INL/CON-25-83205-Revision-0

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Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

A Study on Co-existing Heterogeneous Wireless Networks for Data Transmission within a Nuclear Facility

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doi.org/10.13182/NPICHMIT25-46738

ABSTRACT

Deployment of wireless technologies is a salient need for modernization, automation, and improved operation of nuclear power plants (NPPs). As a single technology cannot support the ever-changing needs, it is required to have a heterogeneous wireless network architecture to address the different technical and economic challenges. However, the coexistence of these multi-band heterogeneous wireless networks brings numerous challenges due to the factors including dissimilarity in their channel access mechanism, distance between nodes, transmit power level and many more. This paper develops real-world experiments and simulations of wireless coexistence for Wi-Fi, fifth generation cellular (5G), and Zigbee in the unlicensed band to understand the challenges and opportunities. The experiments were conducted over the Platform for Open Wireless Data-driven Experimental Research (POWDER) testbed at the University of Utah. In addition, this paper is the first to propose a novel packet rate control technique at the network layer to create temporary opportunities for 5G or Zigbee signal transmissions focusing its application in a nuclear facility while using the shared band. The performance of the proposed coexistence solution is validated with experimental results and simulation.

1. INTRODUCTION

Recent data indicates a great interest within the nuclear industry in investigating multiple wireless solutions to facilitate real-time data transmission for diverse applications. While wired connections can provide reliable data transmission, the incurred deployment cost from these connections is relatively high. In addition, the current nuclear fleet is at a great economic disadvantage due to the heavy dependence on operating staff for routine maintenance and monitoring [1]. Wireless connectivity can enhance operational efficiency without compromising safety and reliability of the nuclear power plant (NPP) [2][3].

While considering an appropriate spectrum for wireless usage in industrial nuclear applications, several spectrum bands have been considered. The 2.4 GHz industrial, scientific and medical (ISM) band has gained immense popularity due to its availability and non-licensing requirements. Wireless technologies, such as Wi-Fi and Zigbee, have been operating within this limited spectrum. In addition, third-generation partnership project (3GPP) has proposed extending fifth-generation cellular (5G) operations in the 5 GHz unlicensed spectrum [4] which is also utilized by Wi-Fi (operating under 802.11 a, n, ac, and ax standards). Different nuclear applications may require varying data types over the wireless network to satisfy the required quality of service (QoS) and latency level. Therefore, a one-size-fits-all solution for enabling automation in NPPs is not feasible. Consequently, coexistence of these technologies including Wi-Fi, Zigbee and 5G in critical environments can tackle this problem with improved operational efficiency. However, the coexistence of such wireless technologies in the limited unlicensed band is challenging due to the ever increasing number of devices that lead to higher interference and congestion. Therefore, innovative solutions to ensure harmonious coexistence and optimal performance of these wireless solutions for NPP operations are needed.

The coexistence between Wi-Fi and Zigbee in 2.4 GHz ISM band has been investigated with theoretical and experimental studies. Authors in [5] addressed the coexistence problem by introducing a novel Zigbee packet format with redundancy in the header and payloads for improved error correction. Authors in [6] study the coexistence by scheduling Zigbee traffic during Wi-Fi intervals, which are modeled as Pareto distributions. The study in [7] mutes Wi-Fi transmission during Zigbee communication by injecting fake Wi-Fi packets with a modified length in the header. Detecting these fake packets, the Wi-Fi interferer refrains from transmitting, thereby creating idle period for Zigbee to operate without interference. Other works mitigate the interference with informed decision to change information using the medium access control (MAC) layer [8,9]. In contrast, the 5G New Radio-Unlicensed (5G-NR-U) prefers listen before talk (LBT) technique for spectrum sharing with Wi-Fi, which is based on carrier-sense multiple access with collision avoidance (CSMA/CA) mechanism [10]. While 5G-NR-U is a scheduled and synchronous radio access technology where transmissions are expected to begin at fixed slot boundaries, LBT is asynchronous where the end procedure may not always align with slot boundaries. In such a case, the 5G transmitter, also referred as gNodeB (gNB), must postpone transmission to align the end of LBT with the available slot boundary. Zajac et al. [11] conducted two simulations to obtain this alignment utilizing a gap-based and reservation-signal-based access. The performed simulations show that the latter allows for a fairer co-existence between gNBs but wastes more energy and radio resources, while the former provides a higher spectral efficiency with an increased collision rate. However, when 5G-NR-U utilizes LBT and Wi-Fi uses CSMA/CA, the fairness cannot be guaranteed [12]. Luo et al. [13] evaluated 5G-NR-U parameters under 3GPP constraints and observed the Wi-Fi's fixed parameters could starve 5G-NR-U, indicating the need for frequent parameter adjustment for improved fairness. The work in [14] utilizes stochastic geometry to investigate multi-user orthogonal frequency division multiple access and suggests that by disabling the use of legacy contention signals for Wi-Fi, the coexistence performance can be improved. Unlike the studies related to Wi-Fi and Zigbee coexistence in [5–9], this paper generates temporal white spaces by controlling packet rate at the network layer for avoiding interference. On the other hand, the works on Wi-Fi and 5G coexistence [11–14] mostly focus on simulations with novel solutions but do not specifically focus on their deployment for nuclear use cases. We address this gap by performing a thorough coexistence study with both simulation and experiment targeting the NPPs to enable automation and diverse critical applications.

