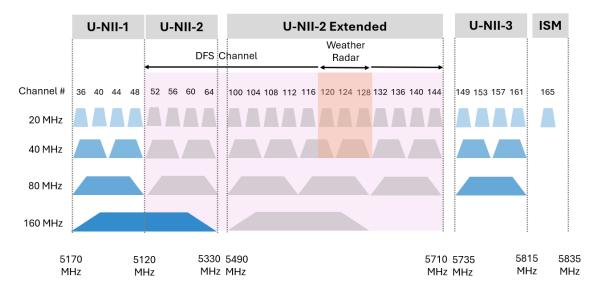


Figure 2. Channel allocation in Wi-Fi 5 GHz band.

2.1.2. Channel Access Mechanism

Wi-Fi technology is a contention-based mechanism that uses opportunistic transmission using distributed coordination function (DCF) based on carrier sensed multiple access with collision avoidance (CSMA/CA). DCF allows multiple independent stations to interact without central control [7].

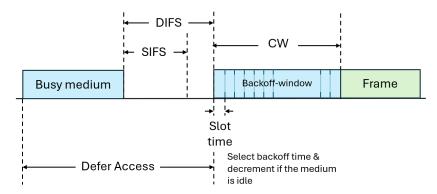


Figure 3. Wi-Fi channel access mechanism.

When a packet is ready to be transmitted, each node checks the availability of the wireless channel (i.e., idle or busy). If the channel is busy (due to another node transmitting), stations defer access. If the channel is idle, the transmitting station checks whether the channel remains idle for a DCF inter frame space (DIFS) duration—the minimum idle time before transmitting a data frame. If the channel is still found idle, the back off procedure is initialized. The back off algorithm selects a random number of time slots (each long) drawn from a uniform distribution over the interval, where is known as the minimum contention window. The counter is decremented each time the channel is sensed idle. If the channel is sensed busy at any time during a back off slot, then the back off procedure is paused. The procedure resumes only after the channel is sensed idle again for a DIFS period. Transmission commences when the back off timer reaches 0. The flowgraph of the procedure is shown in Figure 4.

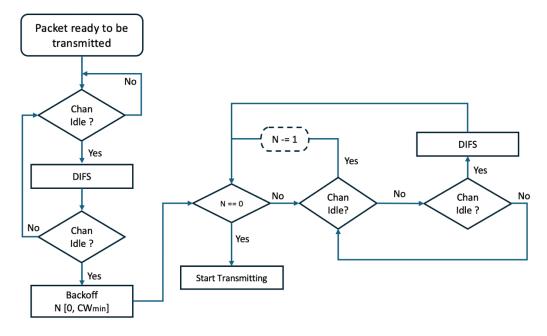


Figure 4. Wi-Fi: CSMA/CA flow diagram.

After the transmission is completed, the transmitter expects an acknowledgement (ACK) from the receiver that confirms the frame is successfully received. An ACK might not always be received by the transmitter. This can happen due to interference from a nearby node transmitting on the same channel, causing signal disruption at the receiver. As a result, the data packets become corrupted, preventing the receiver from decoding correctly. When the transmitter does not receive the ACK within a specified period, it re-transmits.

2.1.3. Channel Status Detection

There are two existing mechanisms to check whether the channel is idle or busy: (1) energy detection (ED) and (2) preamble detection (PD) [8]. In ED, devices measure the energy of the received signal locally and determine the channel availability. If the measured energy is greater than a predetermined threshold, the channel is declared busy. Otherwise, the channel is considered idle, and devices can begin to compete for the channel. PD, on the other hand, requires detection of a known preamble signal. Upon reception of the preamble, its energy is compared against the PD threshold. The channel is declared busy if the energy is greater than the PD threshold, and idle otherwise.

2.2. Zigbee

Zigbee is a low-power, short-range wireless sensor network protocol offering data rates up to 250 Kbps. IEEE 802.15.4 standard defines the physical layer (PHY) and medium access control (MAC) layer specifications, while Zigbee is built on top of the 802.15.4 standard and defines the networking and application layer specification, making it a complete end-to-end solution for internet of things (IoT) networks [9]. Though the terms Zigbee and IEEE 802.15.4 are used interchangeably, in this report we consider only the PHY and MAC layer of the Zigbee standard.

2.2.1. Zigbee Channel Allocation and Medium Access

Zigbee operates in the 2.4 GHz, 900 MHz, and 868 MHz frequency bands (2.4 GHz being the most common). Zigbee uses mesh networking, enabling devices to form self-organizing networks. This makes it ideal for intelligent home or industrial automation, monitoring, and sensor networks. The 2.4 GHz band is divided into 16 non-overlapping channels (numbered from 11 to 26), each 2 MHz wide. Therefore, 16 Zigbee devices can operate simultaneously in close vicinity, as depicted in Figure 5.



Figure 5. Zigbee channel allocation in 2.4 GHz ISM band.

Similar to Wi-Fi, Zigbee uses CSMA/CA for channel access. It uses ED functionality to determine the activity of other systems in the channel. If there is a signal present in the operating band whose energy is higher than the threshold, the Zigbee transmitter backs off, retries, and transmits by following the Zigbee CSMA/CA protocol.

2.3. 5G

The increase in multimedia applications requiring high bandwidth aggregated with a huge number of user devices has led to exponential growth in mobile data traffic. To cater to this increasing demand for data, 3GPP has developed standards for 5G radio interface referred to as new radio (NR). 5G-NR supports wireless connectivity for a wide range of applications that require a high data rate and low latency.

5G-NR operates across various frequency ranges that are mainly divided into two categories: FR1 (410 to 7125) MHz, known as sub 6 GHz band, and FR2 (24.25 to 52.6) GHz, known as millimeter wave band. The FR1 is suitable for wide area coverage, often used in urban, sub-urban, and rural deployments. Due to the lower frequencies, it has better propagation characteristics and can penetrate obstacles more effectively. The FR2 is ideal for high capacity and high-speed data transmission over short distances, commonly used in densely-populated areas (e.g., stadiums, hotspots). Due to higher frequencies, it has shorter range and is more susceptible to obstacles and atmospheric absorption.

Due to the scarcity of licensed spectrum, the unlicensed spectrum has gained significant attention in recent years due to being free to use. 3GPP in its release 16 [5] introduced significant enhancement to 5G-NR, including the use of unlicensed spectrum, known as 5G-NR-U (specifically in the 5 GHz band), which is already being used by Wi-Fi networks worldwide. Therefore, ensuring the efficient and fair coexistence of Wi-Fi and 5G-NR-U is of great importance.

2.3.1. 5G-NR-U Channel Access Mechanism

Unlike Wi-Fi that uses CSMA/CA for channel access, 5G-NR-U performs the *listen before talk* (LBT) procedure before each transmission, as per 3GPP specification [10]. When a packet is ready to be transmitted, the node checks whether the channel is idle during the *prioritization period*. The prioritization period consists of a fixed defer duration of and a fixed number of slots each. The value of depends on channel access priority class (CAPC) from 3GPP specifications, as given in Table 1.

Table 1. 3GPP channel access priority class.

Priority class	m (slot)	CW_{min}	CW_{max}	MCOT (ms)
1	1	3	7	2
2	1	7	15	3
3	3	15	63	8 or 10
4	7	15	1023	8 or 10

If the channel is found idle after the prioritization period, it starts the back off procedure, or else the node stops the LBT procedure and waits until the channel is sensed idle again in the prioritization period.

