Coexistence Strategy for 5G New Radio and Wi-Fi Communication Systems

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Abstract

The proliferation of wireless technologies, particularly 5G New Radio (NR) and Wireless Fidelity (Wi-Fi) operating within the increasingly crowded unlicensed spectrum, necessitates robust coexistence strategies to mitigate interference and ensure equitable resource sharing. This study investigates the complex interactions between 5G NR and Wi-Fi systems, focusing on enhancing their concurrent performance. A discrete-event simulator was developed using Python and the SimPy library to model and evaluate various channel access mechanisms, including Wi-Fi's Distributed Coordinated Function (DCF) and NR-U's Listen-Before-Talk (LBT) based Gap Mode and Reservation Signal (RS) Mode.

The research systematically analyzes the impact of several optimization techniques on key performance metrics such as channel occupancy, channel efficiency, collision probability, and fairness (Jain's Fairness Index (JFI) and Joint Airtime Fairness). These optimizations include desynchronizing NR-U gNB transmissions, disabling NR-U's random backoff procedure in Gap Mode, and adaptively adjusting Wi-Fi's Contention Window (CW) based on network node density, applied to both symmetric and various asymmetric node configurations

Simulation results demonstrate that baseline coexistence mechanisms often lead to inefficient spectrum use and unfairness, with either Wi-Fi's aggressiveness marginalizing NR-U or NR-U's synchronized access (in RS Mode) causing high collision rates. However, a sequentially optimized Gap Mode strategy, culminating in the dynamic, density-aware adjustment of Wi-Fi's CW, proved highly effective. This Optimized Gap Mode (with dynamically adjusted Wi-Fi CW) strategy achieved near-perfect fairness (JFI > 0.97) and balanced channel occupancy ($\sim$45-50% for each technology) across various symmetric and asymmetric node densities, while maintaining consistently low collision rates (less than 8%) for both systems. This study concludes that adaptive, multi-faceted strategies, particularly those that manage the contention behaviour of incumbent technologies like Wi-Fi, are vital for facilitating scalable and efficient coexistence in shared unlicensed spectrum bands.

Contents

List of Figures

List of Tables

List of Acronyms

3GPP 3rd Generation Partnership Project.

4G Fourth Generation.

5G Fifth Generation.

5G NR Fifth Generation New Radio.

5G NR-U Fifth Generation New Radio Unlicensed.

ABS Almost Blank Subframes.

ALBT Adaptive LBT.

AP Access Point.

APIs Application Programming Interfaces.

AR Augmented Reality.

BE Best Effort.

BSF Blank Subframe.

CA Carrier Aggregation.

CC Component Carrier.

CCA Clear Channel Assessment.

CCA-CS Carrier Sense-Based CCA.

CCA-ED Energy Detection-Based CCA.

COT Channel Occupancy Time.

CSAT Carrier Sense Adaptive Transmission.

CSMA/CA Carrier Sense Multiple Access with Collision Avoidance.

CTS2S Clear to Send to Self.

CUPS Control and User Plane Separation.

CW Contention Window.

DCF Distributed Coordinated Function.

DIFS Distributed Inter-Frame Space.

DSS Dynamic Spectrum Sharing.

DSSS Direct Sequence Spread Spectrum.

ECCA Extended Clear Channel Assessment.

eICIC enhanced Inter-Cell Interference Coordination.

eMBB Enhanced Mobile Broadband.

eNBs Evolved Node Bs.

ETSI European Telecommunications Standards Institute.

EU European Union.

FBE Frame Based Equipment.

FCC Federal Communications Commission.

FHSS Frequency Hopping Spread Spectrum.

gNB Next Generation Node B.

HARQ Hybrid Automatic Repeat reQuest.

ICASA Independent Communications Authority of SA.

IoT Internet of Things.

IP Internet Protocol.

ITU-R ITU's Radiocommunication Sector.

JFI Jain's Fairness Index.

LAA LTE-Licensed Assisted Access.

LBE Load Based Equipment.

LBT Listen-Before-Talk.

LTE Long Term Evolution.

LTE-A LTE-Advanced.

LTE-U LTE-Unlicensed.

LWA LTE Wi-Fi Link Aggregation.

MAC Medium Access Control.

MCOT Maximum Channel Occupancy Time.

MCS Modulation and Coding Scheme.

MIMO Multiple Input Multiple Output.

mMTC Massive Machine-Type Communications.

mmWave Millimeter Wave.

MNO Mobile Network Operator.

MU-MIMO Multi-User MIMO.

NAV Network Allocation Vector.

NR-U New Radio-Unlicensed.

NSA Non-Standalone.

OFDM Orthogonal Frequency Division Multiplexing.

OFDMA Orthogonal Frequency Division Multiple Access.

PDCP Packet Data Convergence Protocol.

PHY Physical Layer.

PP Prioritization Period.

QAM Quadrature Amplitude Modulation.

QoS Quality of Service.

RAT Radio Access Technology.

RATs Radio Access Technologies.

RF Radio Frequency.

RS Reservation Signal.

SA Standalone.

SBA Service-Based Architecture.

SC-FDMA Single Carrier Frequency Division Multiple Access.

SDL Supplemental Downlink.

SIFS Short Inter-Frame Space.

SSID Service Set Identifier.

TDD Time Division Duplex.

TWT Target Wake Time.

U-NII Unlicensed National Information Infrastructure.

UHF Ultra-High Frequency.

URLLC Ultra-Reliable Low Latency Communications.

VHF Very High Frequency.

VR Virtual Reality.

Wi-Fi Wireless Fidelity.

WiGig Wireless Gigabit.

WRC World Radiocommunication Conference.

Chapter 1

Introduction

1.1 Background to the study

The exponential growth in mobile data traffic strains licensed spectrum capacity, compelling traditional cellular operators to leverage unlicensed bands for network augmentation [1]. Concurrently, unlicensed spectrum offers an accessible pathway for a diverse range of other entities aiming to establish local or private Fifth Generation (5G) networks, often because obtaining dedicated licensed spectrum from national regulators is not feasible or desired for their specific use cases. This dual impetus has led to technologies like Long Term Evolution (LTE) and, more recently, Fifth Generation New Radio Unlicensed (5G NR-U) operating in frequencies traditionally dominated by Wireless Fidelity (Wi-Fi) [1, 2]. Wi-Fi, an IEEE 802.11-based technology, provides ubiquitous, cost-effective connectivity and relies on a contention-based access paradigm. The convergence of Wi-Fi's distributed approach with the more scheduled nature of cellular systems within the shared, limited unlicensed spectrum creates significant coexistence challenges [2, 3]. Ensuring fair and efficient spectrum sharing, managing mutual interference, and maintaining Quality of Service (QoS) for these heterogeneous technologies are thus critical research problems [1, 2]. Consequently, the development and rigorous evaluation of robust coexistence strategies are essential for optimizing network performance and maximizing spectral efficiency for concurrently operating 5G NR-U and Wi-Fi systems.

1.2 Objectives of this study

1.2.1 Problems to be investigated

This study primarily focuses on achieving seamless coexistence between Fifth Generation New Radio (5G NR) and Wi-Fi systems by addressing interference challenges and optimizing spectrum utilization. To accomplish this, it aims to develop efficient spectrum-sharing techniques that enable heterogeneous wireless technologies to operate without significant disruption. Additionally, the research will design dynamic resource allocation algorithms to enhance bandwidth utilization, ensuring optimal network performance. Another key aspect involves implementing interference detection and mitigation strategies to improve communication reliability. Lastly, the study will evaluate the effectiveness of these coexistence strategies through simulations, analysing key performance metrics such as occupancy, efficiency, and collision probability.

1.2.2 Purpose of the study

The purpose of this study is to develop and evaluate an adaptive coexistence strategy that enhances the performance of both 5G NR-U and Wi-Fi systems operating in shared unlicensed spectrum, addressing the critical challenges of interference management, fair spectrum sharing, and dynamic resource allocation. Through simulation-based evaluations, the research aims to design a robust framework that mitigates mutual interference, ensures equitable access to the spectrum, and dynamically allocates resources to optimize network performance under varying conditions. By achieving these objectives, the study seeks to contribute a practical and efficient solution for the seamless operation of heterogeneous wireless technologies in increasingly crowded frequency bands, supporting the growing demand for high-capacity, reliable wireless connectivity.

1.3 Scope and Limitations

This study focuses on the development and simulation-based evaluation of a coexistence strategy for 5G NR-U and Wi-Fi systems operating in the shared 5 GHz unlicensed spectrum. The scope encompasses a comprehensive literature review of existing coexistence strategies, spectrum management principles, and relevant wireless communication technologies.

It also includes the design of a conceptual framework for spectrum sharing and interference mitigation, the implementation of algorithms for dynamic resource allocation and interference management, and the use of simulation tools—specifically (Python/Matlab/NS-3) to model and analyze coexistence scenarios. The effectiveness of the proposed strategy is evaluated through key performance metrics such as channel occupancy, channel efficiency, collision probability, and fairness indices.

However, the study is subject to several limitations. The reliance on a simulation-based approach, while providing valuable insights, may not fully capture real-world complexities, including hardware-specific behaviors, environmental interference, or unpredictable user traffic patterns. The use of simplified traffic models, such as fixed payload sizes for Wi-Fi and maximum channel occupancy times for NR-U, could overlook the diversity of traffic types and patterns encountered in practice. The focus on Medium Access Control (MAC)-layer mechanisms also means that potential optimizations at the physical layer or through cross-layer approaches are not explored. This focus on MAC-layer mechanisms may limit the generalizability of the proposed coexistence strategy to diverse or unseen network conditions where physical layer or cross-layer interactions play a more dominant role. These limitations should be considered when interpreting the results and assessing the applicability of the proposed coexistence strategy to practical deployments.

1.4 Plan of development

To systematically address the challenges of 5G NR-U and Wi-Fi coexistence, this study unfolds in a structured manner. The following chapters progressively build the argument, from foundational concepts and existing research through to the development, implementation, and rigorous evaluation of the proposed adaptive coexistence strategy, culminating in a discussion of the findings and recommendations for future work.

- **Chapter 1: Introduction:** Establishes the project's context, objectives, scope, and this plan of development.
- **Chapter 2: Literature Review:** Provides a comprehensive review of radio spectrum fundamentals, unlicensed spectrum operations, relevant cellular (LTE, 5G NR) and Wi-Fi technologies, existing coexistence mechanisms, and related prior research.
- **Chapter 3: Conceptual Framework for Coexistence:** Details the theoretical underpinnings of the Wi-Fi and NR-U channel access mechanisms investigated and

outlines the proposed optimization strategy for their coexistence, along with the performance metrics used for evaluation.

- **Chapter 4: Simulation Framework Implementation:** Describes the discrete-event simulator developed for this study, detailing the engineering tools used and the implementation of core simulation components modeling Wi-Fi and NR-U nodes.
- **Chapter 5: Simulation Design and Testing:** Presents the simulation setup, outlining key assumptions, parameters, and the methodology for the sequence of experiments conducted to test the coexistence strategies.
- **Chapter 6: Results and Performance Analysis:** Presents and analyzes the findings from the simulation experiments, systematically evaluating the impact of each optimization step and comparing the performance of different coexistence modes.
- **Chapter 7: Discussion of Findings:** Interprets the simulation results in greater detail, discussing the performance of each coexistence mechanism, observed trade-offs, and the implications of the findings, alongside study limitations.
- **Chapter 8: Conclusions:** Summarizes the key findings and contributions of the project, reiterating the effectiveness of the proposed optimized coexistence strategy.
- **Chapter 9: Recommendations for Future Work:** Offers suggestions for future research and potential enhancements to the developed coexistence strategies.

Chapter 2

Literature Review

This chapter provides a comprehensive review of the existing literature on spectrum management, cellular technologies in unlicensed spectrum, Wi-Fi standards, and coexistence mechanisms. It sets the foundation for understanding the challenges and solutions in the coexistence of 5G NR-U and Wi-Fi systems by exploring the evolution of these technologies and the strategies proposed to address shared spectrum use.

2.1 Radio Frequency Spectrum Overview

The Radio Frequency (RF) spectrum, a cornerstone of modern wireless communication, it spans an impressive range from 3 Hz to 3,000 GHz. This invisible resource powers an array of technologies, from radio and television to mobile networks and satellite systems. Its importance cannot be overstated, without the RF spectrum, the seamless connectivity we rely on on a daily basis would collapse. To manage this finite resource effectively, specific frequency bands are designated for distinct purposes. For instance, the Very High Frequency (VHF) band (30 MHz to 300 MHz) supports FM radio and television broadcasting, while the Ultra-High Frequency (UHF) band (300 MHz to 3 GHz) facilitates mobile communications, television, and satellite links [4]. This structured allocation ensures interference-free communication and optimizes spectrum use.

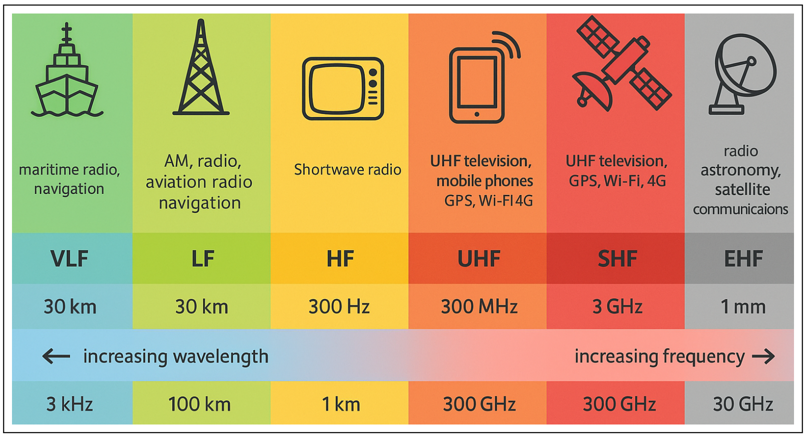

Figure 2.1: RF Spectrum Bands and Applications [5]

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2.2 Spectrum Management Principles

Managing the RF spectrum has evolved dramatically since the dawn of radios. Once a free-for-all resource, the spectrum's growing demand necessitated robust coordination to prevent chaos and interference. This shift birthed national and international regulatory frameworks [6]. Globally, the ITU's Radiocommunication Sector (ITU-R) leads the charge, allocating frequency bands, setting technical standards, and updating the Radio Regulations during World Radiocommunication Conference (WRC) [6]. These treaties ensure harmonious spectrum use across borders.

Nationally, agencies like the Federal Communications Commission (FCC) in the United States and the Independent Communications Authority of SA (ICASA) translate ITU guidelines into local policies. They manage spectrum licensing, granting users exclusive rights to specific frequencies. This system not only prevents interference but also generates significant revenue through spectrum auctions [8, 7].

2.3 Spectrum Access Paradigms

2.3.1 Licensed Versus Unlicensed Spectrum

The RF spectrum is split into licensed and unlicensed domains, each with distinct advantages. Licensed spectrum, allocated through auctions or administrative processes, grants exclusive rights to entities like Mobile Network Operator (MNO). This exclusivity ensures reliable, high-quality service and encourages infrastructure investments, such as cell towers and satellite networks [8, 7]. However, it comes at the cost of market concentration and higher consumer prices due to limited competition [7].

In contrast, unlicensed spectrum is a playground for innovation. Freely accessible within regulatory power limits, it fosters competition and empowers developers to create technologies like Wi-Fi, ZigBee, and Internet of Things (IoT) devices without navigating licensing hurdles [9, 7]. Unlicensed spectrum has driven global technological progress, complementing licensed networks by offloading cellular traffic to Wi-Fi, thus boosting overall efficiency [10, 7]. While unlicensed spectrum may reduce auction revenues, a balanced policy blending both approaches maximizes long-term economic and technological gains [7]. The challenge lies in quantifying the value of unlicensed spectrum, as its benefitial innovations and consumer empowerment are harder to measure upfront.