This paper identifies the challenges of a coexisting environment with Wi-Fi, ZigBee, and 5G communications with extensive experiments. While the experiments address many challenges, the solution requires additional investigation to understand the interference mitigation opportunities for their particular application in nuclear fields. Therefore, we also develop simulations that offer more flexibility in designing the network while providing critical insights on the coexistence performance. We propose a network layer co-ordination with rate control mechanism that minimizes interference in a coexisting wireless network. More specifically, our method employs a network traffic management tool, called token bucket filter (TBF), that controls the flow of packets from network layer while ensuring the specified transmission rate limits. We strategically introduce temporal white spaces in the wireless spectrum by controlling the rate at which data packets move to the data link and physical layer for transmission. Also, our approach does not incur any additional complexity to the network's physical or MAC layer, thus reducing network overhead. To the best of our knowledge, this paper is the first to propose a novel packet rate control strategy at the *network layer* to facilitate the coexistence of wireless heterogeneous networks. Our findings demonstrate that the proposed method substantially enhances performance of a coexisting network, paving the way for resilient wireless communications for an NPP environment.

2. SYSTEM MODEL AND CONFIGURATION

This section describes the system model and hardware configurations considered for coexistence performance evaluation in this paper.

2.1. Wi-Fi and Zigbee Hardware Devices and Configuration

To experimentally set up a Wi-Fi network, the TP-LINK N750 router is configured as an access point (AP) and linked to two laptops, one connected via Ethernet as a server and the other wirelessly as a client as shown in Figure 1a. We used iperf3 to measure network performance and traffic generation while adhering to the FCC's (Federal Communications Commission) transmit power regulation in Table I.

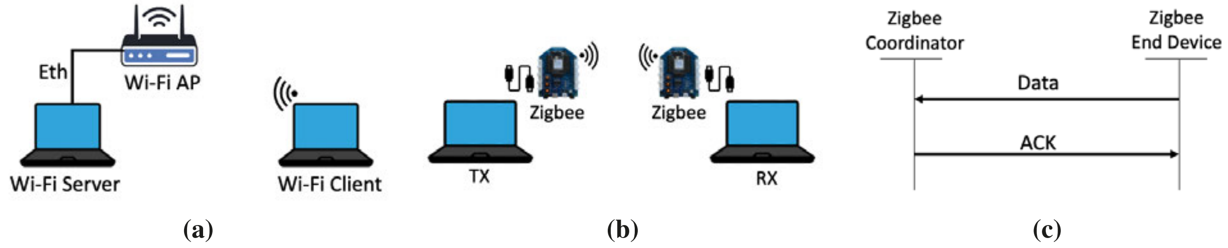


Figure 1: (a) Wi-Fi network, (b) Zigbee network and (c) Zigbee message flow

For Zigbee, we utilized the XBee Zigbee mesh kit modules manufactured by Digi Internationals [15], which complies with the Zigbee standard. These XBee devices have a 60-meter indoor coverage range. We used Python and XCTU (XBee configuration and test utility), an application provided by Digi for configuration and traffic generation. Communication between the XBee modules and XCTU software is established via a USB (universal serial bus) that connects to a laptop as depicted in Figure 1b. Once the Zigbee coordinator receives data and sends an ACK (acknowledgment) back, it is counted as a successful delivery (depicted in Figure 1c). Otherwise, it is counted as a failure. The considered Wi-Fi and Zigbee packet sizes are 1,500 and 100 bytes, respectively.