To start the back off procedure, a random number is selected between, where is the minimum contention window that determines the number of slots to back off. The transmitting node then waits for the number of slots, each long. For each idle slot, the value of is decremented by 1. When the channel is found busy, the process of decrementing is paused, and resumed only after the channel is sensed idle again after the prioritization period. When becomes zero, the node is permitted to transmit. The transmission time must not exceed the maximum channel occupancy time, as per the CAPC table.

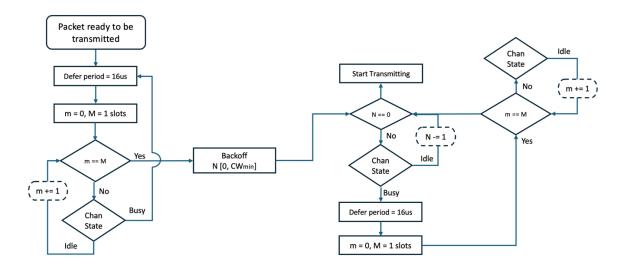


Figure 6. 5G-NR-U listen before talk (LBT) flowgraph.

After a successful transmission, the receiver sends an ACK back to the transmitting node. On the other hand, if a collision occurs or the ACK is not received before the timeout period, the transmitting node retransmits after exponentially increasing the contention window size (but keeping less than or equal to , as per the CAPC table. The flowgraph for LBT is depicted in Figure 6.

In contrast to Wi-Fi, in which channel access is random, 5G-NR-U transmission is scheduled. This means that the 5G base station tower, known as *next generation node B* (gNB), can only start transmission at the beginning of a synchronization slot [11]. The LBT procedure as a random-access method may end at any point in time and not in the beginning of a synchronization 5G-NR-U slot. This can lead to the creation of significant gaps between the end of the LBT procedure and the start of the transmission in which another node can start transmitting. An example is shown in Figure 7.

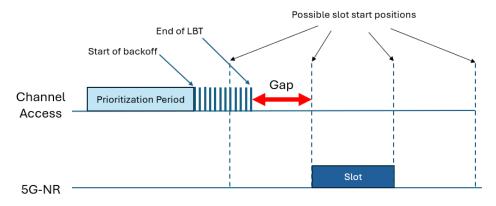


Figure 7. 5G-NR-U Gap between LBT and slot boundary.

Note that during the downlink transmission, the gNB performs LBT. Once gNB starts communicating with the user equipment (UE), it schedules uplink resources on fixed timeslots for uplink transmissions by UE.

3. CO-EXISTENCE CHALLENGES

The advancement of wireless communication technologies has led to the shared use of unlicensed spectrum bands by various standards. While this shared use aims to maximize spectrum efficiency and support increasing demand for wireless connectivity, it also introduces several co-existence challenges. Addressing these challenges is crucial for ensuring harmonious operation and performance of multiple technologies. Some of the main challenges of co-existence for these networks are as follows:

- Channel sensing mechanism: Different wireless technologies adopt different channel sensing techniques, such as energy detection and preamble detection, to detect the availability of the channel. For instance, most commercial Wi-Fi APs sense the channel using preamble-based detection, while Zigbee and 5G-NR-U use energy-based detection. This difference can lead to inefficient spectrum use. During the Wi-Fi active period, Zigbee or 5G-NR-U devices must back off until the channel is idle again, resulting in fewer transmitted packets and degraded performance in terms of data rate for both Zigbee and 5G-NR-U.
- Transmit power level: Wi-Fi devices transmit signal with a power level between 20 to 30 dBm, which is approximately 30 times higher than Zigbee's power level of 0 dBm. This significant difference in transmit power implies that Wi-Fi signals can easily overpower Zigbee signals, causing interference and reducing the effective throughput of the Zigbee network. 5G-NR-U gNB, on the other hand, have a higher transmit power (36 dBm maximum) compared to Wi-Fi. This higher power can lead to stronger signals that may cause the Wi-Fi network to back off while using energy-based detection.
- Distance between transceivers: The distance between transmitting nodes plays a crucial role in co-existence. Wi-Fi and 5G-NR-U devices often have varying ranges, with Wi-Fi generally covering shorter distances, especially in indoor environments, and 5G-NR-U gNB potentially covering larger areas. The varying coverage area can lead to imbalances in spectrum usage, where one technology might dominate over the other, particularly in edge scenarios where the coverage areas overlap. This can result in degraded performance at the 5G UE devices when receiving heavily attenuated signals from gNB, due to interference from nearby Wi-Fi transmitters that are transmitting at a relatively higher power. Although 5G may transmit at 36 dBm, the greater distance between the UE and the gNB can cause significant signal attenuation, meaning the Wi-Fi transmitters, typically operating at 20-30 dBm over shorter distances, can be more disruptive to the UE.

- 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. For instance, Wi-Fi channel 1 overlaps with four Zigbee channels (11, 12, 13, and 14). Other Zigbee channels might also face interference at Wi-Fi hotspots where the entire 2.4 GHz spectrum is utilized by multiple WLAN APs configured to use orthogonal channels. Simultaneous transmissions from multiple devices, potentially using different technologies on overlapping channels, can result in interference and degradation in performance.
- Quality of service (QoS): QoS mechanisms are used to prioritize different types of traffic based on their requirements, such as latency, jitter, and bandwidth. For instance, Wi-Fi might prioritize real-time traffic like video calls, while Zigbee prioritizes low power sensor data.
 5G-NR, on the other hand, might have requirements for ultra-low-latency communication. The co-existence of these technologies can create challenges in maintaining QoS, as interference and contention for the overlapping channels can degrade QoS.

4. LITERATURE REVIEW

The co-existence of multiple wireless technologies in the 2.4 and 5 GHz unlicensed band has been extensively researched and investigated due to the widespread adoption of Wi-Fi, Zigbee, and the recent developments in 5G-NR-U. Numerous theoretical and experimental studies have been performed to address these challenges. In this chapter, we present an overview of the existing literature and research efforts on the co-existence of these wireless technologies.

4.1. Wi-Fi and 5G-NR-U

Before we highlight existing work on the co-existence of 5G-NR-U and Wi-Fi, we review the work addressing Wi-Fi co-existence with long-term evolution-unlicensed (LTE-U) and licensed assisted access (LTE-LAA). Huang et al. presented several mechanisms to improve LTE-U and Wi-Fi co-existence [12]. These mechanisms utilize the time, frequency, or power at the LTE-U system for enhanced co-existence. For instance, in the time domain, LTE-U uses carrier sense adaptive transmission that periodically turns off the LTE transmission to allow Wi-Fi adequate access time. With power control, the goal is to adjust the output power of LTE for the desired trade-off between LTE throughput and opportunistic Wi-Fi transmission.

In contrast to LTE-U, LBT is deployed in LTE-LAA. With LBT, two transmitting gNB, both using LBT guarantees fairer co-existence. In carrier sense adaptive transmission, LTE-U is more dominant than Wi-Fi due to the exponential back off in CSMA/CA. Therefore, LBT is adopted as the standard for spectrum sharing in 5G-NR-U.