2.3.2 Key Unlicensed Spectrum Bands

Unlicensed spectrum spans several frequency bands each offering unique strengths. The 2.4 GHz band, one of the earliest unlicensed bands, supports Wi-Fi (802.11b/g/n), Bluetooth, and ZigBee. Its lower frequency ensures broad coverage but leads to congestion due to widespread use, offering 85 MHz across 14 channels with regional variations [11]. The 5 GHz band, with roughly 500 MHz of bandwidth, supports advanced Wi-Fi standards (802.11a/n/ac/ax) and cellular offloading technologies like LTE-Unlicensed (LTE-U) and LTE-Licensed Assisted Access (LAA). Its sub-bands (Unlicensed National Information Infrastructure (U-NII)-1 to U-NII-4) enable channel bonding up to 160 MHz, ideal for high-throughput, low-latency applications in indoor and small-cell settings [11]. These bands illustrate the trade-offs in unlicensed spectrum coverage versus capacity, accessibility versus congestion.

2.4 Cellular Technologies in Unlicensed Spectrum

2.4.1 Long Term Evolution (LTE)

LTE, developed by the 3rd Generation Partnership Project (3GPP), marked a significant advancement in mobile broadband, designed to meet increasing demands for higher data rates, lower latency, and robust Internet Protocol (IP)-based services [12]. It introduced an Orthogonal Frequency Division Multiplexing (OFDM) based air interface for the downlink and Single Carrier Frequency Division Multiple Access (SC-FDMA) for the uplink, enhancing efficiency and mitigating interference [13]. The network architecture, known as the Evolved Packet System (EPS), comprises the Evolved Universal Terrestrial Radio Access Network (E-UTRAN), featuring Evolved Node Bs (eNBs) as base stations, and the Evolved Packet Core (EPC)[12] [13].

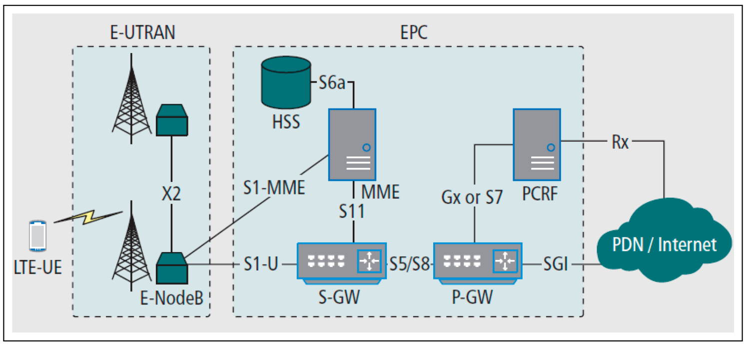

Figure 2.2: LTE Evolved Packet System (EPS) Architecture [14]

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A key enhancement introduced in LTE-Advanced (LTE-A), the evolution of LTE, was Carrier Aggregation (CA) [12, 13]. This feature allowed for the combination of multiple Component Carrier (CC) to achieve wider effective bandwidths and more flexible spectrum utilization, a foundational concept that paved the way for cellular technologies to operate across diverse and fragmented spectrum holdings, including initial explorations into unlicensed bands. The principle of CA continues to be a vital component in subsequent cellular generations, as will be discussed further in the context of 5G NR (Section 2.4.2)."

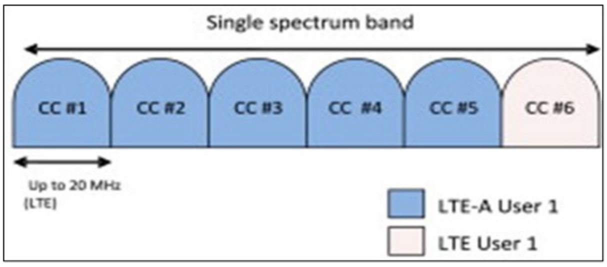

Figure 2.3: LTE-A Carrier Aggregation [12]

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2.4.2 5G New Radio (NR)

The 5G wireless mobile system represents a significant leap in communication technology, delivering faster data rates, ultra-low latency, increased capacity, and enhanced energy efficiency compared to previous generations. It supports a massive number of connected devices, making it essential for applications like the IoT, industrial automation, Augmented

Reality (AR), Virtual Reality (VR), autonomous vehicles, and other advanced services across sectors such as healthcare, automotive, smart cities, and manufacturing [6]. To cater to diverse needs, 5G services are grouped into three categories namely Enhanced Mobile Broadband (eMBB) for high-speed internet, Ultra-Reliable Low Latency Communications (URLLC) for mission-critical tasks, and Massive Machine-Type Communications (mMTC) for vast IoT networks [15, 17].

5G's prowess stems from a suite of cutting-edge technologies, Among these, CA remains a cornerstone in 5G NR, building upon its successful implementation in LTE-Advanced [12] [13]. This technology enables the system to achieve significantly wider operational bandwidths by merging multiple frequency bands (CC) into a single data stream [17]. This enhanced bandwidth is critical for delivering high data rates. CA in 5G NR supports aggregation across various spectrum types, including licensed and unlicensed bands used by New Radio-Unlicensed (NR-U). Other key technologies include Massive Multiple Input Multiple Output (MIMO) which leverages spatial multiplexing and beamforming to boost capacity, while flexible numerology adjusts subcarrier spacing (15 kHz to 240 kHz) to suit varied use cases [17]. Dual connectivity, allowing simultaneous LTE and 5G NR connections, improves mobility, while Dynamic Spectrum Sharing (DSS) enables LTE and 5G to coexist in the same licensed band, easing the transition to 5G [17]."

At its core, 5G's cloud-native Service-Based Architecture (SBA) uses standardized Application Programming Interfaces (APIs) for scalability and agility, Control and User Plane Separation (CUPS) optimizes resources and network slicing which creates tailored virtual networks for specific applications, from smart factories to emergency services [17]. 5G's deployment comes in two architectures namely Non-Standalone (NSA), which leans on Fourth Generation (4G) infrastructure for control signaling, and Standalone (SA), which unleashes 5G's full potential with a dedicated core network. These models are implemented via 3GPP-defined options (e.g., Options 2, 3, 4, 5, and 7), configuring master and secondary nodes wthin the radio access network [16, 17].

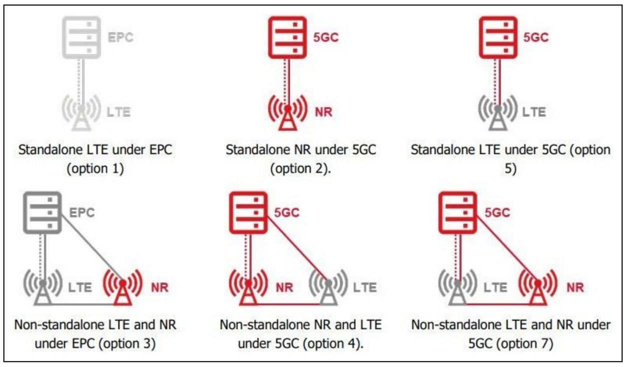

Figure 2.4: 5G NSA and SA Deployment Architectures [18]

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Spectrum is the lifeblood of 5G, divided into low-band (below 1 GHz) for wide coverage, mid-band (1–6 GHz) for balanced speed and reach, and high-band (mmWave, above 24 GHz) for ultra-fast data with limited range. High-band deployments rely on dense small cells and beamforming to overcome propagation challenges [17]. 5G taps licensed spectrum for reliability, unlicensed spectrum (e.g., NR-U) with Listen-Before-Talk (LBT) for coexistence, and shared spectrum via DSS and cognitive radio for efficiency [17].

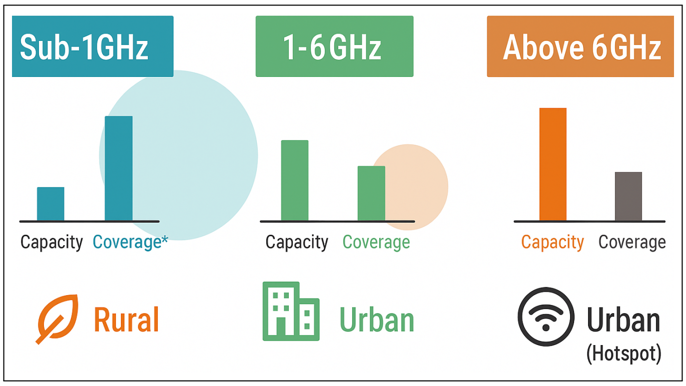

Figure 2.5: 5G NR Spectrum Regimes [18]

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2.5 Wi-Fi Standards: Evolution and Access

2.5.1 IEEE 802.11 Development and Generations

Wi-Fi, based on in the IEEE 802.11 standard, has come a long way since its 1997 debut, when it delivered a modest 2 Mbps in the 2.4 GHz band using techniques like Direct Sequence Spread Spectrum (DSSS) and Frequency Hopping Spread Spectrum (FHSS). Its Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol ensured efficient data transmission [18, 2, 19]. By 1999, 802.11a brought 54 Mbps to the 5 GHz band via OFDM, though its shorter range limited adoption. Meanwhile, 802.11b gained traction with 11 Mbps in the 2.4 GHz band. In 2003, 802.11g merged the best of both, hitting 54 Mbps with broader compatibility [2, 19].

The 2009 release of 802.11n (Wi-Fi 4) was a game-changer, supporting both 2.4 GHz and 5 GHz bands and reaching 600 Mbps through MIMO, channel bonding, and frame aggregation. Wi-Fi 5 (802.11ac), launched in 2013, pushed the 5 GHz band to 7 Gbps with wider 160 MHz channels, 256-Quadrature Amplitude Modulation (QAM) modulation, and Multi-User MIMO (MU-MIMO). Wi-Fi 6 (802.11ax), introduced in 2019, hits theoretical speeds of 9.6 Gbps across 2.4 GHz, 5 GHz, and 6 GHz bands. Features like 1024-QAM, OFDM, and Target Wake Time (TWT) boost efficiency, especially for IoT devices [2, 19]. Wi-Fi 6's cellular-inspired Orthogonal Frequency Division Multiple Access (OFDMA) and Hybrid Automatic Repeat reQuest (HARQ) reflect a shift toward coordinated spectrum use [18].

Venturing into the 60 GHz (Millimeter Wave (mmWave)) band, 802.11ad (Wireless Gigabit (WiGig)) enables ultra-fast, short-range communication, enhanced by 802.11ay's channel aggregation up to 8.64 GHz and advanced MIMO [18]. Wi-Fi 6E extends 802.11ax into the 6 GHz band, easing congestion, while Wi-Fi 7 (802.11be) aims for over 40 Gbps with 320 MHz channels and 4096-QAM, supporting 8K streaming and industrial automation [2].

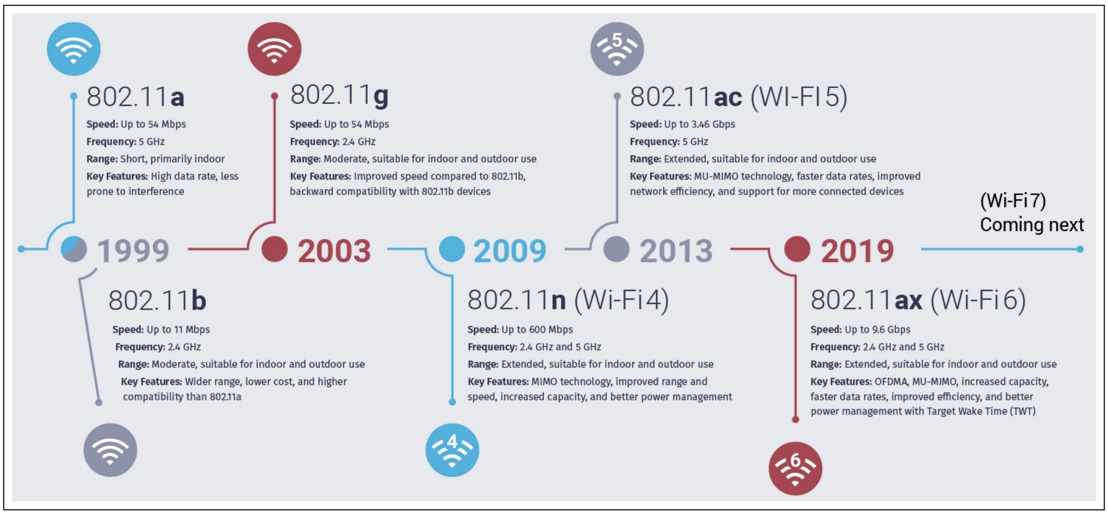


Figure 2.6: Evolution of IEEE 802.11 Wi-Fi Standards [20].

2.5.2 Clear Channel Assessment (CCA) in Wi-Fi

Wi-Fi's channel access hinges on Clear Channel Assessment (CCA), a cornerstone of its CSMA/CA protocol. CCA comes in two forms namely Carrier Sense-Based CCA (CCA-CS) and Energy Detection-Based CCA (CCA-ED) [16].

Carrier Sense-Based CCA (CCA-CS)

CCA-CS, or Preamble Detect CCA, is Wi-Fi's first line of defense against transmission collisions. By detecting Wi-Fi-specific preambles, devices determine if the channel is busy, deferring transmission to avoid interference. Upon detecting a preamble, the device extracts the transmission duration from the frame header's Duration/ID field, updating its

Network Allocation Vector (NAV) which is a virtual timer that reserves the channel. This approach saves energy by reducing constant channel sensing. The sensitivity threshold for CCA-CS in a 20 MHz channel is typically -82 dBm, flagging any stronger Wi-Fi signal as active [16, 15].

Energy Detection Based CCA (CCA-ED)

CCA-ED takes a broader approach, measuring total channel energy without decoding specific signals. This is critical for LTE-U systems, which can't interpret Wi-Fi preambles, and for Wi-Fi devices facing non-Wi-Fi interference. If energy exceeds a threshold (e.g., -62 dBm for 20 MHz channels in 802.11n), the device holds off transmission. Setting the right threshold is a balancing act, if too low the spectrum goes underused and if too high the interference spikes [16, 15].

2.6 Convergence of Cellular and Wi-Fi Technologies

The expansion of cellular systems like 5G NR-U [2] into unlicensed spectrum, long dominated by Wi-Fi, has spurred a notable technological convergence driven by competition. Though developed from distinct design philosophies for licensed (cellular) and license-free (Wi-Fi) access, both Radio Access Technologies (RATs) are increasingly adopting similar features to enhance performance in these shared bands [2]. Newer Wi-Fi standards (e.g., IEEE 802.11ax) incorporate cellular-inspired OFDMA and HARQ, while cellular technologies operating in unlicensed bands (e.g., LAA, NR-U) have implemented Wi-Fi-like LBT mechanisms for fair channel access [2, 16]. This trend, described by Lagen et al. [2] as "adopting the best of both worlds," aims for efficient utilization of large bandwidths. However, this convergence does not inherently resolve all coexistence challenges due to differing underlying operational frameworks. Thus, understanding this evolving landscape is vital before examining the specific mechanisms designed to enable their harmonious operation.

2.7 Coexistence Mechanisms in Shared Spectrum

Navigating the crowded 5 GHz unlicensed band, where LTE and Wi-Fi coexist, requires clever strategies to ensure both technologies harmonious. Coexistence mechanisms like LBT, Duty Cycling, Carrier Sense Adaptive Transmission (CSAT), Almost Blank Subframes (ABS), and Adaptive LBT (ALBT) are designed to minimize interference and promote fair spectrum sharing. These approaches balance the needs of cellular and Wi-Fi systems, fostering harmony in a shared digital space [16, 2].