Table I: Hardware and device configuration parameters

Parameters	Wi-Fi	Zigbee	5G-NR-U
Device	TP-LINK N750	Digi XBee mesh kit	USRPs
Center Frequency	2.4 GHz (with Zigbee) 5.75 GHz (with 5G-NR-U)	2.4 GHz	5.75 GHz
Transmit Power	22 dBm	$(-5$ to $8)$ dBm	$(0$ to $35)$ dB gain
Bandwidth	20 MHz (with Zigbee) 40 MHz (with 5G-NR-U)	2 MHz	40 MHz
Protocol	802.11n	802.15.4	5G-NR-U

2.2. Wi-Fi and 5G Hardware Devices and Configuration

For the 5G-NR-U network, we utilized the Platform for Open Wireless Data-driven Experimental Research (POWDER) [16] indoor over-the-air (OTA) testbed at the University of Utah. POWDER is an open platform designed for experimental wireless research, offering user access to a wide range of computing, networking, and radio resources. To deploy 5G in POWDER, we used the 5G open air interface (5G-OAI) [17], which is an open-source software stack. The gNB is connected to a B210 radio device and hosted on a next unit of computing (NUC) node connected to the docker host. The user equipment (UE) is configured on a separate NUC and connected to a B210 radio device via USB. The Wi-Fi network is deployed at a distance of 18 feet from the 5G network as shown in Figure 2.

2.3. Model for Wi-Fi and 5G-NR-U

In order to understand the coexistence scenario accurately, we also performed simulations that help in flexible network design to investigate more challenging scenarios that are not possible in a controlled ex-

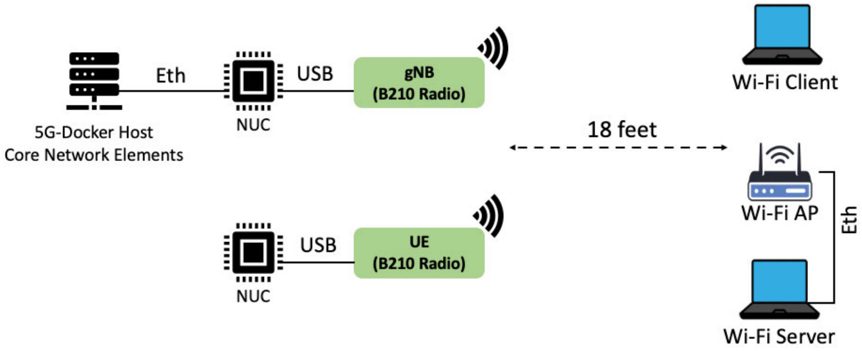


Figure 2: 5G-NR-U and Wi-Fi coexistence network

perimental setup. To do so, we require a channel model to evaluate the performance. A wireless channel model considering key components such as path loss, fading, and shadowing are essential for simulating and analyzing the performance of wireless systems. We consider an indoor path loss model for Wi-Fi [18] in (1). This model includes components such as free space path loss (PL_{indoor}), additional losses from floor (PEL_{floor}) and wall penetration (PER_{wall}), along with log-normal shadow fading (γ). For 5G simulations, we use the 3GPP urban macro-cell (UMa) outdoor non-line-of-sight (NLOS) model [19] in (2). This model accounts for variables such as the heights of the gNB (25m) and UE ranges from $1.5m$ to $22.5m$, with d representing the distance between them. The UMa model is particularly effective in densely populated urban areas due to its wide coverage and high capacity. A detailed network layout for Wi-Fi and 5G coexistence is shown in Figure 3.

$$PL_{\text{overall}} = PL_{\text{indoor}}(d)_{\text{dB}} + PEL_{\text{floor,dB}} + PEL_{\text{wall,dB}} + \gamma_{\text{dB}} \tag{1}$$

$$PL_{UMa-NLOS} = 13.54 + 39.08 \times log_{10}(d) + 20 \times log_{10}(f_c) - 0.6(h_{UE} - 1.5) \tag{2}$$