However, 5G-NR-U uses scheduled and synchronous radio access technology, where transmissions are expected to begin at fixed slot boundaries. LBT is an asynchronous channel access mechanism, and the end of an LBT procedure may not coincide with a slot boundary (as discussed in chapter 2). Zajac et al. conducted a performance analysis by simulating two types of solutions to obtain this alignment [11], gap-based, or reservation signal (RS) based access. The gap-based approach adds an extra period of no activity before the LBT back off procedure to make sure the number of back off slots align with the slot boundary. The RS-based access transmits energy into the medium after the back off procedure and before the slot boundary to block other nodes from accessing the channel and reserving the idle time. The simulation results show that RS-based access allows for a fairer co-existence between base stations, but wastes more energy and radio resources. The gap-based access results in a higher spectral efficiency, but with a higher collision probability.

Now, when 5G-NR-U uses LBT and Wi-Fi uses CSMA/CA, given the differences between LBT and CSMA/CA, the fairness between the 5G-NR-U and Wi-Fi is not guaranteed. Hirzallah et al.'s evaluation [13] indicates that under heavy traffic, 5G-NR-U often achieves higher throughput than Wi-Fi. The loss

of control and management frames of Wi-Fi due to collisions with NR-U transmission leads to degraded Wi-Fi performance. Therefore, the tuning of both LBT and CSMA/CA is important for a fairer coexistence.

Luo et al. [14] evaluate different 5G-NR-U parameters under the 3GPP fairness constraints. They note that Wi-Fi networks usually have fixed channel access parameters while 5G-NR-U is starved, as its parameters are significantly larger than those of Wi-Fi, reducing the throughput of the 5G-NR-U network. They suggest that changes for fair co-existence must be deployed at the 5G-NR-U nodes (e.g., tuning back off window size).

4.2. Wi-Fi and Zigbee

Numerous studies have examined the performance of networks where Wi-Fi and Zigbee coexist, and the findings consistently show that Wi-Fi networks often cause significant performance degradation in the Zigbee's network. This conclusion is also supported in our previous report [15]. Some approaches employ physical layer solutions to mitigate interference. For instance, BuzzBuzz [16] introduces a new Zigbee packet format that incorporates header and payload redundancy. This format uses multiple headers, providing Zigbee nodes with several opportunities to detect incoming packets. Additionally, error-correcting codes are employed to help decode corrupted payloads. WISE [17] proposes an approach that aims to enhance co-existence in the temporal domain. WISE harnesses the white spaces between Wi-Fi transmissions, modeled as a Pareto distribution, and opportunistically schedules Zigbee traffic therein.

Several existing works that focus on the co-existence protocol in the MAC layer can be divided into two categories: coordinated and uncoordinated. The coordinated mechanisms achieve interference management through exchanging coordinated information among other devices, such that the devices can make appropriate decisions to avoid interference. Zhang et al. present CBT [18] that allows a separate Zigbee node to schedule a busy tone concurrently with the desired transmission, thereby improving the visibility of Zigbee devices to Wi-Fi. GapSense [19] prepends a customized preamble containing pulses to each packet, and the gaps between them are used to convey coordination information the neighbor devices can act upon. On the other hand, uncoordinated mechanisms let a device identify the heterogeneous signal type before making appropriate channel access decisions. The signal identification can be achieved through utilizing some physical layer features (e.g., received signal strength indicator, interference pattern, and link quality indicator). TIIM [20] decides whether a communication will be successful under interference through a machine learning classifier based on both received signal strength indicator and link quality indicator, and then applies the best co-existence strategy to improve performance, such as forward error correction and channel switching. G-Bee [21] lets a Zigbee device first identify the Wi-Fi channel before transmitting its own data packets on the guard band of the Wi-Fi channel to avoid interference.

Unlike the previous solutions, we propose preventing interference by using an upper-layer rate control mechanism. This mechanism employs traffic shaping and rate control algorithms at the network layer to regulate the rate at which packets are transferred to the data link layer. This method effectively creates temporal gaps, providing opportunities within the time domain for co-existing networks (such as Zigbee) to utilize. Additionally, our approach introduces no extra complexity to the physical or MAC layers, thus avoiding additional overhead.

5. PREVENTION OF INTERFERENCE USING UPPER-LAYER COORDINATION

In this chapter, we propose a dynamic interference prevention technique for heterogeneous wireless networks using upper-layer coordination and rate control. This method does not require any change in the physical or MAC layer of the protocol. Therefore, it is deployable with existing hardware.

5.1. Wi-Fi Data Rate vs. Packet Rate

The physical *data rate* of Wi-Fi packets is influenced by the modulation scheme. Higher-order modulation, including quadrature amplitude modulation (QAM), allows more bits per symbol (e.g., QAM-16 encodes 4 bits per symbol, while QAM-64 encodes 6 bits per symbol). However, higher-order modulation requires a "good" channel with a stronger and more stable signal. A higher data rate is always desirable as that reduces transmission latency, although shorter transmission times minimize collision.

The *packet rate*, on the other hand, is the number of data packets transmitted per unit of time. It represents the speed at which the packets are sent over the network and is a key factor in network performance. A higher packet rate can improve data transfer efficiency, but may also lead to wireless network contention. Unlike the physical data rate, which is dynamically adjusted by the system (based on signal to noise ratio and the modulation scheme), packet rate is typically controlled at the transport layer (e.g., the transmission control protocol layer)). However, the transport layer depends on loss indicators to adjust its rate. In the absence of loss indicators, the transport layer is unable to suitably perform this function. We also note that not all transport layers (e.g., user datagram protocol) support packet rate control. In our work, we propose preventing interference between heterogeneous wireless networks by controlling the packet rate at the network layer and not depending on transport layer functions or the Wi-Fi physical data rate control. We note that our network layer rate control applies only to the wireless link. Any transport layer rate control works end-to-end.

5.2. Token Bucket Filter

To control the packet rate at the network layer, we use the token bucket filter (TBF), which is a network traffic shaping and rate-limiting algorithm. TBF is often used in network devices like routers and switches to manage the flow of data packets to ensure a smoother transmission rate, avoid congestion, and adhere to network policies [22]. TBF is characterized by two parameters: token rate, the rate at which the tokens are added into the bucket, and bucket size, the maximum number of tokens the bucket can hold. Each data packet coming from the transport layer requires a token to be sent over the network. If the bucket has a token, the packet is sent, and the corresponding token is removed from the bucket. If there are no tokens, the packet is either queued until tokens are available or dropped, depending on the implementation. If tokens are not used immediately, they accumulate in the bucket up to its maximum capacity, allowing for bursty traffic. Once the bucket is full, any additional tokens are discarded until some tokens are consumed. By controlling the rate at which the tokens are added and the maximum bucket capacity, the algorithm regulates the average packet rate and allows for short-term bursts. Figure 8 shows a flow diagram of TBF.

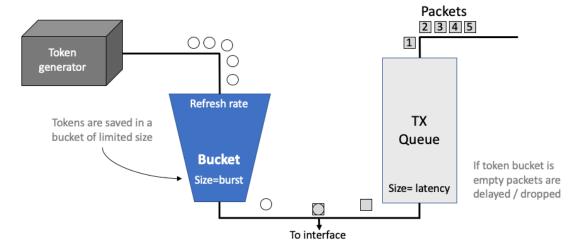


Figure 8. Flowgraph of token bucket filter.