2.7.1 Listen Before Talk (LBT)

LBT is the cornerstone of fair spectrum sharing in the 5 GHz band, It requires devices to sense the channel before transmitting, ensuring no one else is using it. This approach mirrors Wi-Fi's longstanding CSMA/CA protocol mentioned in section 2.5.2, a time-tested method for avoiding collisions [16, 2]. The 3GPP outlines four LBT categories namely Category 1 which skips sensing entirely, Category 2 which uses fixed-duration sensing without backoff, Category 3 which adds random backoff with a fixed contention window, and Category 4 which is the most sophisticated, it employs random backoff with a variable contention window, closely aligning with Wi-Fi's CSMA/CA for seamless coexistence [21]. In LTE's LAA, introduced in 3GPP Release 13, LBT leverages CCA to confirm channel availability, making it essential for fair operation [28]. LBT can be categorised into two types which are Frame Based Equipment (FBE) and Load Based Equipment (LBE).

Frame Based Equipment (FBE)

FBE is a time-slotted access mechanism, where the LTE system follows a predefined, fixed transmission frame structure, regardless of the current level of traffic demand or channel occupancy. It divides time into fixed frames, each with an idle period for CCA and a Channel Occupancy Time (COT) for transmission if the channel is clear. If the channel is busy, the device waits for the next cycle. This predictability is FBE's strength, making it easy to implement, but its lack of adaptability to real-time traffic or congestion can limit efficiency, especially in busy networks [21]. Compared to the more flexible LBE, FBE's rigidity often falls short in dynamic environments.

Load Based Equipment (LBE)

LBE, in contrast, adapts to the rhythm of the network. It performs CCA before each transmission, using a contention-based backoff mechanism akin to Wi-Fi's CSMA/CA. If the channel is idle, LBE transmits immediately; if busy, it enters an Extended

Clear Channel Assessment (ECCA) phase, selecting a random backoff counter from a contention window. The counter decrements with each idle slot until it hits zero, allowing transmission [21]. This dynamic responsiveness makes LBE ideal for high-density, unpredictable environments, maximizing spectrum efficiency and minimizing interference. LBE's flexibility positions it as a superior coexistence strategy compared to FBE [21].

2.7.2 Duty Cycling Method

The Duty Cycling Method offers a simpler approach, allowing LTE-U to share the 5 GHz band with Wi-Fi without constant channel sensing. It operates in fixed ON/OFF cycles where LTE-U transmits during the ON period and goes silent during the OFF period, giving Wi-Fi a chance to transmit [16, 2, 1]. Governed by European Telecommunications Standards Institute (ETSI) rules, LTE-U must stay quiet for at least 5% of each cycle to ensure fairness [1]. This predictable framework is straightforward but not without challenges.

Basic Cell ON/OFF Mechanism

The Basic Cell ON/OFF Mechanism is a straightforward time-division multiplexing (TDM) strategy, with LTE-U alternating between transmission and silence. While it enables shared access, it doesn't fully resolve coexistence issues. Wi-Fi's CSMA/CA may miss LTE-U transmissions, leading to collisions that degrade performance, especially in dense networks [16].

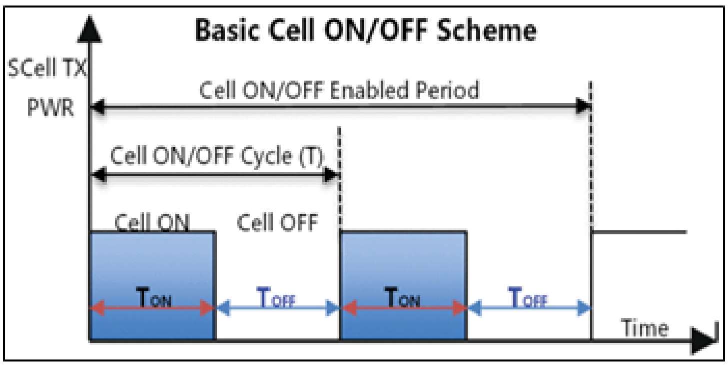


Figure 2.7: Basic Cell ON/OFF Mechanism for LTE-U Coexistence [16].

Enhanced Cell ON/OFF Mechanism

To tackle these issues, an Enhanced Cell ON/OFF Mechanism introduces Clear to Send to Self (CTS2S) signaling. Before its ON period where LTE-U broadcasts a CTS2S signal, alerting Wi-Fi devices to pause. This proactive step reduces collisions, boosting spectrum efficiency, and ensuring fairer access for both technologies [16].

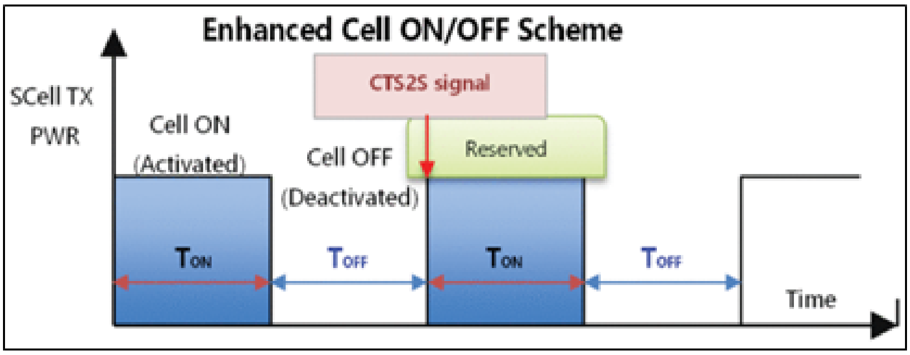


Figure 2.8: Enhanced Cell ON/OFF Mechanism with CTS2S [16].

2.7.3 Carrier Sense Adaptive Transmission (CSAT)

CSAT designed to enable fair spectrum sharing between LTE-U systems and Wi-Fi networks in the unlicensed 5 GHz band, especially in regions where LBT is not mandated [21, 22, 1]. CSAT operates as a dynamic, time-domain multiplexing technique wherein LTE-U base stations (BSs) transmit in ON/OFF cycles just like how the duty cycle mechanism operates. During OFF periods, LTE-U listens to the channel to monitor Wi-Fi activity. If significant Wi-Fi usage is detected, LTE-U reduces its transmission duration in subsequent cycles; if the medium is relatively free, LTE-U can increase its duty cycle to improve throughput [21, 1]. This dynamic adjustment helps LTE-U act as a more considerate neighbour to Wi-Fi systems, even in the absence of real-time per-transmission sensing like LBT [21, 1]. This adaptability makes CSAT a considerate neighbor, fostering coexistence without the need for constant pre-transmission checks like LBT. Its strength lies in responding to real-time network conditions, making it ideal for dense environments where traffic ebbs and flows unpredictably [22, 1].

2.7.4 Almost Blank Subframes (ABS)

ABS facilitate LTE and Wi-Fi coexistence in unlicensed spectrum, particularly where LBT is not required, such as in the U.S., China, and South Korea. Introduced in 3GPP Release

10 for enhanced Inter-Cell Interference Coordination (eICIC), ABS was originally designed to reduce interference between macro and small cells. In coexistence scenarios, ABS mutes LTE transmissions in specific subframes, creating time-domain gaps that allow Wi-Fi access with reduced interference [21, 22]. ABS coordination occurs via the X2 interface shown in Figure 2.3, but since it lacks channel sensing, it does not comply with LBT requirements in regions like Europe and Japan. It is often combined with CSAT, carrier selection, or power control to improve efficiency. Its only limitation is that more ABS subframes benefit Wi-Fi but reduce LTE throughput, requiring careful parameter tuning based on network load [21, 22]. Compared to CSAT, which alternates LTE ON/OFF cycles at the MAC layer, ABS operates at the physical layer by muting transmissions in select subframes, offering finer control but requiring coordination. ABS can also integrate with LBT or other interference management techniques for improved fairness [22].

2.7.5 Adaptive Listen Before Talk (ALBT)

ALBT has been proposed as an enhanced coexistence mechanism for LTE-U and Wi-Fi in the 5 GHz unlicensed spectrum, addressing the limitations of traditional LBT [23]. Unlike standard LBT, which requires devices to sense an idle channel before transmitting, LTE-U does not inherently follow this procedure, often leading to potential Wi-Fi disruptions. ALBT introduces dynamic channel selection, coexistence gaps, and adaptive channel sensing to enable fairer spectrum sharing. It treats all unlicensed channels as a shared pool, allowing LTE-U to switch frequencies after set intervals instead of occupying a single channel continuously. This approach prevents LTE-U from monopolizing the spectrum and provides Wi-Fi devices with more frequent access. Coexistence gaps temporarily pause LTE-U transmissions and are adjusted based on Wi-Fi traffic, increasing in duration when demand is high and decreasing when it is low. Continuous sensing and switching allow LTE-U to identify and move to idle channels, which helps reduce congestion and ensures compliance with regional spectrum-sharing regulations, such as mandatory LBT in the European Union (EU). By enhancing adaptability, ALBT supports efficient spectrum use while accommodating various regulatory environments [23].

2.8 Defining and Measuring Fairness in Coexistence

The efficient and equitable sharing of unlicensed spectrum between 5G NR-U and Wi-Fi requires a robust approach to fairness to prevent resource starvation or monopolization by either technology. Fairness in wireless networks, is a complex concept tied to impartial resource allocation, ensuring equitable channel access opportunities in coexistence scenarios [25]. In heterogeneous 5G networks, fairness becomes even more critical highlighting the need to balance resources across different tiers (e.g., macro cells, small cells) and user priorities to maintain both user-level and cell-level fairness [26].

Frame fairness around three core questions: (1) What is fairness? (2) How do we measure it? and (3) How do we achieve it? [25]. In the context of NR-U and Wi-Fi coexistence, fairness often means providing equal channel access opportunities or distributing airtime equitably. However, differences in access mechanisms such as NR-U's LBT-based approach versus Wi-Fi's distributed CSMA/CA, can lead to performance imbalances due to varying LBT parameters, backoff strategies, and transmission behaviours [25]. To measure fairness (Q2), Jain's Fairness Index (JFI) is widely adopted [25, 26]. JFI is defined as:

$$\mathrm{JFI} = \frac{(\sum x_i)^2}{n \cdot \sum x_i^2} \tag{2.1}$$

where x_i is the resource share (e.g., airtime) of technology i, and n is the number of technologies. JFI ranges from $1/n$ (worst-case fairness) to 1 (perfect fairness). Its desirable properties include scale independence, boundedness, and continuity [25]. In this study, JFI is used to evaluate the fairness of spectrum sharing between NR-U and Wi-Fi, particularly under varying node densities.

Achieving fairness (Q3) in unlicensed spectrum scenarios is challenging due to the technologies' differing contention behaviours. Strategies like adaptiveContention Window (CW) adjustments, as explored in this thesis, aim to mitigate interference and promote equitable channel access. Metrics like JFI are essential for quantifying the success of such strategies, ensuring robust coexistence frameworks that maximize performance for both NR-U and Wi-Fi [25, 26].

2.9 3GPP Technologies for Unlicensed Bands

2.9.1 LTE-Unlicensed (LTE-U)

LTE-U, pioneered by Qualcomm and championed by the LTE-U Forum (including Verizon, Ericsson, and Samsung), brings LTE to the 5 GHz unlicensed band in regions like the

U.S., China, and India, where LBT isn't mandatory [16, 11]. It offloads downlink traffic to unlicensed spectrum while keeping control and uplink signalling in licensed bands, resembling a Supplemental Downlink (SDL) setup. Built on pre-Release 13 LTE standards, LTE-U requires minimal tweaks for deployment [11]. Its a Duty Cycle-Based Coexistence Mechanism which uses fixed ON/OFF cycles, but this static approach can disrupts Wi-Fi in crowded networks, underscoring the need for more dynamic strategies [16].

2.9.2 Licensed Assisted Access (LAA)

LAA, introduced in 3GPP Release 13, is a standardized approach for LTE operation in the 5 GHz band, designed for regions such as Europe and Japan where LBT is mandatory [16], [14]. Leveraging CA, it uses licensed spectrum for control and QoS, while offloading data to unlicensed spectrum, as illustrated in Figure 2.9 [16]. LAA supports both SDL, for downlink-only traffic, and Time Division Duplex (TDD), which enables uplink and downlink over the unlicensed band but introduces added device complexity [21]. Channel access is managed using FBE and LBE LBT mechanisms. LAA has since evolved into enhanced (eLAA) and further enhanced (feLAA) versions to improve spectral efficiency and network performance [2].

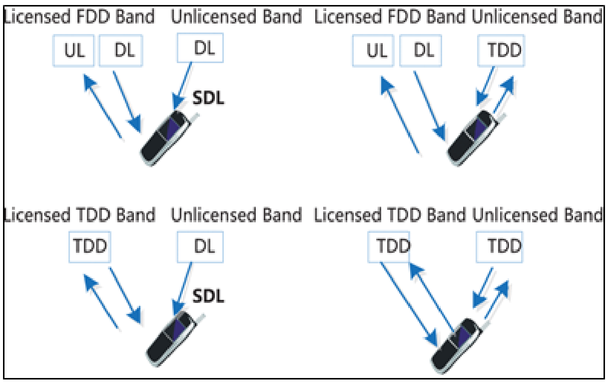


Figure 2.9: LTE Carrier Aggregation with Unlicensed Bands for LAA [16].

2.9.3 MulteFire

MulteFire is a standalone LTE technology designed to operate entirely in the unlicensed 5 GHz spectrum without relying on a licensed anchor, distinguishing it from LTE-U and LAA, which require licensed spectrum for control signaling and QoS [16]. Developed by Qualcomm, it enables independent LTE deployments similar to Wi-Fi, making it well-suited for private LTE, enterprise networks, and neutral- host scenarios where licensed spectrum is unavailable [21]. As it operates exclusively in unlicensed bands, MulteFire must fully comply with regional regulations, including LBT, to ensure fair coexistence with Wi-Fi and other technologies [16]. While it lacks the enhanced control and QoS of licensed-anchor LTE, MulteFire leverages advanced LTE physical and MAC layer techniques to deliver high performance relative to other unlicensed technologies [21]. Building on LAA and enhanced LAA (eLAA), it combines LTE's reliability with Wi-Fi-like deployment flexibility. However, its standalone operation can increase channel occupancy, potentially boosting throughput at the cost of greater interference with incumbent Wi-Fi systems [24].By merging LTE's reliability with Wi-Fi's deployment ease, MulteFire paves the way for flexible, localized networks [21].

2.9.4 LTE Wi-Fi Link Aggregation (LWA)

LTE Wi-Fi Link Aggregation (LWA), as presented in [24], enhances LTE network performance while ensuring fair coexistence with existing Wi-Fi systems. It aggregates LTE and Wi-Fi traffic by utilizing the unlicensed 5 GHz band through existing Wi-Fi access points. Unlike other LTE unlicensed solutions, LWA does not require a separate LBT protocol, instead leveraging the existing Wi-Fi protocol for LTE transmission to maintain compatibility and reduce interference. In this architecture, the base station schedules packets at the Packet Data Convergence Protocol (PDCP), transmitting some over LTE and others over Wi-Fi. These are reassembled at the PDCP layer on the user equipment (UE) side, ensuring seamless data flow. LWA enhances spectral efficiency and allows operators to reuse existing Wi-Fi infrastructure with minimal hardware upgrades, making it cost-effective and easily deployable. It promotes coexistence by using similar transmission protocols, minimizing interference and supporting fairness in spectrum usage. Wi-Fi access points can still serve non-LWA traffic via separate Service Set Identifier (SSID), while the LTE core network handles functions like authentication, billing, and security without additional gateways [24].