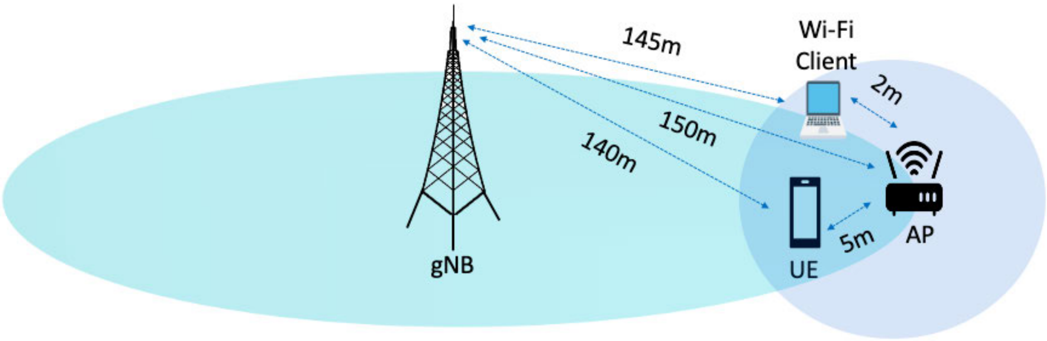


Figure 3: Simulated coexistence network diagram of Wi-Fi and 5G-NR-U

For simulation, we employed Python's SimPy library [20], a process-based discrete-event simulation framework well-suited for modeling interacting systems. We set up a Wi-Fi client connected to an AP that uses CSMA/CA to prevent simultaneous transmissions. The 5G-NR-U component consists of one gNB and one UE, utilizing the LBT mechanism for channel access. In our setup, the UE is positioned close to the Wi-Fi network, whereas the gNB is placed further away to simulate a typical network environment. The simulator can be scaled to accommodate any number of APs, clients, or UEs, offering extensive flexibility for various testing scenarios.

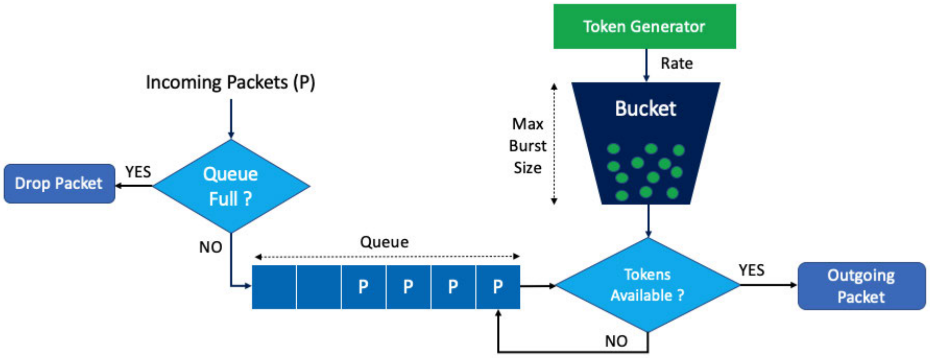


Figure 4: Flow graph of token bucket filter

3. INTERFERENCE MITIGATION STRATEGY

We introduce a novel strategy to mitigate interference through packet rate management at the network layer. This technique does not apply the physical data rate control which is generally used in existing solutions to optimize coexistence performance in wireless heterogeneous networks. The proposed solution uses TBFs for controlling the number of transmitted wireless data packets.

TBF is a queuing discipline designed to control wireless traffic rate. The model of TBF draws an analogy of a bucket (Figure 4) with a fixed capacity into which tokens (corresponds to bytes) are continuously added at a fixed rate. The operation of TBF is defined by three primary parameters: token rate T_r, the rate at which the tokens are added into the bucket; bucket size b, the maximum number of tokens the bucket can hold; and latency l, the maximum time a packet can remain in the queue before being discarded. Each data packet coming from the transport layer requires a token to be sent over the network. As the incoming rate of data packets and token rate can be different, this can produce three scenarios: (a) the data packet arrives in TBF at a rate that is equal to the rate of incoming tokens, (b) the data packets arrives in TBF at a rate that is smaller than the token rate, and (c) the data packet arrives at a rate exceeding the token generation rate. The last scenario can be used to control the outgoing traffic on an interface. The TBF packet generation rate is given as,

$$P_r = \frac{T_r}{P_s} \tag{3}$$

where P_s is the packet size. If a packet arrives and the token is not available, the packet can wait for a specified period of time or simply drop out. Through this mechanism, we utilized the TBF approach to effectively regulate the number of packets forwarded to the next layers.