5.3. Wi-Fi White Space

In wireless communication, white space refers to the unused or idle portions of the radio frequency spectrum. These gaps occur between active transmissions and can be utilized by other devices in the network using the same band. Huang et al. [17] present a channel utilization trace captured in a real-world Wi-Fi network comprised of 2 APs and 18 active users, revealing that the wireless channel remains idle for a significant portion of time. Even with associated Wi-Fi traffic surges, the channel is idle more than 60% of the time. Generally, this idle period is random and does not follow any specific pattern. Therefore, injecting packets from another wireless network such as Zigbee into these temporal white spaces is challenging.

To reduce interference in co-existing networks, we propose a strategy that controls packet rate using TBF. This technique ensures compliance with predetermined packet rate thresholds. By managing the packet flow to the data link layer and subsequently to the physical layer for transmission, our approach strategically introduces temporal white spaces. These spaces are opportune moments within the time domain that co-existing networks can leverage. Rather than entirely stopping transmissions from a higher-power network, our method temporarily scales down the packet rate when the low-powered network's performance degrades. This adjustment facilitates a momentary low-interference environment, thereby enhancing the reliability of low-powered or priority traffic networks.

6. EXPERIMENTAL SETUP

In this chapter, we experimentally study the co-existence of Wi-Fi and Zigbee in the 2.4 GHz band. There is no overlap between Wi-Fi and 5G-NRU-U in the 2.4 GHz band. We study the co-existence of Wi-Fi and 5G-NR-U in the 5 GHz band using the platform for open wireless data-driven experimental research (POWDER) testbed [23] at the University of Utah. We detail the various hardware components utilized, their configurations, and the characteristics of the wireless environment where the experiments were conducted.

6.1. Hardware and Device Configuration

6.1.1. Wi-Fi

To set up the Wi-Fi network, we used a commercially available TP-LINK (N750) router that supports both the 2.4 GHz and 5 GHz bands, covering all 802.11 standards (a/b/g/n/ac). For testing co-existence with Zigbee devices, we configured the Wi-Fi router to operate on the 2.4 GHz band with a 20 MHz

bandwidth using the 802.11n protocol. We chose the 802.11n version due to its support for multiple input multiple output antenna technology, which its predecessor lacks, enabling more efficient data transmission and reception. Additionally, 802.11n offers backward compatibility with earlier standards and is widely adopted. For testing co-existence between Wi-Fi and 5G-NR-U in the 5 GHz band, we configured the same router to operate on aggregated 20 MHz channels (153+157), providing a 40 MHz bandwidth.

The router was configured as an access point (AP) and connected to two laptops: one laptop acted 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 shown in Figure 9. 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 throughput, packet loss, and jitter. The router's transmit power was set at max 22 dBm following federal communications commission regulations.



Figure 9. Wi-Fi network setup.

6.1.2. Zigbee

To establish a Zigbee network, we utilized the XBee Zigbee mesh kit modules manufactured by Digi International, [24] which comply with the Zigbee standard. The initial attraction to the XBee modules was based on 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 co-existence with Wi-Fi. The XBee devices can operate with transmit power ranging from -5 to 8 dBm and have a 60-meter (200-foot) indoor range. For configuration and traffic generation between transmitter and receiver XBee modules, we used the XBee configuration and test utility (XCTU) software, 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 10.

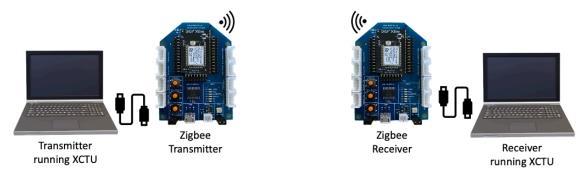


Figure 10. Zigbee network setup.

Zigbee is mainly used in low-power, low data rate applications, such as wireless sensor networks for industrial monitoring, home automation, and health care systems. In this report, we configure the Zigbee

devices to operate as sensing and reporting nodes. Specifically, we set up the Zigbee transmitter (also known as the coordinator) to request data from the Zigbee receiver (referred to as end-device) every second. Upon receiving the request, the end device sends the data (randomly generated in the experiment, with size 100 bytes) back to the coordinator. If the data is successfully received, the coordinator responds with an ACK back to the end device, or else a retransmission is required. Figure 11 shows the data flow in a Zigbee network.

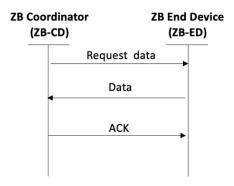


Figure 11. Data flow in Zigbee network.

6.1.3. 5G-NR-U

To establish the 5G-NR-U network, we utilized the POWDER [23] indoor over-the-air testbed at the University of Utah. POWDER is an open platform designed for experimental wireless research, offering users access to a wide range of computing, networking, and radio resources. The POWDER indoor over-the-air lab is equipped with several B210 and X310 software-defined radios from Ettus research. These devices are highly flexible and programmable, enabling users to create and test different wireless network protocols, spectrum analysis, and more. These devices are connected to compute nodes, which can be provisioned and configured using software.

The OpenAirInterface (OAI) is an open-source 5G software stack that provides an end-to-end solution for mobile networking research and experimentation [25]. Within POWDER, all core network functions of 5G are deployed as docker containers in a single server. The gNB is hosted on a next unit of computing device, connected via 1G Ethernet to the docker host and via USB to a B210 radio device. The UE is deployed on a separate next unit of computing device, which is also connected to a B210 radio device via USB. A schematic representation is shown in Figure 12.



Figure 12. 5G-NR-U network setup.

The 5G-NR-U is configured to operate in standalone mode using an unlicensed spectrum with a 40 MHz bandwidth, ranging from 5730 to 5770 MHz, which coincides with Wi-Fi channels 153 and 157.

6.2. Test Environment

6.2.1. Wi-Fi and Zigbee Co-existence

The co-existence experiment between Wi-Fi and Zigbee was carried out in an anechoic chamber facility at the University of Utah. We chose to run our experiment within the anechoic chamber to minimize interference from Wi-Fi and Zigbee sources not in our control. The anechoic chamber's walls, ceilings, and floor are coated with high-loss microwave absorbers. This setup reduced external interference that might otherwise undermine the integrity of our collected data. As a result, the reliability and accuracy of our research findings were assured. Figure 13 shows the inside of the anechoic chamber and a schematic showing distance between the nodes.

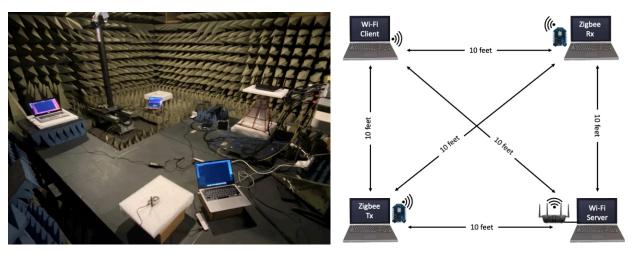


Figure 13. Wi-Fi and Zigbee co-existence network setup.

6.2.2. Wi-Fi and 5G-NR-U Co-existence

We conducted the Wi-Fi and 5G-NR-U co-existence test in the POWDER indoor lab at the University of Utah. The lab is set up in a typical office environment, containing tables, chairs, and other common items.

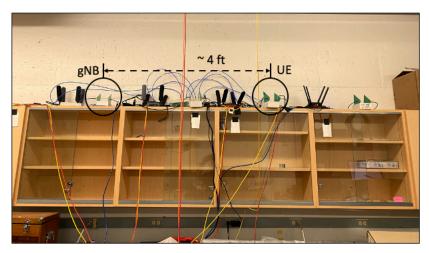


Figure 14. 5G-NR-U network.