2.9.5 New Radio-Unlicensed (NR-U)

NR-U, introduced in 3GPP Release 16, extends 5G NR into unlicensed spectrum with native support for high efficiency [16, 2]. It supports two deployment modes namely SA, ideal for private 5G networks and enterprise use, and NSA, which aggregates unlicensed spectrum with licensed 5G carriers to enhance capacity [16, 27]. To ensure fair coexistence with technologies like Wi-Fi and WiGig, NR-U employs LBT and aligns with CSMA/CA protocols [2].

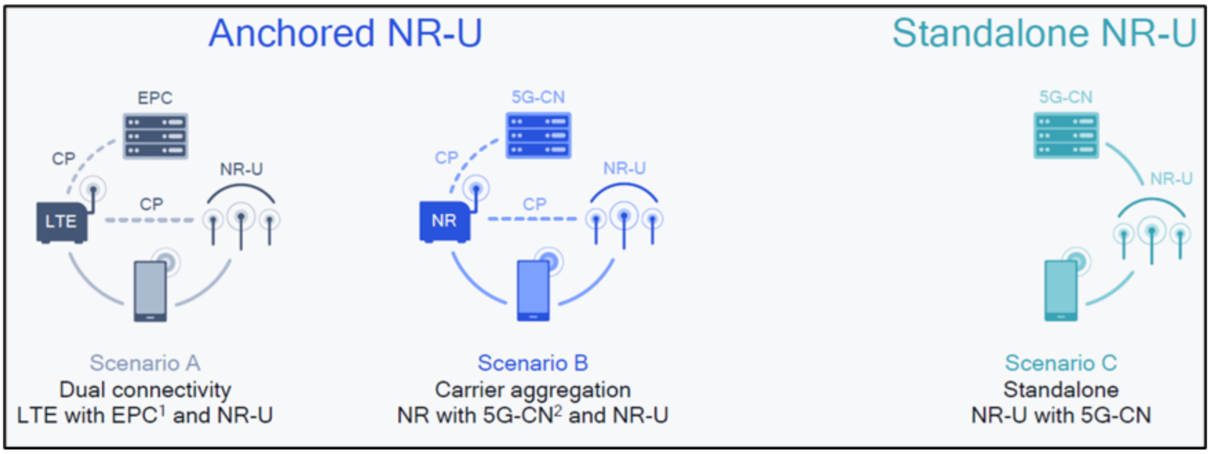


Figure 2.10: Deployment Modes for NR-U: Anchored (NSA) and Standalone [28].

NR-U includes enhancements such as flexible frame structures, grant-less uplink, and asynchronous HARQ to reduce latency and improve reliability in congested environments [2]. It operates across the 2.4 GHz, 5 GHz, 6 GHz, and 60 GHz mmWave unlicensed spectrum, supporting massive bandwidths up to 6.4 GHz, high-order MIMO, MU-MIMO, and 1024-QAM modulation [27, 2]. In mmWave deployments, beamforming is used to address propagation challenges. Despite its advantages, NR-U faces challenges related to coexistence and resource management. Complex MAC and Physical Layer (PHY) layer interactions, lack of inter-Radio Access Technology (RAT) coordination, and the opportunistic nature of LBT-based access complicate efficient scheduling and interoperability [2]. Despite its advantages, NR-U faces challenges related to coexistence and resource management. Complex MAC and PHY layer interactions, lack of inter-RAT coordination, and the opportunistic nature of LBT-based access complicate efficient scheduling and interoperability [2].

2.10 Review of Related Coexistence Research

The challenge of enabling harmonious coexistence between cellular technologies and Wi-Fi in unlicensed spectrum has spurred significant research, exploring various mechanisms and evaluation methodologies. This section critically reviews key studies pertinent to the coexistence strategies investigated in this thesis.

Early experimental work, such as that by Xu et al. [16], focused on LTE-U and its coexistence with Wi-Fi, primarily investigating duty-cycle based mechanisms like Basic Cell ON/OFF and an Enhanced Cell ON/OFF scheme incorporating CTS2S messaging.

Their field trials demonstrated that while basic duty-cycling offered some improvement over uncoordinated operation, the introduction of a reservation signal (CTS2S) significantly enhanced "peaceful coexistence," particularly by allowing Wi-Fi to better recognize LTE-U's channel occupancy. This finding underscores the general principle that clear channel reservation or yielding mechanisms are beneficial. However, Xu et al.'s work centered on LTE-U's duty-cycle approach and did not directly address the LBT based access modes of 5G NR-U which are central to this thesis, nor did it explore adaptive tuning of the incumbent Wi-Fi's parameters.

Simulation-based evaluations, like Bojović et al. [29], provided comparisons between different LTE-based unlicensed access schemes such as LAA (which uses LBT) and LTE-U (often modeled with CSAT, a form of adaptive duty-cycling). Their ns-3 study concluded that no single unlicensed LTE technology was universally superior in coexistence, with performance being highly dependent on specific traffic conditions, interference patterns, and implementation details of the politeness mechanisms. This highlights the complexity of achieving fair and efficient coexistence and suggests that static solutions are unlikely to be optimal across diverse network conditions. While informative for the LTE-unlicensed landscape, this study did not specifically investigate the nuanced LBT procedures of 5G NR-U, particularly its Gap Mode, nor the potential for dynamic, multi-faceted optimization strategies involving both the newcomer (NR-U) and the incumbent (Wi-Fi).

Time-domain solutions, such as the use of ABS or Blank Subframe (BSF) in LTE to create transmission opportunities for Wi-Fi, were explored by Almeida et al. [31]. Their simulations showed that strategically muting LTE transmissions could significantly boost Wi-Fi throughput, albeit at the cost of LTE capacity. This work reinforces the concept that creating "gaps" in the cellular transmission can benefit Wi-Fi. This is conceptually similar to the OFF periods in NR-U's RS mode or the inherent gaps created during LBT deferral in NR-U's Gap Mode. However, Almeida et al. focused on LTE and did not address the specific LBT contention resolution within NR-U's Gap mode or the optimization of parameters for both NR-U and Wi-Fi simultaneously.

More recent research, exemplified by Lagen et al. [31] and Patriciello et al. [2], has begun to address 5G NR-U coexistence, particularly in mmWave bands (60 GHz) with WiGig (IEEE 802.11ad). These studies used ns-3 simulations to compare NR-U operating with LBT (Category 3 or 4), a duty-cycle mode, and an always-on transmission mode. A key finding was that LBT and duty-cycling are vital for harmonious coexistence, significantly reducing NR-U's negative impact on WiGig compared to an always-on approach. These studies are significant as they directly address NR-U and LBT. However, their primary focus on mmWave bands means that propagation characteristics and the relative impact of interference differ from the sub-7 GHz scenarios typically considered for initial NR-U/Wi-Fi coexistence. Moreover, while they evaluated different NR-U operational modes, the optimization of the incumbent WiGig's parameters or a dynamic, density-aware adjustment of Wi-Fi's contention window in a sub-7 GHz context was outside their scope.

Collectively, the reviewed literature establishes the importance of politeness mechanisms (LBT, duty-cycling, blanking periods) for enabling coexistence. However, a significant portion of the detailed work has focused on LTE-based unlicensed access or mmWave NR-U scenarios. There remains a clear need for a focused investigation into optimizing LBT-based 5G NR-U modes, specifically Gap Mode, in sub-7 GHz bands where it directly competes with prevalent Wi-Fi standards. Crucially, existing studies have not extensively explored the strategy of adaptively tuning the incumbent Wi-Fi system's parameters (such as the CW) in response to varying network densities as a means to achieve robust fairness and efficiency for both NR-U and Wi-Fi. This thesis aims to address this gap by building upon foundational simulation work [3] to systematically evaluate and propose an optimized Gap Mode strategy that incorporates NR-U specific enhancements and a novel, density-aware dynamic adjustment of Wi-Fi's CW.

Chapter 3

Conceptual Framework for Coexistence

This chapter outlines the conceptual framework developed to address the coexistence of 5G NR-U and Wi-Fi systems. It details the operational mechanisms of Wi-Fi's Distributed Coordinated Function (DCF) and NR-U's channel access modes, introduces the proposed optimization strategy, and defines the performance metrics that will be used to evaluate its effectiveness in subsequent simulation-based analyses.

3.1 Wi-Fi Distributed Coordination Function (DCF)

Wi-Fi systems achieve channel access in shared unlicensed spectrum primarily through their DCF, a contention-based protocol operating on the principles of CSMA/CA. The fundamentals of CSMA/CA, including the CCA mechanisms (CCA-CS and CCA-ED) employed by Wi-Fi to sense the medium, were detailed in Section 2.5.2. As illustrated in (Figure 3.1), the mechanism relies on several key steps. Before any transmission attempt, a Wi-Fi station must first sense the channel. If the channel is perceived as idle for a specified Distributed Inter-Frame Space (DIFS) period, the station proceeds to a randomized backoff stage. During this stage, the station selects a random backoff interval, which is a discrete number of time slots. This selection is made from a CW, whose size is dynamically adapted based on network conditions and previous transmission success or failure, a process known as binary exponential backoff.

The station then decrements its backoff counter for each time slot that the channel remains

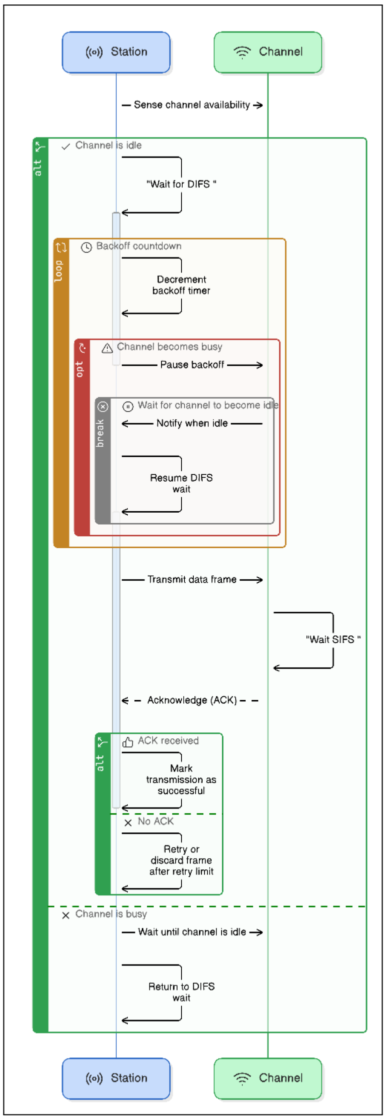


Figure 3.1: Wi-Fi Distributed Coordination Function (DCF) Flow [32].

idle. If the channel becomes busy before the counter reaches zero, the backoff procedure is paused and resumes (after another DIFS) once the channel is idle again. When the backoff timer eventually reaches zero and the channel is still idle, the station initiates its data frame transmission. Following the successful reception of this data frame, the receiving station is expected to return an Acknowledgment (ACK) frame after a Short Inter-Frame Space (SIFS) period. The reception of this ACK confirms successful data delivery to the transmitting station [3].

3.2 NR-U Channel Access Modes

As established in Section 2.9.5, 5G NR-U employs LBT mechanisms, detailed generally in Section (Catergory 4), to enable fair coexistence in shared spectrum. For this study, we focus on two primary LBT-based channel access procedures for NR-U downlink operation as defined by 3GPP and relevant literature [3, 33] namely Reservation Signal (RS) Mode and Gap Mode. The conceptual operation of these modes, particularly how they integrate LBT with NR's scheduled nature, is outlined below.

3.2.1 Reservation Signal (RS) Mode Operation

The RS mode (illustrated in Figure 3.2) allows gNBs to secure channel access while aligning transmissions with NR synchronization slot boundaries [33]. Following a successful LBT procedure (which includes an initial Prioritization Period, observation slots, and a randomized backoff from a contention window as per Category 4 LBT outlined in Section 2.7.1), an NR-U node transmits a non-data jamming signal (RS) to reserve the channel until the next synchronization slot, preventing Wi-Fi or other NR-U nodes from accessing the medium during this gap [3].This approach mimics Wi-Fi's contention resolution, where the gNB with the smallest backoff value gains priority, achieving near-perfect airtime distribution (Jain's fairness index $\sim$0.99) [33]. RS enhances fairness by enabling TDM and reducing intra-RAT (NR-U) collisions, but it is inefficient, consuming a portion of the Maximum Channel Occupancy Time (MCOT) without transmitting user data, reducing overall efficiency [33]. In dense deployments, RS incurs high collision rates and has been criticized for extending NR-U's channel occupancy beyond regulatory limits, disadvantaging Wi-Fi [33]. While RS provides a baseline for coexistence, its resource inefficiency and regulatory concerns make it less favourable than optimized alternatives like Gap mode [3].

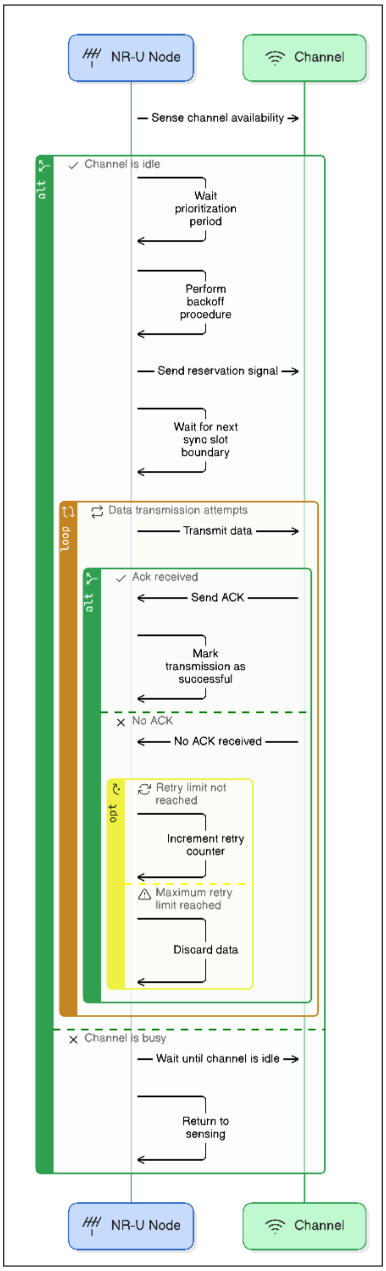


Figure 3.2: NR-U Reservation Signal (RS) Mode Channel Access [3].

3.2.2 Gap Mode Operation

Gap-based access mode is a resource-efficient alternative to RS Mode, addressing RS's inefficiencies and regulatory concerns by eliminating non-data jamming signals [3]. Instead of reserving the channel, Gap Mode introduces an idle period (i.e. gap) after or during the LBT procedure to align transmissions with NR-U's scheduled slot boundaries, ensuring that the entire MCOT is used for data transmission [33]. This significantly improves channel efficiency, making it ideal for high-throughput scenarios [3]. However, Gap Mode faces fairness challenges, particularly in dense deployments, where dominant gNBs with advantageous slot alignment can monopolize access, causing severe fairness degradation

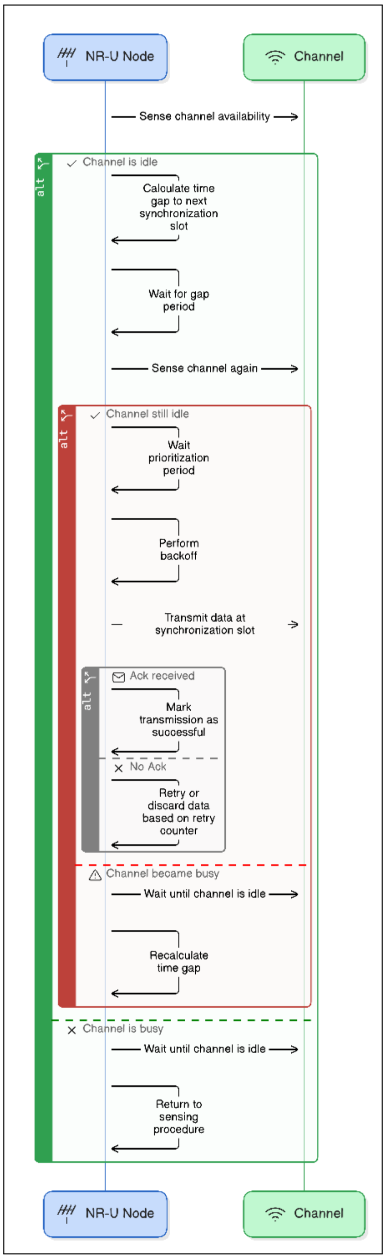


Figure 3.3: Baseline NR-U Gap Mode Channel Access [3].