The white spaces are idle spaces in the RF spectrum band. These spaces create opportunity for other wireless devices to utilize the spectrum. However, injecting packets from other wireless network into these temporal white spaces is challenging due to their randomness. Using the TBF approach, we reduce the packet flow rate and strategically generate white spaces. These opportunistic moments in the time domain are leveraged by ZigBee and 5G for data transmission. In particular, by maintaining fairness without completely stopping communication of a higher-powered (Wi-Fi in our experiment) network, our method temporarily scales down its packet rate when the low-powered network's (Zigbee and 5G for this work) performance degrades. This adjustment facilitates a momentary low-interference environment, thereby enhancing the reliability of the coexisting wireless solutions. Figure 5 shows time-frequency utilization when token generation rate of Wi-Fi is controlled with TBF and how it helps in generating temporal white spaces in the spectrum.

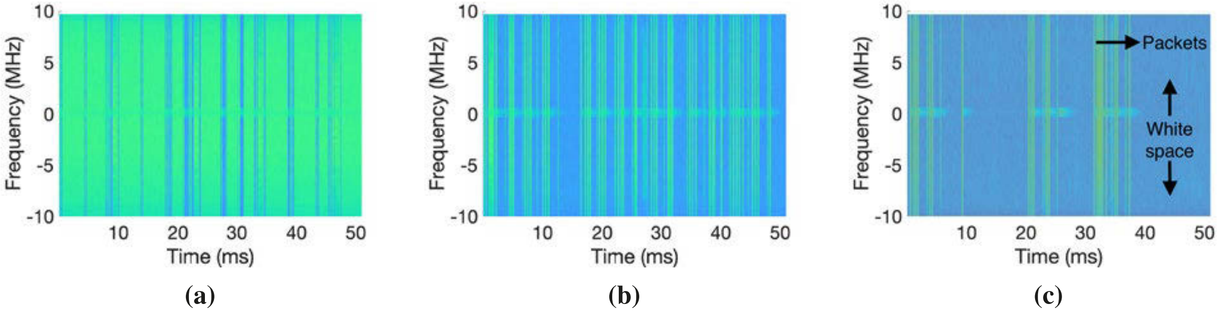


Figure 5: Wi-Fi spectrogram with controlled token generation rate (a) 50 (b) 10 and (c) 5 Mbps

4. RESULTS

4.1. Wi-Fi and ZigBee

The coexistence experiment was conducted in a typical indoor office environment having external Wi-Fi AP's (for office communication) influence. Understanding the wireless properties in such an indoor environment is essential for their real-world deployment in nuclear fields. We chose Wi-Fi channel 1 and Zigbee channel 12 as the overlapping channels to perform our coexistence experiment. Each Wi-Fi and Zigbee device was located 10 feet apart as shown in Figure 6(a). The coexistence experiment was performed for 60 seconds with Zigbee continuously transmitting packets. The Wi-Fi was only active between 20th to 40th second. As depicted in Figure 6(b), there was a significant drop in Zigbee's throughput, from 12 Kbps to 0.85 Kbps, when Wi-Fi was active. In contrast, the Wi-Fi throughput remained stable, averaging 100 Mbps during this period.