To conduct the co-existence experiment in such a scenario, we separate the radio units, which are B210 (one configured as gNB and another as UE) devices, by a distance of 4 feet, as shown in Figure 14. The Wi-Fi network was deployed in the same room with the AP (transmitter) approximately 18 feet away from the gNB, as shown in Figure 15.



Figure 15. Wi-Fi and 5G-NR-U co-existence network setup.

For the 5G network, we consider only downlink traffic (from gNB to UE). Therefore, to generate data traffic, we used iPerf3, with traffic generated from the 5G core network and received at the UE through the gNB.

7. EXPERIMENT RESULTS

This chapter presents the results of the co-existence experiments between Wi-Fi and Zigbee in the 2.4 GHz band and Wi-Fi and 5G-NR-U in the 5 GHz band. For the Wi-Fi and Zigbee co-existence, we focused solely on the network performance when interference prevention mechanisms were applied at the network layer. Baseline and co-existence performance without these mechanisms have already been covered in our previous report [15].

7.1. Wi-Fi and Zigbee

Using the setup and configuration discussed in Chapter 6, we turned on both the Wi-Fi and Zigbee network simultaneously for 1 minute. During this time, the Zigbee nodes requested and transmitted data every second, while the Wi-Fi data rate remained constant (Wi-Fi client downloading from server). Figure 16 shows a comparison between the Wi-Fi throughput and Zigbee packet error percentage. Each point on the graph represents data accumulated over a 1-minute period. The results clearly indicate that percentage of Zigbee packet errors rises with increasing Wi-Fi throughput.

Our goal is to minimize Zigbee packet errors while maximizing the Wi-Fi data rate. To achieve this, we dynamically control the Wi-Fi packet rate at the network layer using TBF, with the Zigbee packet error percentage serving as an input parameter to a system controller node that monitors the Zigbee network and sends instructions to the Wi-Fi AP. The TBF is built into the Linux system of Wi-Fi AP and can be used to control the traffic flow. The control node calculates the Zigbee packet error percentage over a 5-second period. If the error percentage is 20% or higher (i.e., at least one packet is corrupted every 5 seconds), the controller instructs the Wi-Fi AP to reduce the packet rate such that the Wi-Fi throughput is decreased multiplicatively by a factor of two. If no error occurs in Zigbee network, the packet rate is increased such that the Wi-Fi throughput is additively increased with a step size of 2 Mbps.

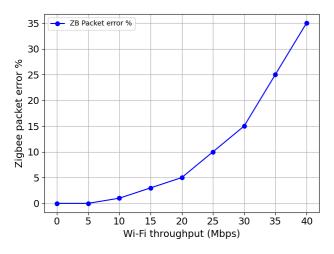


Figure 16. Zigbee packet error percentage vs. Wi-Fi throughput.

Figure 17 shows the result of dynamic control of the Wi-Fi packet rate based on the Zigbee packet error percentage. This result illustrates that Wi-Fi throughput is at 50 Mbps when the 40% Zigbee packet error occurs. When the Wi-Fi throughput decreases multiplicatively, the Zigbee packet error percentage also decreases, resulting in a relative improvement in the ZigBee's performance. When no error occurs in the Zigbee network, an additive increase of the Wi-Fi throughput is observed. After 60 seconds, Zigbee communication ends and Wi-Fi is allowed to operate without any rate control from the Zigbee network. With this approach, we can minimize Zigbee packet error by controlling the Wi-Fi packet rate.

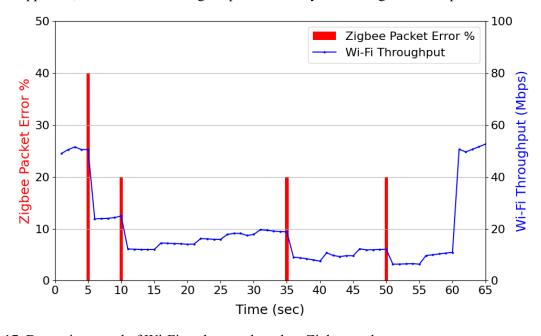


Figure 17. Dynamic control of Wi-Fi packet rate based on Zigbee packet error percentage.

It is important to note that packet errors are observed at certain points (e.g., the 35th and 50th seconds) even when Wi-Fi throughput is around 20 and 10 Mbps. This happens for two main reasons. First, when the Wi-Fi packet rate is high, the likelihood of collisions between Zigbee and Wi-Fi packets is also high. Second, when the Wi-Fi packet rate is reduced, the chance of collisions is lower but not completely eliminated. Collisions can still occur (with a lower probability) because the two networks are not synchronized, and Wi-Fi may transmit a packet whenever the packet is ready and it detects an idle

channel. As discussed in Chapter 5, by using TBF in a Wi-Fi network, we create temporal white space by scaling down the packet rate whenever the Zigbee packet error reaches 20%. This adjustment provides a momentary low-interface environment for Zigbee, thereby reducing the probability of packet collision.

7.2. Wi-Fi and 5G-NR-U

Before presenting the experimental results of co-existence of Wi-Fi and 5G-NR-U, we briefly describe the 5G-NR-U signaling and transmit power configuration in our experiment.

7.2.1. 5G-NR-U Signaling

The 5G-NR-U setup in POWDER operates in standalone mode, meaning both data and signaling are transmitted over the unlicensed spectrum. Due to software limitations, the non-standalone setup is not available, where data would be carried on the unlicensed spectrum and signaling on the licensed spectrum. In 5G-NR-U, signaling is handled by the synchronization signal block (SSB), which is broadcast periodically. By default, the SSB has a periodicity of 20 ms, but it can be configured to 40, 80, or 160 ms based on network requirements. The UE must monitor and decode the SSB not only for initial synchronization, but also for tasks like mobility management and recovery after a radio link failure. If the UE fails to receive or correctly decode the SSB continuously within a specified time frame, it will disconnect from the gNB. In a real 5G-NR network, the UE would automatically initiate a re-attachment procedure in such cases. However, due to limitations of the available OAI 5G-NR-U protocol stack, the experiment in this setup requires a manual restart after the UE disconnects from the gNB.

7.2.2. 5G-NR-U Transmit and Receive Power

The B210 radio devices used in the experiment are equipped with a single antenna. Thus, our experimental setup does not support transmit beamforming. Without any front-end amplifier and the gNB transmitting signals at maximum gain, the UE measures a received power of approximately -110 dBm when placed 4 feet away. According to the 3GPP technical specifications and considering that the threshold for reference signal received power at the UE in the OAI software is set to -120 dBm (the minimum power required for the UE to establish a connection with the gNB), our setup essentially creates a realistic scenario where the UE is far away from the gNB but within its coverage area.

7.2.3. 5G-NR-U Channel Access

According to 3GPP specifications, 5G-NR-U uses the LBT mechanism for channel access when operating in the unlicensed band. However, the OAI software stack used in this experiment does not implement any channel sensing mechanism and transmits packets without sensing whether other devices are occupying the shared band. Therefore, packet collisions are inevitable.