[33]. Additionally, Wi-Fi can exploit the idle gap period to dominate channel access, leading to imbalanced occupancy [3]. Synchronization sensitivity further complicates performance, as misaligned slot boundaries risk persistent blocking or collisions [33].

3.3 Proposed Coexistence Optimization Strategy

Due to the drawbacks of RS, we chose to utilize gap-based access for NR-U, to address the shortcomings of the gap-based access changes will be made to it so as to increase the fairness of the method. We will use the proposed optimizations methods in [3] such as desynchronizing NR-U nodes, disabling NR-U's backoff and adjusting Wi-Fi's CW.

3.3.1 Optimizing NR-U Gap Mode Behaviour

Desynchronizing NR-U Nodes

When NR-U nodes share identical synchronization slot boundaries, they simultaneously may initiate LBT procedures after gap periods, leading to massive intra-RAT collisions as multiple nodes compete for the channel at the same time. This collision-prone behaviour not only wastes channel resources but also allows Wi-Fi to dominate during the resulting contention-free periods, as NR-U nodes are too busy colliding to secure airtime. By introducing a random desynchronization offsets to stagger NR-U nodes' synchronization slots, their LBT attempts spread out over time, mimicking Wi-Fi's statistical multiplexing. This reduces collisions among NR-U nodes and but still creates intermittent "quiet periods" where Wi-Fi can access the channel without competition [3].

Disabling NR-U's Backoff

In standard operations, NR-U nodes use a randomized backoff procedure, waiting a variable number of slots after sensing an idle channel, as shown in Figure 3.3. In Gap Mode, however, this backoff adds unnecessary latency, as nodes already wait through a mandatory gap period to align with synchronization slots. By disabling backoff, NR-U nodes can transmit immediately after the gap if the channel is clear, reducing delays. This adjustment levels the playing field, countering Wi-Fi's ability to exploit NR-U's backoff delays to dominate the channel [3].

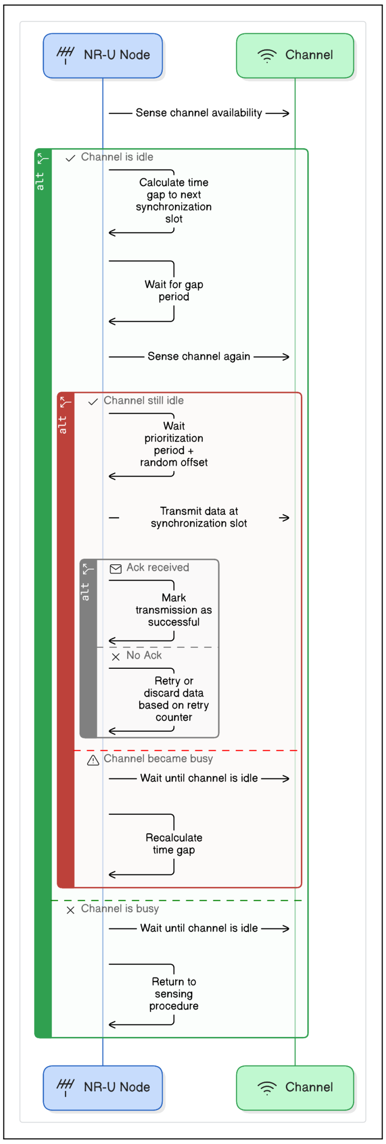


Figure 3.4: Optimized NR-U Gap Mode Channel Access

3.3.2 Adjusting Wi-Fi Contention Window (CW)

Wi-Fi's default CSMA/CA protocol employs a small CW range (see Table 5.1) enabling rapid channel access after short backoff periods. This aggressiveness allows Wi-Fi to dominate unlicensed bands, particularly during NR-U's gap periods, where synchronized nodes pause for alignment, creating opportunities for Wi-Fi to monopolize the channel. By increasing Wi-Fi's minimum CW size, the protocol forces Wi-Fi to wait longer before transmitting, effectively slowing its access rate and reducing its ability to exploit gaps [3].

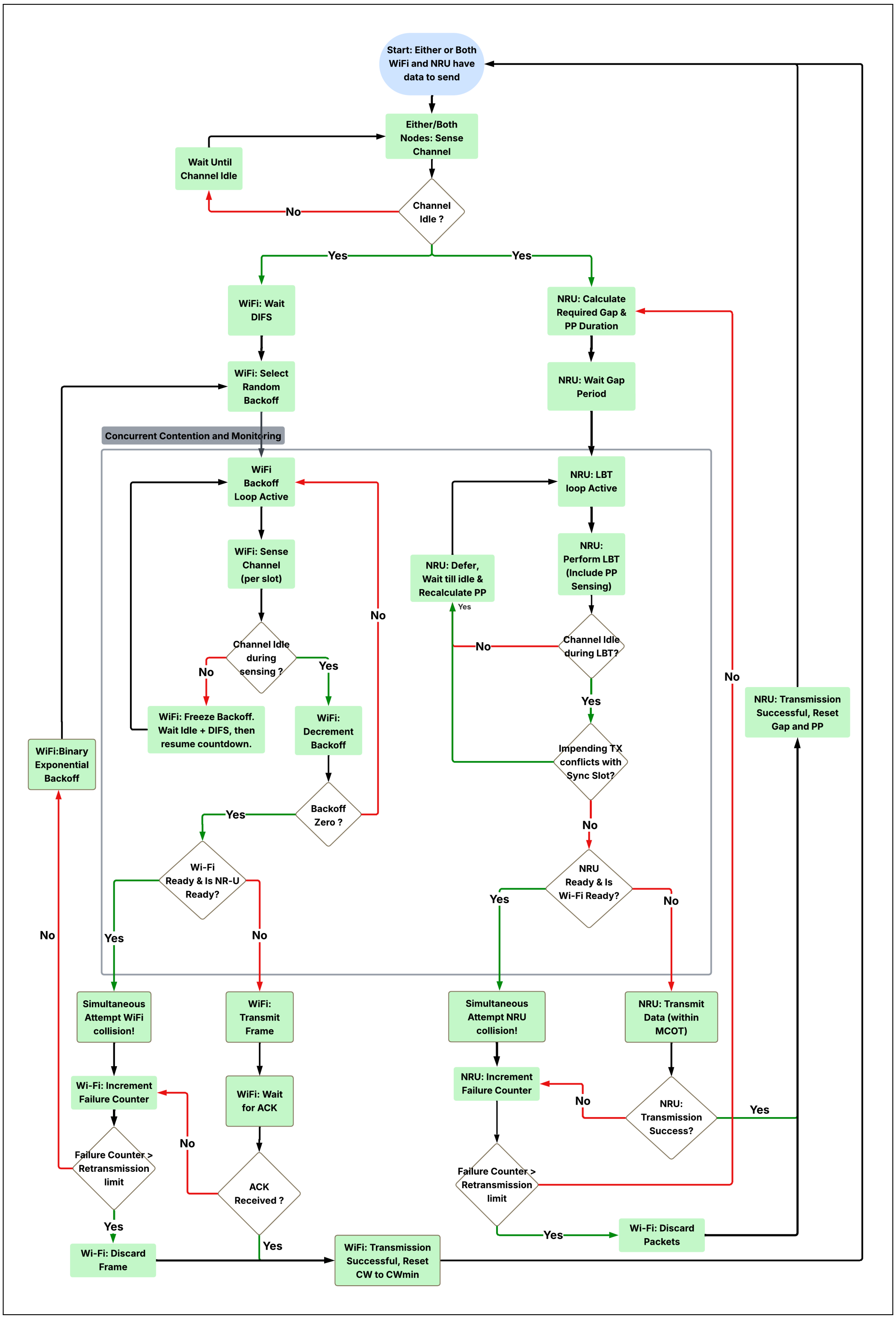


Figure 3.5: Coexistence Flowchart for Wi-Fi and Optimized NR-U Gap Mode.

3.4 Coexistence Strategy Flowchart

Figure 3.5 provides a visual representation of the dynamic operational flow for the proposed coexistence strategy, illustrating the key interactions and decision points for both Wi-Fi stations (employing DCF) and NR-U gNBs (operating under the Optimized Gap Mode Strategy). The process begins when nodes of either technology have data to transmit, initiating independent channel sensing and access procedure. Wi-Fi follows its standard DCF procedure; observing a DIFS period, then entering a randomized backoff using its (potentially dynamically adjusted) CW. Its backoff counter decrements for each idle slot time. If the channel becomes busy (e.g., due to an NR-U transmission or another Wi-Fi station), the Wi-Fi station pauses its backoff counter. It resumes decrementing after the channel is sensed idle again for a DIFS period. Upon the backoff timer reaching zero on an idle channel, the Wi-Fi station transmits its data frame and awaits an Acknowledgment (ACK)

Concurrently, an NR-U gNB operates under its Optimized Gap Mode logic, as detailed in Section 3.3.1. When it has data, it first calculates the necessary gap period to align the start of its LBT procedure such that a potential transmission would commence precisely at its next (desynchronized) synchronization slot boundary. This LBT procedure includes a mandatory Prioritization Period (PP) for initial channel sensing. Since random backoff is disabled for NR-U in this optimized strategy (as per Section 3.3.1),if the channel is sensed idle throughout the entire PP, the LBT is considered successful, and the gNB is eligible to transmit immediately following the PP, at the target synchronization slot. If the channel is sensed busy during the PP, or if an impending transmission would conflict with its synchronization slot timing, the NR-U node defers and re-initiates the process to target a subsequent synchronization opportunity.

When a node from either technology successfully contends for the channel (Wi-Fi's backoff expires on an idle channel; NR-U completes a successful LBT aligned with its sync slot), it checks for simultaneous channel wins by the other technology. If both a Wi-Fi station and an NR-U gNB (or multiple nodes of the same technology) attempt to transmit at overlapping times, a collision occurs. In such an event, both nodes typically invoke their respective failure mechanisms; Wi-Fi usually increases its CW according to binary exponential backoff and attempting retransmission, For NR-U the gNB then prepares for a retransmission attempt, which involves re-initiating the gap alignment and LBT process for a subsequent synchronization slot.

Conversely, if a node wins clear access to the channel and its transmission is successful, it proceeds with data delivery (data and ACK exchange for Wi-Fi; data transmission up to MCOT for NR-U). Following a successful transmission, a Wi-Fi station resets its CW upon receiving an ACK. Similarly, an NR-U gNB, upon successful transmission, resets its failed_transmissions_in_row counter to zero. Both technologies then prepare for their next contention cycle if more data is pending, otherwise they will keep retransmitting until the retransmission limit is reached.

3.5 Performance Evaluation Metrics

The following metrics were chosen to collectively provide a multidimensional lens to evaluate the coexistence strategy. Collision probability and efficiency focus on technical robustness, while JFI and joint metrics ensure regulatory fairness. Channel occupancy bridges both, reflecting real-world spectrum sharing. Together, they validate the optimization efforts to achieve sustainable 5G/Wi-Fi harmony in the unlicensed bands.

3.5.1 Channel Occupancy

Channel occupancy measures the proportion of time a wireless technology (e.g., Wi-Fi or NR-U) uses the shared radio channel during a simulation. It reflects spectrum access efficiency and is key to assessing fairness, interference, and overall network performance in coexistence scenarios [3]. To enable consistent comparisons across simulations, we normalized channel occupancy by expressing it as a fraction of the total simulation time. Ideally, fair coexistence is achieved when both technologies occupy the channel equally (Wi-Fi = $\sim$ 50%, NR-U = $\sim$ 50%).

$$\text{Channel Occupancy}_i = \frac{(\text{Total Data Airtime}_i + \text{Total Control Airtime}_i)}{\text{Total Simulation Time}} \tag{3.1}$$

Where i, representing the RAT we are using, it can either be Wi-Fi or NR-U.

3.5.2 Channel Efficiency

Channel efficiency quantifies the proportion of time spent transmitting user data, excluding control overhead such as ACKs and reservation signals. It reveals protocol trade-offs by highlighting how much airtime is dedicated to actual payload transmission [3]. To ensure fair comparisons across different scenarios and simulation durations, we normalized channel efficiency by expressing it as a fraction of total simulation time. This approach enables consistent evaluation across configurations like standalone Wi-Fi, NR-U with reservation signals, and coexistence setups. Ideally, fair coexistence is achieved when both technologies occupy the channel equally (Wi-Fi = $\sim$ 50%, NR-U = $\sim$ 50%).

$$\text{Channel Efficiency}_i = \frac{\text{Total Data Airtime}_i}{\text{Total Simulation Time}} \tag{3.2}$$

Where i, representing the RAT we are using, it can either be Wi-Fi or NR-U.

3.5.3 Collision Probability

Collision probability measures how often transmission attempts overlap—either between Wi-Fi and NR-U or among NR-U/Wi-Fi nodes, revealing limitations in channel access protocols. High collision rates, especially from synchronized NR-U transmissions during gap periods, indicate poor coexistence performance. This metric is essential for assessing the effectiveness of strategies like desynchronization, which distributes NR-U access attempts over time to minimize conflicts .The optimal collision probability is close to 0, indicating minimal interference and effective channel coordination [3].

$$\text{Collision Probability}_i = \frac{\text{Number of Failed Transmissions}_i}{\text{Total Transmission Attempts}_i} \tag{3.3}$$

Where i, representthe RAT we are using, it can either be Wi-Fi or NR-U.

3.5.4 Jain's Fairness Index (JFI)

JFI quantifies how evenly airtime is shared between technologies, with values ranging from 0.5 (indicating severe imbalance) to 1.0 (representing perfect fairness). This metric ensures that neither Wi-Fi nor NR-U dominates channel access, supporting evaluations of coexistence strategies. It is particularly useful in validating enhancements like contention window tuning or desynchronization, which aim to promote equitable spectrum usage [25, 3].

$$JFI = \frac{(\sum \text{airtime}_i)^2}{n \times \sum (\text{airtime}_i^2)} \tag{3.4}$$

Where $\mathbf{airtime}_i$ and n, the normalized channel occupancy (airtime) for RAT i and number of technologies respectively

3.5.5 Joint Airtime-Fairness Metric

While JFI effectively quantifies the equity of resource distribution, it does not inherently capture the overall efficiency of spectrum utilization. To provide a more holistic evaluation that considers both these critical aspects, this study adopts a Joint Airtime-Fairness Metric, as proposed and utilized in the foundational simulation work by Cichoń [3]. This metric combines JFI with the normalized total channel airtime achieved by both Wi-Fi and NR-U systems. As defined in [3], the Joint Airtime-Fairness is calculated as:

$$\text{Joint Fairness} = JFI \times (\text{airtime}_{Wi-Fi} + \text{airtime}_{NR-U}) \tag{3.5}$$

Where $\text{airtime}_{\text{Wi-Fi}}$ and $\text{airtime}_{\text{NR-U}}$, represent the normalized channel occupancy (airtime) for Wi-Fi and NR-U respectively. The rationale behind this metric, stemming from [3] and supported by general literature on network performance, is to ensure that evaluated coexistence strategies are rewarded not only for achieving equitable spectrum sharing but also for maintaining high overall channel utilization. This approach penalizes solutions that might achieve high fairness at the significant cost of underused spectrum. The metric, as used in [3], ranges from 0 to 1, with higher values indicating a better balance between fair airtime distribution and efficient channel utilization.