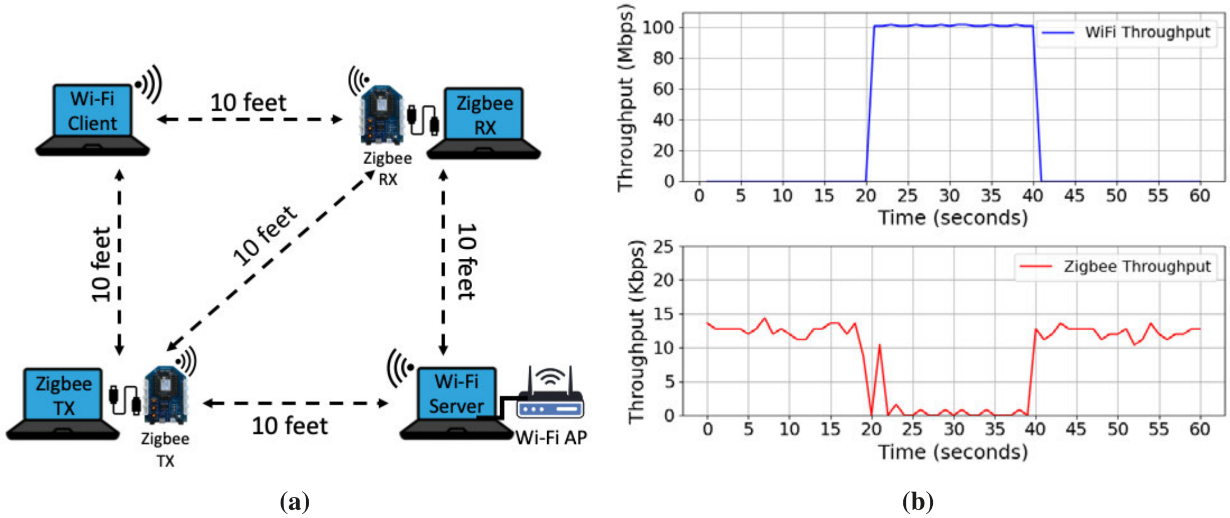


Figure 6: Wi-Fi and Zigbee (a) coexistence network setup (b) throughput performance

For remote monitoring applications to achieve automation in an NPP with low-powered Zigbee, we configured our Zigbee network to transmit small packets (40 bytes) at every one second interval. If an ACK message was not received, it was classified as a frame error, otherwise success. Based on the Zigbee frame error percentage, a central controller system instructs the Wi-Fi AP to regulate its token generation rate. Certain NPP applications may demand a low-powered wireless network to be prioritized over the high-powered one. To replicate this scenario by providing more priority to Zigbee traffic over Wi-Fi, we set the Zigbee frame error threshold limit to be 5%. If ZigBee reaches this threshold, the central controller instructs the Wi-Fi AP to half its token generation rate, thereby decreasing the number of Wi-Fi packets and giving more priority to Zigbee. On the other hand, if error percentage is $\leq 5\%$, the token generation rate is additively increased at a step size of 2 Mbps. This strategy ensures fair coexistence between Wi-Fi and Zigbee communication. Figure 7 demonstrates Zigbee's error percentage while coexisting with Wi-Fi over 1,000 seconds.

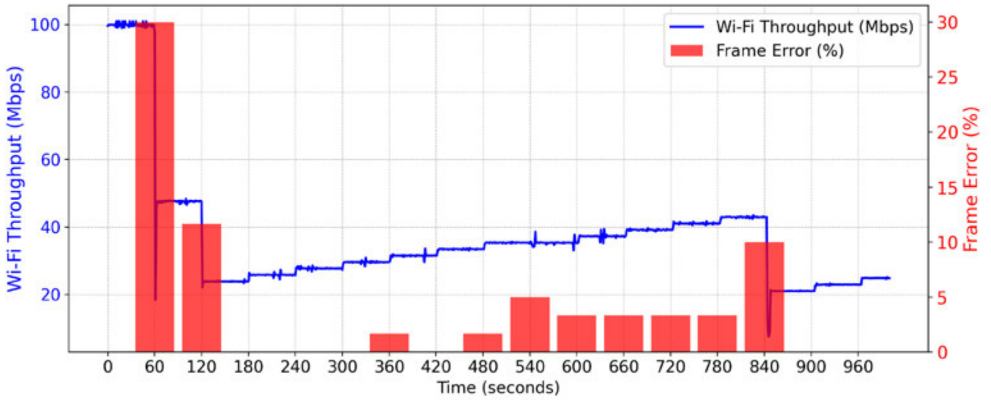
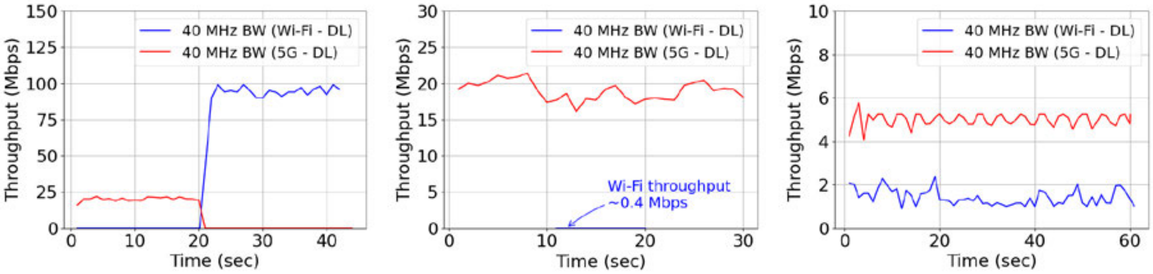