7.2.4. Wi-Fi and 5G-NR-U Co-existence

Figure 18 illustrates the throughput of Wi-Fi and 5G-NR-U when they coexist. Initially, 5G-NR-U transmission achieves a throughput of 20 Mbps. At the 20-second mark, Wi-Fi traffic begins with a throughput of approximately 100 Mbps. As soon as Wi-Fi transmission starts, 5G-NR-U throughput drops to zero, and the UE disconnects from the gNB.

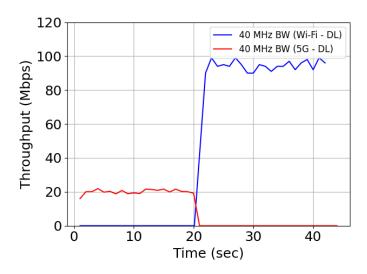


Figure 18. Throughput comparison of Wi-Fi and 5G-NR-U when co-existing.

This occurs for two main reasons, as revealed by the 5G-NR-U trace. First, without LBT in 5G-NR-U, Wi-Fi and 5G-NR-U packets collide continuously, preventing the UE from correctly decoding the interfered packets, leading to retransmissions and reduced throughput. Second, Wi-Fi traffic interferes with the 5G-NR-U SSB. If the UE fails to decode 100 consecutive SSBs, it results in a disconnection from the gNB. The Wi-Fi traffic, on the other hand, is not impacted, as the Wi-Fi client's received power was approximately -75 dBm, which is much higher than the 5G-NR-U network. This can be compared to a typical scenario where the UE and Wi-Fi network are within close proximity (e.g., an indoor environment), while the gNB is located further away from the UE (outdoors, and several hundred feet away).

To improve the co-existence performance of 5G-NR-U, we made two key adjustments. First, we extended the SSB burst periodicity to a maximum of 160 ms, which creates white space within each SSB burst. This reduces the likelihood of Wi-Fi packet collision with SSB. Second, we gradually reduced the Wi-Fi packet rate using TBF to determine the threshold at which the 5G-NR-U network can maintain stable operation. Figure 19 illustrates one such result, showing that 5G-NR-U and Wi-Fi can co-exist (10th to 20th) when Wi-Fi throughput is reduced to as low as 0.4 Mbps. In this scenario, the UE maintains its connection with the gNB and sustains a stable throughput of 20 Mbps.

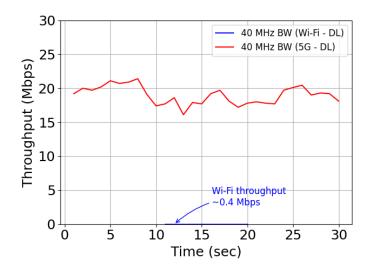


Figure 19. Throughput comparison of Wi-Fi and 5G-NR-U when co-existing with low Wi-Fi packet rate (0.4 Mbps).

Figure 20 presents the results of another co-existence experiment, where both Wi-Fi and 5G-NR-U packet rates were reduced to get an average throughput of 1 and 5 Mbps, respectively, with the SSB periodicity set to 160ms. This experiment achieved stable throughput for both Wi-Fi and 5G-NR-U. However, simply lowering the 5G-NR-U packet rate is not always reliable, as Wi-Fi can still randomly interfere with the 5G-NR-U SSB. This can disconnect UE with the gNB, leading to system instability in the experiment.

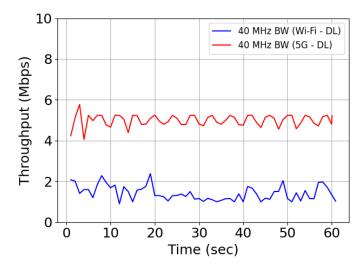


Figure 20. Throughput comparison of Wi-Fi and 5G-NR-U when co-existing with low Wi-Fi (2 Mbps) and 5G-NR-U (5 Mbps) packet rate.

8. SIMULATION

We encountered several limitations during our experimentation on the co-existence of Wi-Fi and 5G-NR-U. These include (1) the inability to vary the distances between 5G-NR-U nodes, as their positions were fixed within the indoor lab setting, (2) a fixed power level for the gNB, (3) the absence of a channel sensing mechanism such as LBT for 5G-NR-U, and (4) 5G-NR-U operation in non-standalone mode. To systematically incorporate and assess the impact of these factors on co-existence performance, we

extended our work by developing a simulator. This simulator allows for evaluation of the potential changes in the network behavior under modified conditions, providing a more comprehensive understanding of how these modifications might influence network co-existence. In this chapter, we first describe our simulator and our simulation model, and then present our results.

8.1. Python Library: SimPy

To develop the simulator, we used Python's SimPy library [26]. SimPy is a process-based discreteevent simulation library that models systems in terms of events happening over time. It is particularly useful for systems that involve interactions between different components (or processes) that have to wait for certain conditions or events to occur before they can proceed.

In the simulation, objects such as APs, clients, gNBs, UEs, and wireless channels are modeled as classes. These classes define the attributes and methods (processes) that the instances (objects) will execute. Processes are represented as Python generators and interact with each other through events. Examples of interactions include waiting for a process to start, finish, or interrupt an existing process. During their lifetime, processes can yield events, temporarily suspending execution until the events complete. This allows multiple processes to wait for the same event. A basic example of a SimPy event is a timeout, where a process remains inactive for a specified simulation time.

The co-existence of Wi-Fi and 5G-NR-U can be effectively modeled using the SimPy library for discrete-event simulation. For example, each AP or gNB in the simulation is represented as an object of the AP or gNB class, which itself implements several methods (processes). The main process begins at seconds, and during the simulation it spawns new processes (e.g., channel sensing, back off, etc.). These processes can be represented as sequences of events over time that change the state of the channel. The simulation model is depicted in Figure 21.

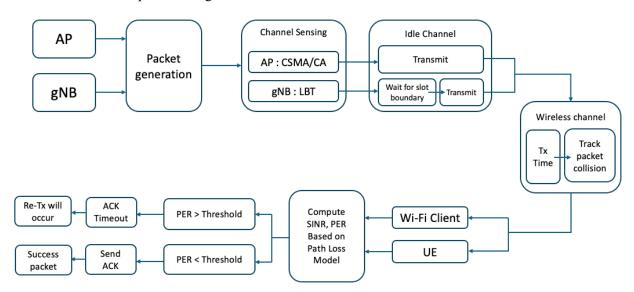


Figure 21. Simulation model with Python SimPy library.

8.2. Wireless Channel Model

A wireless channel model is a mathematical representation used to characterize the behavior of a wireless communication channel. The channel model accounts for various factors that affect the transmission of signal, such as path loss, fading, and shadowing. Path loss describes the reduction in signal strength over distance, while fading refers to the rapid fluctuation of signal amplitude due to multipath propagation. Shadowing is the signal attenuation caused by obstacles like buildings or trees. Wireless channel models are essential for simulating and analyzing the performance of wireless

communications systems to predict and optimize network behavior under different conditions.

8.2.1. Wi-Fi Path Loss Model

Our simulator adopts IEEE 802.11 task group (TG) indoor path loss model [27] for Wi-Fi, which is given by:

(1)

The indoor path loss consists of the free space loss both within a break point distance and after the break point distance (at which the propagation behavior changes), as given below:

if (2)

if (3)

Where is the distance between transceiver nodes in meters, is the breakpoint distance, and is the wavelength of the signal where is the propagation speed and . The other two parameters in the overall path loss equation are and , extra path loss due to floor and wall penetration. In our simulation, we consider all APs to be on the same floor and set the floor loss to zero. We take into consideration path loss due to wall separation, as it is common in home or office environments. The wall penetration loss is given by:

(4)

Here, is the number of walls penetrated and is the penetration loss for a single wall. Finally, we consider log normal shadow fading for non-line of sight (NLoS). To compute the receive power at a Wi-Fi client, we subtract the overall path loss from the transmit power of a Wi-Fi AP.