Chapter 4

Simulation Framework Implementation

This chapter describes the implementation of the simulation framework proposed in chapter 4 used to model and evaluate coexistence scenarios. It details the engineering tools utilized and the core components of the simulator, including the models for Wi-Fi stations and NR-U base stations.

4.1 Engineering Tools Utilized

To simulate the proposed coexistence framework, this study leverages Python, chosen for its versatility and extensive ecosystem. The core of the simulation is built upon the SimPy library, a process-based discrete-event simulation framework ideal for modelling time-sensitive interactions among wireless devices competing for channel access. SimPy's event-driven architecture efficiently captures concurrent wireless processes. For numerical computations, data handling, and visualization, libraries such as NumPy, pandas, and Matplotlib were utilized, respectively. This combination enables rapid prototyping and robust analysis, offering a gentler learning curve compared to alternatives like NS-3 or OMNeT++.

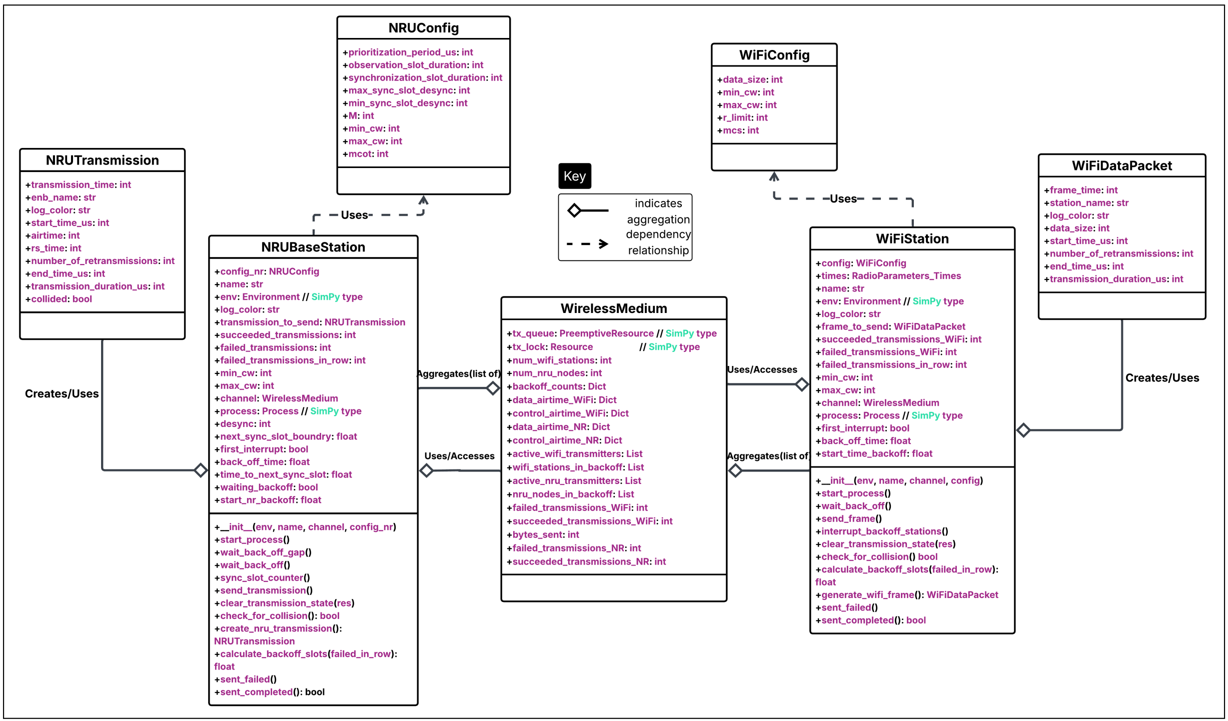


Figure 4.1: Implementation Class Diagram

4.2 Wireless Medium Model (Class: `WirelessMedium`)

The `WirelessMedium` class orchestrates channel access and contention between Wi-Fi and NR-U nodes, modeling the shared channel using SimPy resources (see Listing 4.1). It employs a `simpy.PreemptiveResource tx_queue` for prioritized transmission management and a `simpy.Resource tx_lock` for exclusive channel access, simulating LBT behaviour. Critically, WirelessMedium tracks detailed statistics essential for evaluating coexistence strategies (Chapter 3) and performance metrics (Section 3.5). These include per-technology airtime dictionaries (e.g., `data_airtime_NR`), lists of active transmitters to detect collisions, and counters for transmission successes and failures.

```
@dataclass()
class WirelessMedium:
    """
    Represents the shared wireless medium for the coexistence simulation
    This class is the central component of the simulation, tracking the state
    of the wireless channel, managing access to the shared medium, and collecting
    statistics about transmissions from both Wi-Fi and NR-U nodes
    """
    tx_queue: simpy.PreemptiveResource  # Prioritized transmission queue
    tx_lock: simpy.Resource  # Channel access lock
    num_wifi_stations: int  # Number of Wi-Fi stations
    num_nru_nodes: int  # Number of NR-U nodes
```

```
    backoff_counts: Dict[int, Dict[int, int]]  # Track backoff statistics
    data_airtime_WiFi: Dict[str, int]  # Wi-Fi data transmission airtime per station
    control_airtime_WiFi: Dict[str, int]  # Wi-Fi control signal airtime per station
    data_airtime_NR: Dict[str, int]  # NR-U data transmission airtime per node
    control_airtime_NR: Dict[str, int]  # NR-U control signal airtime per node
    active_wifi_transmitters: List = field(default_factory=list)  # Active Wi-Fi
    transmitters
    wifi_stations_in_backoff: List = field(default_factory=list)  # Wi-Fi stations
    in backoff
    active_nru_transmitters: List = field(default_factory=list)  # Active NR-U
    transmitters
    nru_nodes_in_backoff: List = field(default_factory=list)  # NR-U nodes in
    backoff
    failed_transmissions_WiFi: int = 0  # Failed Wi-Fi transmission count
    succeeded_transmissions_WiFi: int = 0  # Successful Wi-Fi transmission count
    bytes_sent: int = 0  # Total bytes successfully transmitted
    failed_transmissions_NR: int = 0  # Failed NR-U transmission count
    succeeded_transmissions_NR: int = 0  # Successful NR-U transmission count
```

Listing 4.1: WirelessMedium Class Definition

Collision detection is facilitated by maintaining lists of currently `active_wifi_transmitters` and `active_nru_transmitters`. A collision is inferred if, at the point a transmission is assessed, more than one node is present in the combined active transmitter lists, indicating an overlap in their transmission periods defined by their start times and durations. Corresponding counters for overall `succeeded_transmissions` and `failed_transmissions` for each technology are then updated. Each simulated node interacts with this shared WirelessMedium instance to report its status and retrieve channel state information.

4.3 Wi-Fi Station Model (Class: `WiFiStation`)

The `WiFiStation` class simulates an IEEE 802.11 station, implementing the DCF for channel access in the shared unlicensed spectrum, as conceptually outlined in Section 3.1. Each instance models a Wi-Fi node generating data packets, contending for the channel via CSMA/CA with binary exponential backoff, attempting transmissions, and processing outcomes.

Upon initialization (see Listing A.1), a `WiFiStation` is configured with parameters from a `WiFiConfig` object, such as CW limits and Modulation and Coding Scheme (MCS), which influence its operational timings. The station maintains internal state, including transmission success/failure counters and interacts with the shared `WirelessMedium` (Section 4.2) to log its airtime usage. The station's primary operational logic is managed by a SimPy process, `star_process`. This process continuously handles the generation of data frames; each frame is encapsulated as a `WiFiDataPacket` object (defined in Listing A.4). This object stores critical per-packet metadata such as its calculated `frame_time, data_size`, and simulation `start_time_us`, which are essential for subsequent performance metric calculations.The `start_process` then manages the multi-stage transmission attempts for these packets.

```
# From coexistence_simulator.py - WiFiStation class
def calculate_backoff_slots(self, failed_transmissions_in_row):
    """
    Calculates backoff slots using binary exponential backoff algorithm
    """
    upper_limit = (pow(2, failed_transmissions_in_row) * (self.min_cw + 1) - 1)
    upper_limit = min(upper_limit, self.max_cw)  # Cap at max_cw
    back_off = random.randint(0, upper_limit)  # Select random slot
    self.channel.backoff_counts[back_off][self.channel.num_wifi_stations] += 1
    return back_off * self.times.t_slot  # Convert slots to time
```

Listing 4.2: Backoff Calculation in WiFiStation Class

A core element of the DCF model is the randomized backoff mechanism, implemented within the `wait_back_off method` (see Listing A.6). This method uses a `calculate_backoff_slots` function to determine the deferral period by selecting a random number of slots from the current CW. This CW expands exponentially upon consecutive transmission failures, crucial for mitigating collisions (see Listing 4.2 for calculate_backoff_slots logic). After a successful backoff, which includes an initial DIFS period, the `send_frame` method (detailed in Listing 4.3) is invoked. This process involves registering as an active transmitter, acquiring exclusive channel access from the `WirelessMedium`, and signaling channel occupancy to other nodes by interrupting their backoff procedures. Collision detection is performed by querying the `WirelessMedium` for other active transmitters. The success or failure of the transmission, along with ACK reception, dictates updates to station statistics,CW adjustments (reset on success, doubling on failure), and potential retransmissions up to a defined limit.

The outcome of each transmission attempt also updates the corresponding WiFiDataPacket object (e.g., its `end_time_us`, `transmission_duration_us`, and `number_of_retransmissions` attributes), with this per-packet information then being aggregated by the `WirelessMedium` for overall performance analysis.

```
def send_frame(self): # Simplified for illustration
    self.channel.active_wifi_transmitters.append(self)
    res = self.channel.tx_queue.request(priority=(MAX_TRANSMISSION_PRIORITY - self.
    frame_to_send.frame_time))
    try:
        result = yield res | self.env.timeout(0) # Check for preemption
        if res not in result:
            raise simpy.Interrupt("There is a longer frame...")

        with self.channel.tx_lock.request() as lock: # Acquire channel for TX
            yield lock
            self.interrupt_backoff_stations() # Signal channel is busy
            yield self.env.timeout(self.frame_to_send.frame_time) # Transmit
            was_sent = self.check_for_collision() # Check outcome
        # ... (ACK handling and state clearing) ...
    except simpy.Interrupt:
        # ... (Handle preemption - also results in collision check) ...
        was_sent = self.check_for_collision()
    # ... (Update stats based on was_sent) ...
```

Listing 4.3: Core Sending Logic in WiFiStation Class (Simplified)

4.4 NR-U Base Station Model (Class: `NRUBaseStation`)

The `NRUBaseStation` class simulates a 5G NR-U Next Generation Node B (gNB), implementing the LBT-based channel access mechanisms tailored for operation in shared unlicensed spectrum. This class is central to modeling NR-U's behavior, supporting distinct operational modes—specifically the Optimized Gap Mode (focused on in this thesis, characterized by desynchronization and disabled random LBT backoff). A critical aspect of its design is the logic for aligning transmissions with NR-U synchronization slots.

Upon initialization (see A.2 for attributes like `config_nr`), an `NRUBaseStation` instance is configured with parameters from an `NRUConfig` object, such as LBT) CW settings (`config_nr.min_cw`, `config_nr.max_cw`), MCOT, and synchronization slot details. A key aspect of its initialization, particularly for enabling the desynchronized operation characteristic of the Optimized Gap Mode, is handled by the `sync_slot_counter` process (Listing 4.4). As shown, this process assigns each gNB instance a unique random desynchronization offset (`self.desync`), which is applied to its individual `next_sync_slot_boundry`. This ensures that different gNBs do not attempt LBT procedures in perfect unison. Similar to the `WiFiStation`, it maintains internal state variables for tracking transmission success and failure, including a `failed_transmissions_in_row counter`, and registers with the shared `WirelessMedium` (Section 4.2) for airtime statistics. The primary {start_process} then manages transmission attempts based on this individualized, desynchronized slot timing."

The core channel access logic for the Optimized Gap Mode is primarily encapsulated within the `wait_back_off_gap` method (conceptual logic illustrated in Listing 4.5). This method first calculates the `gap_time` required to align the start of the LBT procedure (specifically, the PP) such that a potential transmission can commence at the gNB's individual and desynchronized `next_sync_slot_boundary` (managed by the `sync_slot_-counter`). After waiting for this `gap_time`, the gNB performs the LBT procedure. This involves sensing the channel for a mandatory PP. Given that random LBT backoff is disabled in the Optimized Gap Mode (i.e., config_nr.min_cw = 0 and config_nr.max_cw = 0), if the channel is sensed idle throughout the entire PP, the LBT is considered successful. No additional random backoff slots are counted. If the channel becomes busy during the PP, the LBT attempt fails.

```
def sync_slot_counter(self):
    self.desync = random.randint(self.config_nr.min_sync_slot_desync, self.config_nr.
    max_sync_slot_desync)
    self.next_sync_slot_boundry = self.desync
    yield self.env.timeout(self.desync)
    while True:
        self.next_sync_slot_boundry += self.config_nr.synchronization_slot_duration
        yield self.env.timeout(self.config_nr.synchronization_slot_duration)
```

Listing 4.4: Sync Slot Counter in NRUBaseStation Class

Before each transmission attempt, the `NRUBaseStation` instantiates an `NRUTransmission` object via its `create_nru_transmission` method (see Listing A.5)). This object (defined in Listing A.3)) serves as a data container for the specific transmission burst, storing metadata such as total `transmission_time` (up to MCOT), `enb_name`, and effective `data_airtime`. The `send_transmission` method then manages the actual transmission burst. It interacts with the `WirelessMedium` via its `check_for_collision` method to detect if other nodes transmitted simultaneously.

```
def wait_back_off_gap(self):
   """Implements gap-mode backoff procedure for NR-U
   In gap mode, NR-U stations avoid transmission during sync slots
   and implement a backoff mechanism between sync slots.
   """
```

```
# Calculate backoff time
self.back_off_time = self.calculate_backoff_slots(self.
 failed_transmissions_in_row)
prioritization_period_time = self.config_nr.prioritization_period_us + self.
 config_nr.M * self.config_nr.observation_slot_duration
self.back_off_time += prioritization_period_time

while self.back_off_time > -1:
    try:
        # Request channel access
        with self.channel.tx_lock.request() as req:
            yield req

            # Calculate time to next sync slot
            self.time_to_next_sync_slot = self.next_sync_slot_boundry - self.env.
 now

            # Adjust backoff to avoid transmission during sync slots
            while self.back_off_time >= self.time_to_next_sync_slot:
                self.time_to_next_sync_slot += self.config_nr.
 synchronization_slot_duration

                # Wait until gap between sync slots
                gap_time = self.time_to_next_sync_slot - self.back_off_time
                yield self.env.timeout(gap_time)

                 self.first_interrupt = True
                 self.start_nr = self.env.now

                # Check channel state before proceeding
                if len(self.channel.active_nru_transmitters) +
        len(self.channel.active_wifi_transmitters) > 0:
                        # Channel busy, wait for it to become idle
                        with self.channel.tx_lock.request() as req:
                            yield req
                else:
                    # Channel idle, start backoff
                    log_transmission_event(self, f"Starting to wait backoff: ({
 self.back_off_time}) us...")
                    self.channel.nru_nodes_in_backoff.append(self)
                    self.waiting_backoff = True

                    # Wait for backoff time
                    yield self.env.timeout(self.back_off_time)
                    log_transmission_event(self, f"Backoff waited, sending frame
 ...")
```

```
                        self.back_off_time = -1
                        self.waiting_backoff = False
                        self.channel.nru_nodes_in_backoff.remove(self)

        except simpy.Interrupt:
                # Handle interruption (e.g., when channel becomes busy)
                if self.first_interrupt and self.start_nr is not None and self.
waiting_backoff:
                    log_transmission_event(self, "Backoff was interrupted, waiting
to resume backoff...")
                    already_waited = self.env.now - self.start_nr

                    # Calculate remaining backoff time
                    if already_waited <= prioritization_period_time:
                        self.back_off_time -= prioritization_period_time
                    else:
                        slots_waited = int(
                        (already_waited - prioritization_period_time) / self.
config_nr.observation_slot_duration)
                        self.back_off_time -= ((slots_waited * self.config_nr.
observation_slot_duration) + prioritization_period_time)
                        self.back_off_time += prioritization_period_time
                        self.first_interrupt = False
                        self.waiting_backoff = False
```

Listing 4.5: Gap Mode Backoff Logic in NRUBaseStation Class

The outcome of each transmission attempt subsequently dictates adjustments to the gNB's internal state parameters. Specifically, if a collision is detected by the `check_for_collision` method (or if the LBT procedure itself failed prior to an actual transmission attempt), the `sent_failed` method is invoked. A key action within this method is the incrementation of the `failed_transmissions_in_row` counter maintained by the `NRUBaseStation`. It is important to note that while this counter's increase would traditionally lead to an expanded CW for random backoff slot selection in standard LBT, within the Optimized Gap Mode (where random backoff slots are disabled), this direct influence on backoff duration is nullified. Nevertheless, the `failed_transmissions_in_row` counter remains crucial for tracking consecutive transmission failures, which can inform higher-layer retransmission strategies or enforce overall attempt limits. Conversely, upon a successful transmission where no collision is detected, the `sent_completed` method is triggered. This method not only updates the relevant success statistics and airtime usage within the shared `WirelessMedium` but also, critically, resets the `failed_transmissions_in_row` counter for that gNB back to zero, preparing it for subsequent contention cycles with a baseline failure count.