Figure 7: Coexistence performance with dynamic Wi-Fi packet rate control

As shown, upon detecting the Zigbee frame error percentage exceeding the acceptable threshold limit, the central controller instructs the Wi-Fi AP to reduce its token rate by half, consequently lowering the Wi-Fi throughput to 50 Mbps. This adjustment effectively reduces Zigbee error to 12%. The Wi-Fi token generation rate is further reduced to prioritize Zigbee traffic, resulting in a Wi-Fi throughput of 25 Mbps by the 120th second. This action brings the Zigbee error down to 0%. A low $(< 5\%)$ Zigbee error percentage is observed between 360–780 seconds, while the Wi-Fi token rate is additively increased.

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

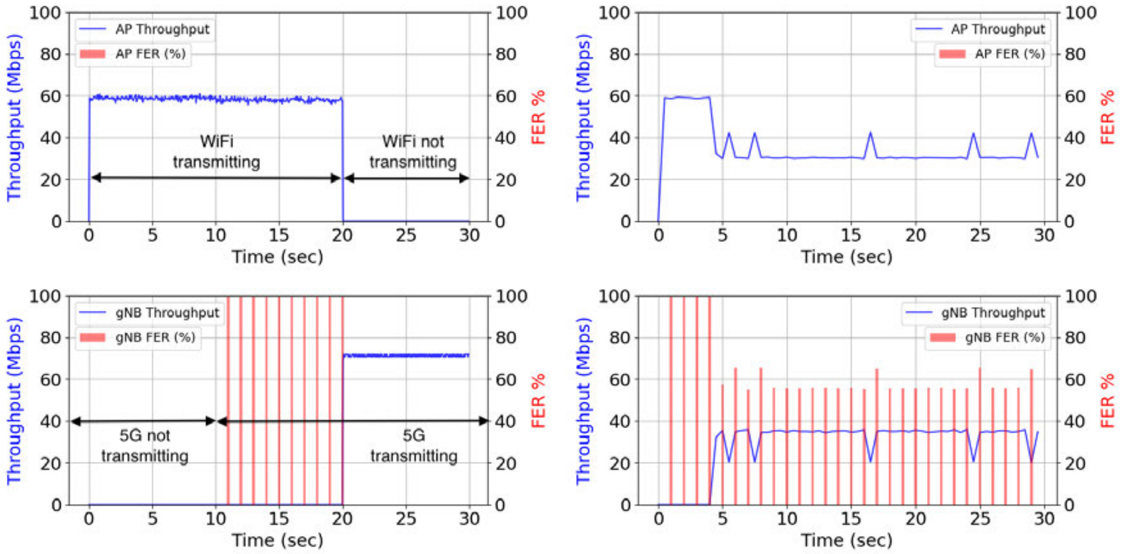
The Wi-Fi and 5G coexistence experiment was conducted using POWDER indoor lab environment.Only the downlink traffic from gNB to UE is considered for simplicity. The measured received signal power at the UE is -110 dBm. The Wi-Fi AP is located 18 feet away from the 5G gNB and UE. This setup replicates a scenario when the 5G UE may experience a weak signal in an NPP environment while coexisting with a Wi-Fi network. The throughput of such a coexisting network is illustrated in Figure 8(a). As soon as Wi-Fi transmission starts at 20th second, 5G-NR-U throughput drops to zero, and the 5G UE gets disconnected from its gNB. This occurs for two reasons. First, the LBT mechanism is absent in the 5G-OAI software stack, as the LBT is not mandatory in the United States. As a result, 5G continuously collides with Wi-Fi frames, causing the frames to be in error and preventing the UE from correctly decoding the data. Second, with the configured setup, the 5G can operate only in standalone (SA) mode, where both the data and control signals are carried in the unlicensed spectrum. Wi-Fi traffic disrupts the gNB's control signal, which is crucial for UE's synchronization, mobility management, and recovery from radio link failures. To improve the performance, we gradually reduced the Wi-Fi packet rate using TBF to determine a threshold at which 5G-NR-U can operate without interruption. Figure 8(b) shows the coexistence performance at 10th to 20th second. The Wi-Fi packet rate is reduced translating a decline in Wi-Fi throughput to 0.4 Mbps. This allows the 5G UE to maintain connection with the gNB with an approximate throughput of 20 Mbps. Figure 8(c) presents another experimentation result where both Wi-Fi and 5G-NR-U packet rate was controlled such that the achievable average throughput is 1 and 5 Mbps, respectively. The performance of our solution meets the acceptable limit for sensor data and control command for nuclear reactor use case, which is 1 Mbps [21]. This experiment achieved stable throughput and connection for both networks while coexisting.