(5)

8.2.2. 5G-NR-U Path Loss Model

For 5G-NR-U, we used the 3GPP urban macro cell outdoor-non line of sight path loss model [28]. This model is typically characterized by high building density and a large number of users. The UMa model provides wide coverage and high capacity, making it suitable for densely-populated urban areas. The path loss equation is given as:

(6)

where height of the gNB is 25m (3GPP standard) [28] and the height of UE (and is the distance between gNB-UE. To compute the receive power at a UE, we subtract the overall path loss from the transmit power of gNB.

(7)

8.3. Simulator Co-existence Model

To incorporate the co-existence of Wi-Fi and 5G-NR-U in the simulator, we considered three Wi-Fi clients (client1, client2, and client3), each connected to their own access point (AP1, AP2, AP3). AP1 and AP2 are placed 5 meters apart, allowing them to detect each other's transmissions, which prevents them from transmitting simultaneously by following CSMA/CA. In contrast, AP3 is located much farther from AP1 (20 meters) and AP2 (23 meters), making it unable to sense the other APs. Clients 1 and 2 are positioned 2 meters away from their respective APs, while client3 is placed between the coverage areas of AP1 and AP3, making it susceptible to interference from AP1.

The 5G-NR-U network consists of one gNB and one UE, separated by a distance . The UE is located closer to the Wi-Fi network, while the gNB is positioned farther away, beyond the sensing range of the Wi-Fi network. The complete network diagram is shown in Figure 22.

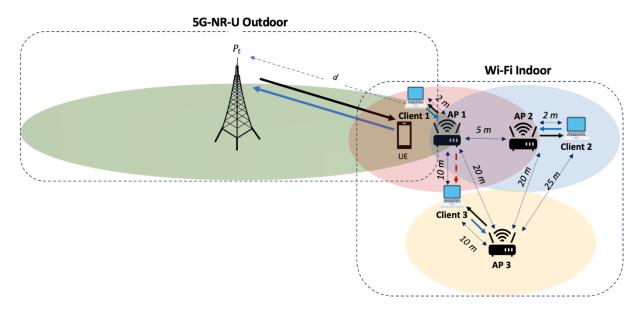


Figure 22. Simulated co-existence network diagram of Wi-Fi and 5G-NR-U.

8.4. Channel Access Mechanism

Before transmission, each AP and gNB sense the channel using CSMA/CA and LBT procedures, respectively, using energy-based detection, as outlined in Section 2. In the simulator, the channel class monitors which nodes are transmitting. When a node wants to transmit, it first retrieves information about active nodes from the channel class. If there are active nodes, the node willing to transmit calculates the received power from active nodes based on the distance and path loss model. If the received power exceeds a certain threshold, the node defers transmission, or otherwise transmits the packet. Each packet is uniquely identified by a sequence number.

8.5. Packet Reception and Interference Calculation

Once a packet is received by the receiver, it checks the collision status of the packet tagged by channel class. Whenever two nodes transmit simultaneously, the collision status flag of a packet is set to 'high' with the associated interfering node name. The receiver of a packet extracts this information and computes the signal to interference and noise ratio (SINR) based on received signal power from legitimate node and interfering node and then computes the probability of bit error [29] given by:

(8)

Here, is the modulation order and is a function of Gaussian distribution defined as:

(9

The is directly related to complementary error function (, defined as the probability that a normally distributed random variable falls outside a certain range. Therefore, the above equation can be simplified to:

(10)

In our simulation, we assume that the error correction code at the receiver will be able to correct 10% of the erroneous bits of a fixed packet size. If the erroneous bits are more than 10% with probability 0.1, the receiver will not send an ACK, which will trigger a retransmission of the same packet when the ACK timeout period expires. To find the probability that more than 10% of the bits are erroneous in a packet, we use binomial distribution that models the number of successes (error bits) in a fixed number of

independent Bernoulli trials (bits in packet), where each trial has two possible outcomes (error or non-error). The probability mass function for binomial distribution is defined as:

(11)

Here, N is the number of trials (bits in packet), k is the number of successes (bit errors), and p is the probability of success in a single trial (bit error probability found initially). The cumulative distribution function of the binomial distribution is used to find the probability of observing up to a certain number of successes (errors), which is crucial in determining the likelihood that the number of errors does not exceed a certain threshold.

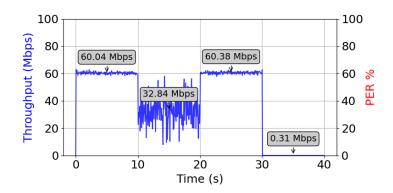
(12)

Finally, to find the probability of more than a certain percentage of errors, we subtract the cumulative distribution function up to the threshold from 1:

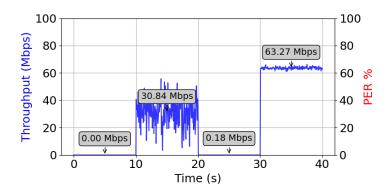
(13)

8.6. Wi-Fi and 5G-NR-U Co-existence Performance in Simulation

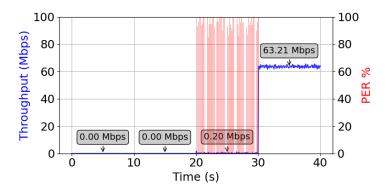
To evaluate the co-existence performance of Wi-Fi and 5G-NR-U, we first measure the throughput and packet error rate (PER) of each network individually. Figure 23 (a, b, and c) shows the throughput and PER for each Wi-Fi (AP1, AP2, and AP3). When only AP1 is transmitting during the first 10 seconds, the average throughput is approximately 60 Mbps. From the 10th to the 20th second, both AP1 and AP2 start transmitting. Since they are within each other's coverage area, they contend for the channel, resulting in the throughput being reduced by half.



(a)



(b)



(c)

Figure 23. Wi-Fi network performance containing 3 APs and 3 clients using CSMA/CA. Throughput and PER (a) AP1 (b) AP2 and (c) AP3.

Between the 20th and 30th seconds, AP1 and AP3 were allowed to transmit simultaneously. While AP1 and AP3 were outside each other's coverage areas and unable to detect each other's transmissions, Client 3 was positioned equidistantly from both AP1 and AP3. As a result, Client 3 received the intended signal from AP3 along with interfering signal from AP1—this interference causes PER, leading to the need for retransmissions. Client 1, positioned closer to AP1 and farther from AP3 (the interferer), did not experience retransmission, as the interference power from AP3 was below the threshold.

From the 30th to 40th seconds, AP2 and AP3 were active in their own coverage area with their associated clients. Since they are separated by a larger distance, they do not interfere and have stable throughput (60Mbps) with no packets in error.

Figure 24 shows the performance of the 5G-NR-U network. When the distance between the gNB and the UE was 140m, a stable throughput of 55 Mbps was achieved. We used a fixed 64-QAM modulation for both the Wi-Fi and the 5G-NR-U network, which remained unchanged regardless of varying channel condition.