Chapter 5

Simulation Design and Testing

This chapter presents the design and testing methodology for the simulation experiments conducted to assess the coexistence strategies. It outlines the simulation environment setup, core assumptions, parameters and the sequence of scenarios tested, to evaluate their impact on performance metrics.

5.1 Simulation Environment Setup

Simulations ran on a high-performance platform featuring a 12th Generation Intel Core i5-12400 processor with 6 cores and 12 threads, paired with Windows 11 Enterprise (Build 22631). This 64-bit system efficiently handled the computational demands of discrete-event simulations, crucial for modelling time-sensitive wireless protocols like LBT and backoff mechanisms. The multi-core architecture supported parallel processing, speeding up simulations and expanding scenario coverage, while seamless integration with Python's SimPy library powered the event-driven framework.

5.2 Core Assumptions and Parameters

5.2.1 Fundamental Assumptions

The simulation models Wi-Fi and NR-U coexistence in shared unlicensed spectrum to analyze their fundamental interaction dynamics. For Wi-Fi, transmissions use a fixed payload size of 1472 bytes to standardize duration, while NR-U transmissions are modelled with a 6 ms MCOT per 3GPP standards, emphasizing channel access behaviour. Wi-Fi operates with MCS index 7 (54 Mbps, 64-QAM, 3/4 coding rate), whereas NR-U abstracts data rates to focus on LBT timing. All fundamental timing parameters for both technologies (e.g., Wi-Fi's 9μs slot time, 16μs SIFS, 43μs DIFS, and 45μs ACK timeout; NR-U's 16μs prioritization period, 9μs observation slots, and a 1000μs synchronization slot duration) align with relevant IEEE 802.11 and 3GPP standards, with specific values detailed in Section 5.2.2 and Appendix A (Tables 5.1 and 5.2).

The simulation includes 1 to 8 nodes per technology (Wi-Fi Access Point (AP) and NR-U gNB) in equal numbers to ensure a fair comparison in typical small to medium-scale deployment scenarios. Each simulation runs for 100 seconds, repeated 10 times with different random seeds for statistical robustness. Consistent with common parameterization in coexistence studies and Tables 5.1 and 5.2, channel access prioritization is uniform: Wi-Fi uses the Best Effort (BE) access category, and NR-U uses priority class 3. This ensures observed performance variations stem from the core coexistence mechanisms and tested node densities, rather than differentiated QoS handling.

Access catergory	**m for DL**	**CWmin**	**CWmax**	**MCOT [ms]**
VO	1	3	7	2.08
VI	1	3	15	4.096
BE	3	15	63	2.528
BK	7	15	1023	2.528

Table 5.1: Standard Wi-Fi Channel Access Parameters per Access Category [3].

Channel access priority class	**m for DL**	**CWmin**	**CWmax**	**MCOT [ms]**
1	1	3	7	2
2	1	3	15	3(4)
3	3	15	63	8 or 10
4	7	15	1023	8 or 10

Table 5.2: Standard NR-U Channel Access Parameters per Priority Class [3].

5.2.2 Simulation Parameters

The baseline parameters for Wi-Fi stations are outlined in Table 5.3. The 2 ms transmission time reflects a typical packet duration. The CW is configured with a CWmin of 15 and a CWmax of 63, governing the backoff procedure. A MCS) index of 7 is used, and the retransmission limit is set to 3, allowing up to three retry attempts per packet, consistent with typical IEEE 802.11n indoor settings.

Parameters	**Value**
Channel access priority class	BE
Transmission time	2ms
CWmin	15
CWmax	63
MCS	7
Retransmission limit	3

Table 5.3: Baseline Wi-Fi Simulation Parameters [3].

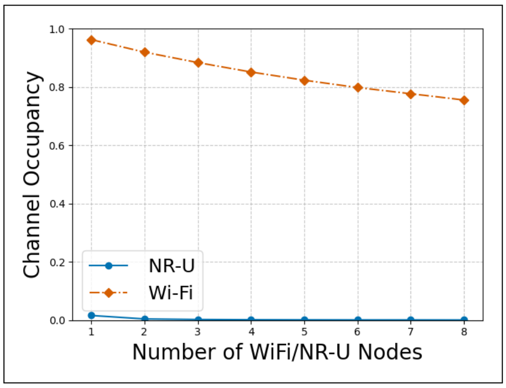
The baseline parameters for NR-U gNBs are specified in Table 5.4. To ensure a comparable backoff behavior with Wi-Fi under baseline conditions, the NR-U CW settings are also configured with a CWmin of 15 and a CWmax of 63. The Number of observation slots for LBT is set to 3. A MCOT limit of 6 ms is enforced to prevent channel monopolization by NR-U. The Synchronization slot duration is 1000, aligning with 3GPP standards for unlicensed spectrum operation. Note that the desynchronization offset parameters (`Min desync`, `Max desync`) are applicable when desynchronization is active (as discussed in Section 5.3.2) and are not part of the most basic default NR-U setup without optimizations.

Parameters	**Value**
Channel access priority class	3
CWmin	15
CWmax	63
Number of observation slots	3
MCOT limit	6 ms
Min desync	N/A
Max desync	N/A
Synchronization slot	1000

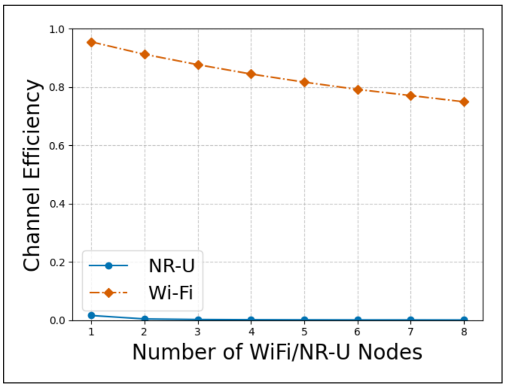
Table 5.4: Baseline NR-U Simulation Parameters [3].

5.3 Simulation Scenarios and Methodology

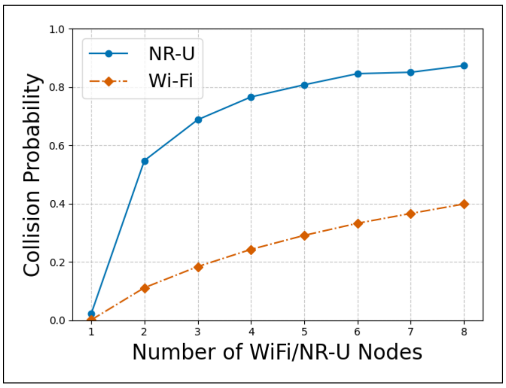
5.3.1 Baseline Coexistence: Default Gap Mode



(a) Channel Occupancy



(b) Channel Efficiency



(c) Collision Probability

Figure 5.1: Default NR-U Gap Mode Coexistence Performance vs. Node Density.

Simulations model a shared unlicensed channel with 1–8 Wi-Fi Access Points (APs) and NR-U gNBs each, using parameters from Tables 5.3 and 5.4. Channel occupancy, efficiency, and collision probability (defined in Section 3.5) are plotted against node density to assess coexistence under increasing network scale, as shown in Figure 5.1.

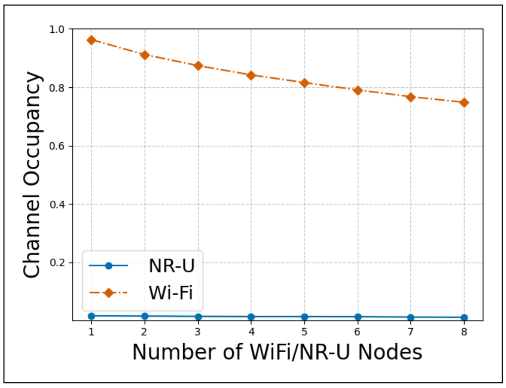
connect thenm

5.3.2 Sequential Optimization of Gap Mode

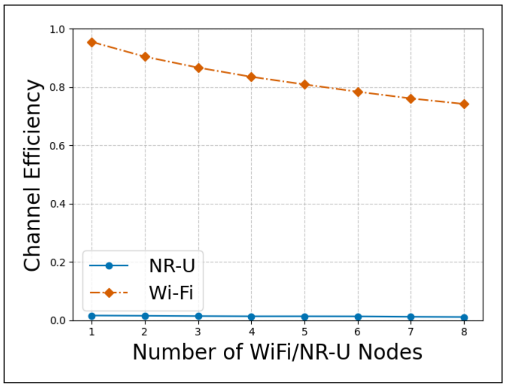
To enhance NR-U's performance and Wi-Fi coexistence in Gap Mode, the following optimizations were simulated sequentially, building upon the parameters defined in Tables 5.3 (Wi-Fi) and 5.4 (NR-U). Results were evaluated via channel occupancy, efficiency, and collision probability metrics.

Desynchronized NR-U gNBs

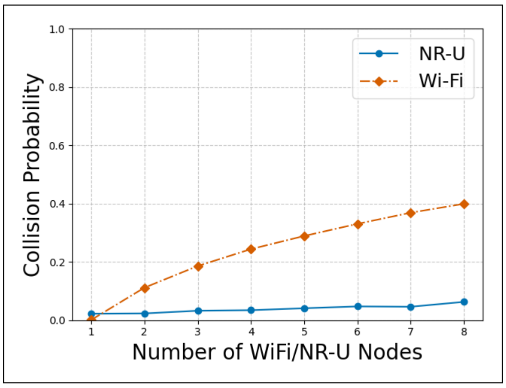
To reduce simultaneous NR-U channel access attempts stemming from shared synchronization boundaries, a random desynchronization offset was introduced. Simulations were conducted using the baseline Wi-Fi parameters from Table 5.3 and the baseline NR-U parameters from Table 5.4, with the modification that each gNB's backoff start time received an additional random offset between 0 and 1000 (i.e., the Max desync value for NR-U was set to 1000). This staggers the LBT attempts of different gNBs. The impact of this desynchronization is shown in Figure 5.2.



(a) Channel Occupancy



(b) Channel Efficiency

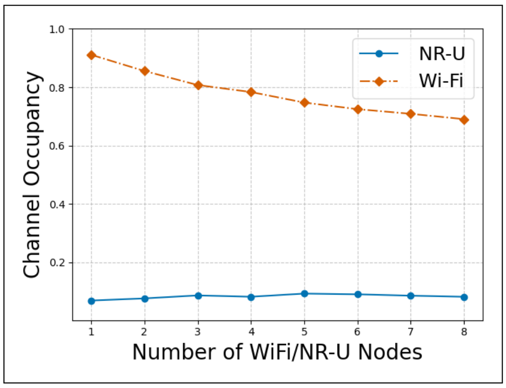


(c) Collision Probability

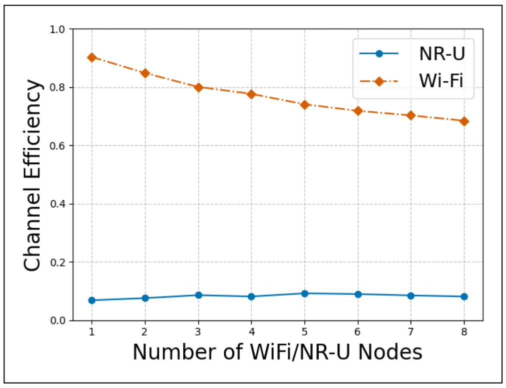
Figure 5.2: Impact of NR-U Desynchronization in Gap Mode vs. Node Density.

Disabling Backoff

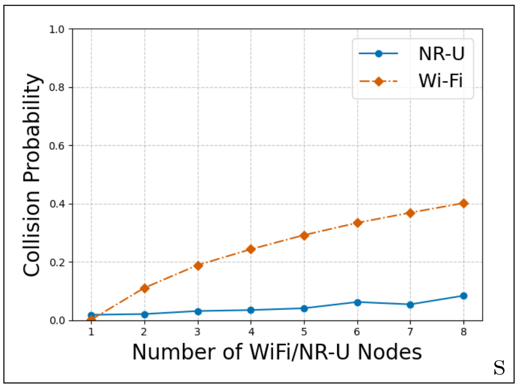
In Gap Mode, NR-U nodes already observe a mandatory gap period for synchronization alignment. The additional randomized backoff procedure (defined by CWmin and CWmax in Table 5.4) adds potentially unnecessary delay. Building upon the desynchronized setup from Section 5.3.2, the NR-U random backoff mechanism was disabled by setting the NR-U `CWmin` and `CWmax` parameters to 0. This allows desynchronized NR-U nodes to transmit immediately after their gap period concludes, provided the channel is sensed idle. Wi-Fi parameters remained unchanged as per Table 5.3, and NR-U desynchronization (0-1000 offset) remained active. Results of disabling the NR-U backoff are shown in Figure 5.2.



(a) Channel Occupancy



(b) Channel Efficiency



(c) Collision Probability

Figure 5.3: Impact of Disabling NR-U Backoff in Gap Mode vs. Node Density.

5.3.3 Fixed Wi-Fi CW Adjustment Strategy

To further balance channel access following NR-U desynchronization and backoff disabling, the Wi-Fi CW was adjusted. This was approached in two steps. First, a parameter sweep simulation was conducted to determine an optimal fixed CW value for Wi-Fi that promotes fairness in a representative scenario (3 Wi-Fi APs vs 3 NR-U gNBs). The NR-U parameters used were those established in Section 5.3.2 (desynchronized, no backoff). The Wi-Fi `CWmin` and `CWmax` were set to the same value and varied systematically, as outlined in Table 5.5. The resulting channel occupancies (Figure 5.4) indicated that a CW value of approximately 197 yielded the most balanced channel sharing for this specific density.