(a) (b) (c)

Figure 8: Coexistence throughput comparison of Wi-Fi and 5G-NR-U (a) without any external control (b) with lowered Wi-Fi packet rate and (c) with reducing both Wi-Fi and 5G packet rate

To systematically incorporate the factors of 5G, which is not available in the controlled experimental environment, e.g., LBT, NSA mode (where control signal are carried in licensed spectrum) on coexistence performance, we extended our work by developing a discrete event simulator in Python. 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 coexistence performance.



(a) (b)

Figure 9: Simulation of Wi-Fi and 5G-NR-U coexistence (a) scenario 1 : without TBF control (b) simulation 2 : TBF control

As depicted in Figure 9(a), when both the Wi-Fi AP and gNB are active between the 10th to 20th seconds, the gNB experienced a high frame error rate (FER) indicating the incapability of gNB and Wi-Fi AP to detect each other. Additionally, since the UE is close to Wi-Fi AP, it received high interference resulting lower throughput. In contrast, the Wi-Fi's throughput is negligibly affected due to the close distance between the Wi-Fi client and AP.

To enhance the coexistence of both networks, we applied the TBF scheme to control the token rates, which are managed by a central controller class in the simulation. This system adopts an adaptive proportional fair queuing algorithm to dynamically adjust the token rates of both networks, aiming to ensure equitable resource allocation. Figure 9(b) shows the coexistence performance of both networks using proportional fair queuing with TBF. The Wi-Fi network applied the TBF approach in the first few seconds (5 seconds) to increase 5G's throughput. Once an optimal packet control is obtained for both networks, they continued to transmit with a steady throughput. Again, a throughput of approximately 30 Mbps indicates the performance of our proposed strategy outperforms the required limit for a nuclear application use case [21].

Our experiment was conducted in the controlled POWDER setup, limiting our ability to modify the environment. Running the same coexistence experiment in an NPP environment could lead to performance degradation. However, our proposed solution would perform effectively even within an NPP facility. In the Zigbee and Wi-Fi coexistence scenario (Section 4.1), we assume an adjustable FER threshold for Zigbee, which could be derived from baseline measurements in a real-world NPP environment without Wi-Fi interference. This threshold would account for factors such as radiation, external electromagnetic interference, and structural complexities typical of an NPP. If the FER exceeds this threshold, the central controller can dynamically adjust the Wi-Fi packet rate to maintain acceptable Zigbee FER. The same principle applies to the coexistence of Wi-Fi and 5G NR.

5. CONCLUSIONS

To achieve automation in NPP operation, coexistence of low-powered and high-powered wireless networks are essential. This paper investigated the coexistence between low-powered Zigbee with a high-powered Wi-Fi network. Also, the coexistence of advanced wireless solutions such as 5G with Wi-Fi is demonstrated with experimental and simulation results. Results showed that our proposed approach with TBF can significantly improve the overall throughput of coexisting wireless networks. Through experimental and simulation results, we have validated that our proposed strategy meets the nuclear-specific throughput requirements. Therefore, the proposed solution can be an initial step toward successful deployment of heterogeneous coexisting wireless networks in NPPs.

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