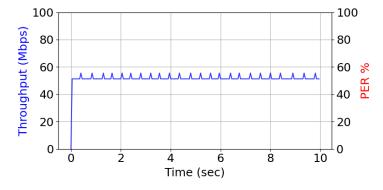


Figure 24. 5G-NR-U network performance containing 1 gNB and 1 UE.

Figure 25 illustrates the co-existence of both networks, showing the distances between each node. The throughput and PER performance of the co-existing networks is shown in Figure 26. It is evident that when both the Wi-Fi AP and gNB were active between the 10th and 20th seconds, the gNB experienced a high PER. This indicates that neither the gNB nor the Wi-Fi AP could detect each other's transmissions, leading to simultaneous transmissions from both networks. Additionally, because the UE was positioned close to the Wi-Fi AP, it received significant interference, resulting in corrupted packets and the need for retransmissions, which negatively impacted the 5G-NR-U throughput. In contrast, the Wi-Fi client experienced a higher SINR due to its proximity to the AP.

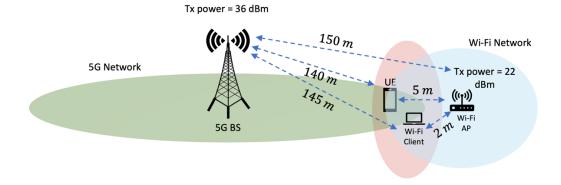
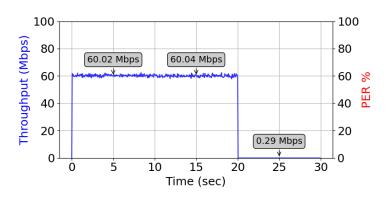
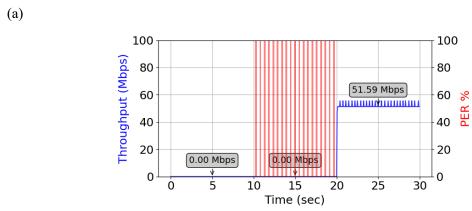


Figure 25. Wi-Fi and 5G-NR-U co-existence network diagram with distance (150m).





(b)

Figure 26. Wi-Fi and 5G-NR-U co-existence performance (a) AP1 and (b) gNB1 when separated by a large distance (150m).

Figure 27 illustrates the co-existence of the network when the distance between them is reduced. The throughput and PER performance are shown in Figure 28 (a) AP1 and (b) gNB1.

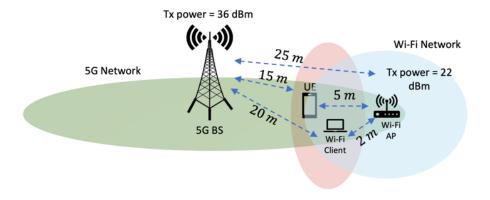
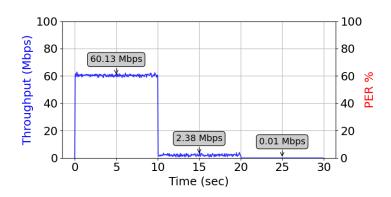


Figure 27. Wi-Fi and 5G-NR-U co-existence when each network is separated by a shorter distance (25m).



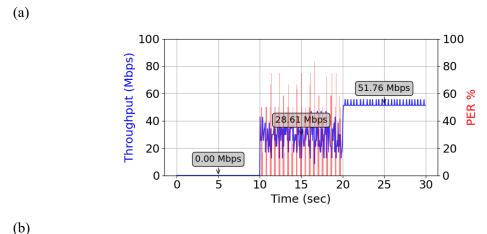


Figure 28. Wi-Fi and 5G-NR-U co-existence performance (a) AP1 and (b) gNB1 when separated by a short distance (25m).

During the co-existence period (from the 10th to the 20th second), the networks' close proximity allowed for mutual detection of transmissions. The Wi-Fi network identified the gNB's transmission as being above the detection threshold power (-82 dBm), prompting it to delay its transmissions. Conversely, the gNB detected the Wi-Fi signal below this threshold and continued its data transmission. AP1 managed to transmit occasionally, either when the 5G network was conducting its LBT procedure or during the brief intervals between the end of LBT and the start of the next slot boundary. This led to interference, resulting in packet errors in both networks. Notably, the 5G-NR-U network was triggered to retransmit

packets due to the packet error percentage threshold being surpassed. Meanwhile, the Wi-Fi network, encountering packets with error percentages below the threshold, did not initiate retransmissions, but its throughput degraded by 96% due to channel contention. 5G-NR-U, on the other hand, had a throughput reduction of 63% due to packet retransmissions.

The simulation shows that the co-existence performance of Wi-Fi and 5G-NR-U networks is influenced by factors such as node positioning, power detection thresholds, and channel access mechanisms. When the UE is near the Wi-Fi AP and far from the gNB, UE experiences strong interference from the AP, leading to packet corruption and reduced throughput. Conversely, bringing the gNB closer to the Wi-Fi AP, enabling mutual detection, results in performance degradation for both networks.

9. SUMMARY AND FUTURE SCOPE OF WORK

This report examines the performance of Wi-Fi and 5G-NR-U coexistence in the 5 GHz unlicensed spectrum. It provides a technical overview of the operational frameworks of these networks and evaluates their performance using the POWDER testbed under coexistence conditions. Experimental results reveal that the control signal of the 5G network is significantly disrupted by Wi-Fi interference, impairing the ability of UE to maintain synchronization with the gNB.

To overcome the challenges identified during the experiments, we developed a Python-based simulator. This simulator integrates variables such as the distance between nodes, transmit power levels, and channel access mechanisms. The simulation demonstrates that in a realistic network scenario—where the UE is closer to a Wi-Fi network and further from the gNB—the performance of the 5G network is negatively affected by Wi-Fi due to high interference power from Wi-Fi AP to the UE. In contrast, the performance of the Wi-Fi network remains unaffected, owing to substantial signal attenuation from the gNB to Wi-Fi clients. When the proximity between the networks decreases, the Wi-Fi network detects the 5G transmissions and competes for channel access. Conversely, the gNB receives Wi-Fi signals that fall below its detection threshold and continues to transmit, resulting in interference that leads to performance degradation in the Wi-Fi network.

Building on our previous report that explored Wi-Fi and Zigbee co-existence in the 2.4 GHz band, this report also introduces an interference prevention mechanism using upper-layer coordination to allow both networks to operate without starving each other. Rather than entirely stopping transmissions from the relatively high-powered network, our method temporarily scales down the packet rate when low-powered network performance degrades. This adjustment facilitates a momentary low-interference environment, thereby enhancing the reliability of the low-power network. The proposed method is not only confined to Wi-Fi and Zigbee, it is equally applicable to scenarios involving the co-existence of Wi-Fi and 5G-NR-U. Our results show that Zigbee or 5G-NR-U networks PER and throughput can be improved by controlling the Wi-Fi packet rate using TBF. This approach does not require any modifications to the physical or MAC layer of the protocol, thus avoiding additional overheads.

In the future, we plan to develop a generalized algorithm and machine learning techniques that can dynamically adjust its parameters based on real-time network condition and requirements. Additionally, since Zigbee and 5G-NR-U are distinct networks with different priorities and QoS requirements, we plan to explore more equitable co-existence algorithms that ensure fairness between Wi-Fi, 5G-NR-U, and Zigbee, rather than disproportionately restricting Wi-Fi's network performance.

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