Parameters	Value
Number of Wi-Fi access points	3
Number of NR-U gNBs	3
Transmission time	2ms
CWmin	32
CWmax	512
CWstep	48
MCS	7
Retransmission limit	3

Table 5.5: Wi-Fi CW Sweep Simulation Parameters (3 APs vs. 3 NR-U gNBs).

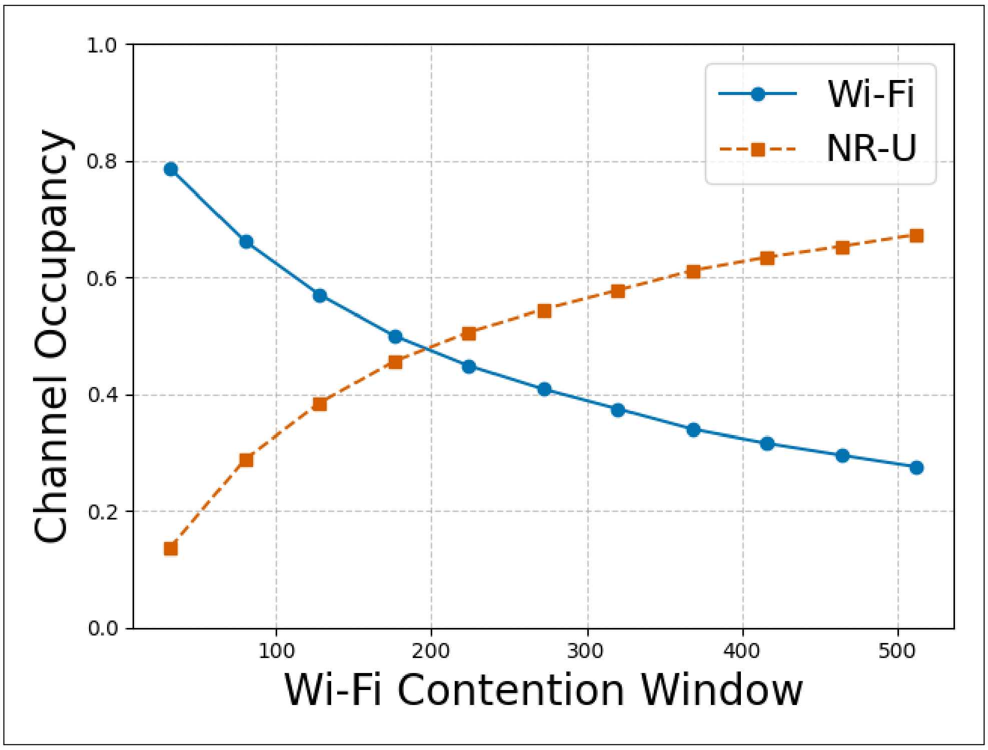
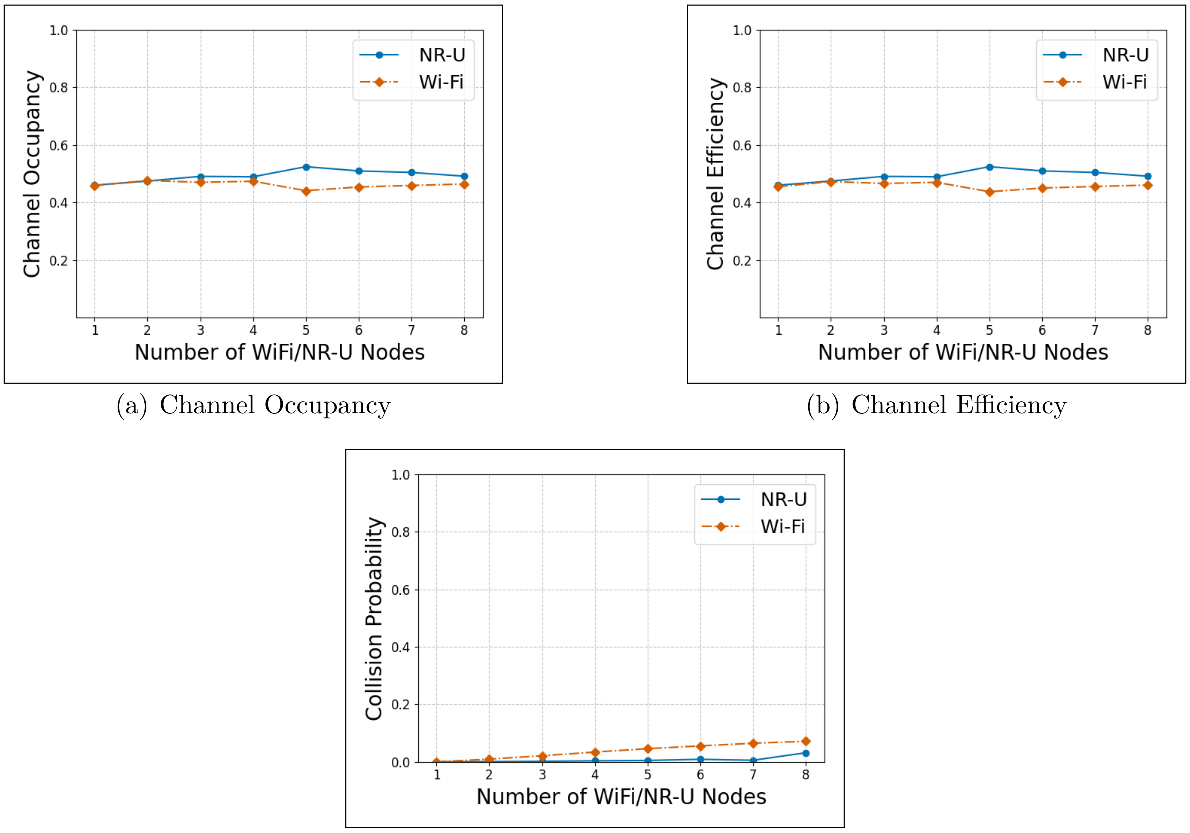


Figure 5.4: Wi-Fi and NR-U Channel Occupancy vs. Wi-Fi CW Size (3 APs vs. 3 gNBs).

Second, simulations were conducted across all node densities (1-8 nodes per technology) using this identified fixed Wi-Fi CW value. Specifically, the Wi-Fi parameters from Table 5.3 were modified so that both `CWmin` = 197 and `CWmax` = 197. NR-U parameters remained desynchronized and without backoff, as described in Section 5.3.2. The effect of using this fixed, adjusted Wi-Fi CW setting across different network scales was assessed by measuring channel occupancy, efficiency, and collision probability, presented in Figure 5.5.



(a) Channel Occupancy

(b) Channel Efficiency

(c) Collision Probability

Figure 5.5: Impact of Fixed Wi-Fi CW (197) with Optimized NR-U Gap Mode vs. Node Density.

5.3.4 Dynamic Wi-Fi CW Adjustment Strategy (Optimized Gap Mode)

While the fixed Wi-Fi CW adjustment from Section 5.3.3 improved fairness, analysis of its impact shows that it does not fully equalize spectrum across all network scales (Figure 5.5(a)). Analysis revealed that a single, static CW value did not consistently achieve equitable spectrum sharing for all tested node densities. This observation strongly suggested that the optimal Wi-Fi CW for balanced coexistence is inherently dependent on the number of competing Wi-Fi and NR-U nodes.

To empirically validate this hypothesis and quantify the relationship between node density and optimal Wi-Fi CW, the parameter sweep methodology described in Section 5.3.3 (originally conducted for a 3-node vs 3-node scenario) was manually repeated for a range of symmetrical node densities (i.e., equal numbers of Wi-Fi APs and NR-U gNBs, from 1 to 8 nodes per technology). For each density, the Wi-Fi CW value that yielded the most balanced channel occupancy between Wi-Fi and NR-U was identified. The results of this extensive investigation, which clearly demonstrate the density-dependent nature of the optimal Wi-Fi CW, are summarized in Table 5.6.

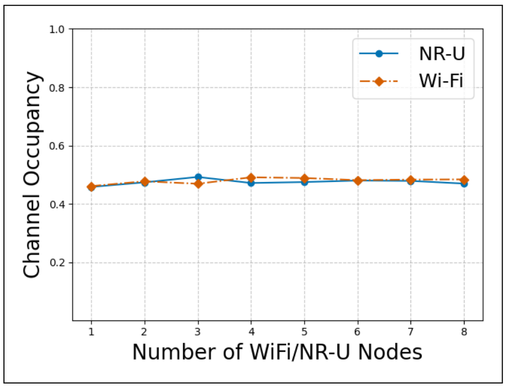
Number of Wi-Fi Nodes	Number of NR-U Nodes	Contention Window
1	1	196
2	2	197
3	3	197
4	4	183
5	5	161
6	6	174
7	7	174
8	8	177

Table 5.6: Optimal Wi-Fi CW Sizes for Balanced Occupancy vs. Node Density.

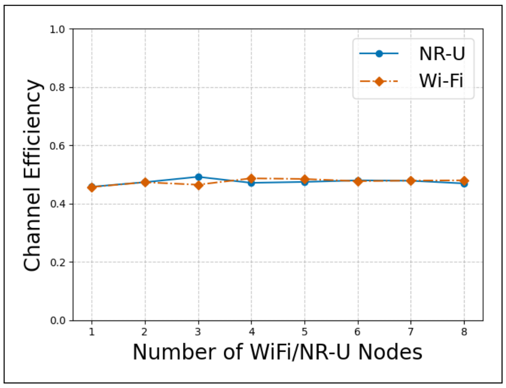
The results revealed a non-linear and non-monotonic relationship which is derived from the observations noted below:

- **Low Density (1-3 nodes per technology):**The optimal Wi-Fi CW was found to be relatively high and stable ($\sim$ 196-197). This is attributed to the need to make Wi-Fi significantly more polite to counterbalance the assertiveness of the optimized NR-U, even with few NR-U nodes.
- **Moderate Density (3-5 nodes per technology):**A decreasing trend in the optimal Wi-Fi CW was observed (from 197 down to 161). As the number of assertive NR-U nodes increases, Wi-Fi's CW must be reduced to allow Wi-Fi to contend more effectively and maintain its share of channel occupancy.
- **Higher Density (5-8 nodes per technology):**The optimal Wi-Fi CW showed a slight tendency to increase again (from 161 up to 177). In highly congested scenarios, a marginal increase in Wi-Fi's politeness may be necessary to manage overall channel contention and prevent excessive collisions, thereby allowing both technologies to achieve balanced access.

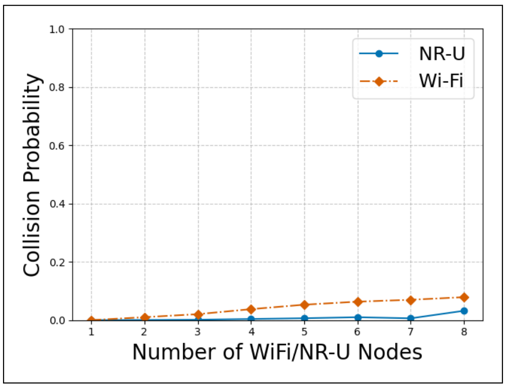
Due to this complex, density-dependent behavior, a direct mathematical formula was not pursued. Having established and quantified this density-dependent relationship Table 5.6, an automated mechanism for dynamically determining and applying the optimal Wi-Fi CW was then implemented for the final 'Optimized Gap Mode' simulations. This was achieved using the `find_optimal_cw` function within the `coexistence_node_sweep.py` utility script. When generating the results for the 'Optimized Gap Mode' (Figure 5.6),



(a) Channel Occupancy



(b) Channel Efficiency



(c) Collision Probability

Figure 5.6: Performance of Optimized Gap Mode Strategy vs. Node Density

for each specific node density under test, this function was invoked. It programmatically performs its own internal CW sweep analysis (or utilizes pre-cached sweep data if available for that density from a previous `run_cw_sweep call`) to calculate the optimal Wi-Fi CW that balances channel occupancy, mirroring the principle demonstrated by the manually derived values in Table 5.6.

This dynamically calculated optimal CW was then immediately used to set both the `CWmin` and `CWmax` for all Wi-Fi stations for the subsequent simulation runs at that particular node density. The core objective was to ensure that the simulation framework could adaptively select the best Wi-Fi CW to maintain balanced channel occupancy as network conditions (specifically, node density) changed. Throughout these 'Optimized Gap Mode' simulations, NR-U parameters remained constant as established in Section 5.3.2 (desynchronized, no random backoff). The resulting performance metrics of this fully optimized strategy, where the Wi-Fi CW was dynamically determined and applied on a per-density basis by the simulation script, are presented in Figure 5.6.

5.4 Coexistence Performance with Asymmetric Node Densities

While the sequential optimization detailed in Section 5.3 focused on symmetric node densities (equal numbers of Wi-Fi APs and NR-U gNBs), practical wireless deployments frequently exhibit an imbalance. For instance, a dense Wi-Fi environment might encounter only a few active NR-U cells, or conversely, an extensive NR-U deployment might interact with a limited number of Wi-Fi APs. To comprehensively evaluate the proposed Optimized Gap Mode (adjusted Wi-Fi CW) strategy, its performance under such asymmetric conditions was investigated. This investigation extended the principles of dynamic Wi-Fi CW adjustment, as established for symmetric scenarios in Section 5.3.4, to these imbalanced configurations, executed using the `coexistence_asymetric_node_sweep.py` script. The core idea is that the Wi-Fi CW must be specifically optimized for each unique combination of Wi-Fi and NR-U nodes to achieve the most equitable channel sharing.

To ensure a diverse evaluation, eight unique pairs were randomly selected from a predefined list (`POTENTIAL_ASYMMETRIC_PAIRS` in the script). This list was carefully curated to encompass various combinations where the number of Wi-Fi APs (ranging from 1 to 8) was not equal to the number of NR-U gNBs (also ranging from 1 to 8). The curation also aimed to exclude configurations where preliminary analysis indicated that achieving balanced channel occupancy would necessitate Wi-Fi CW values far outside the practically tested range, an issue exemplified by scenarios such as 1 Wi-Fi AP versus 6 NR-U gNBs (as illustrated in Figure 5.7, showing occupancy curves that may not intersect within typical CW limits).

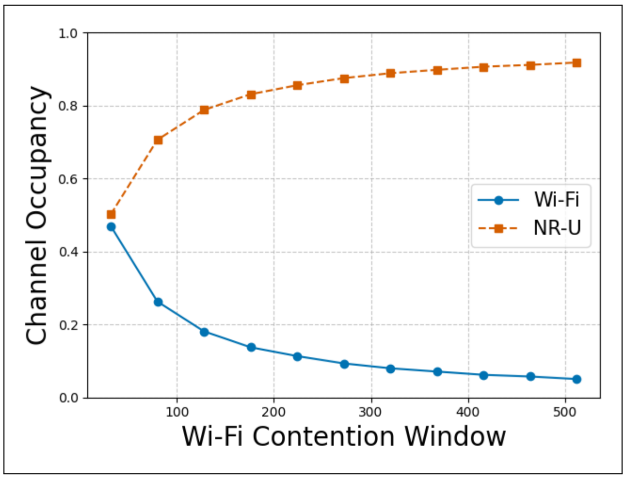
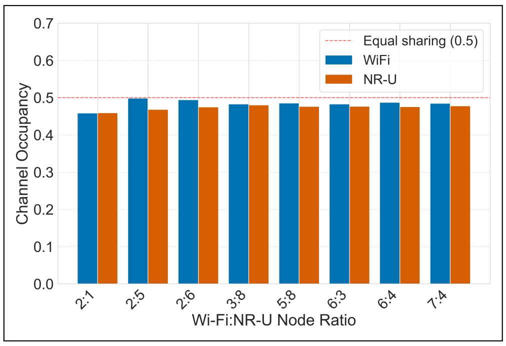


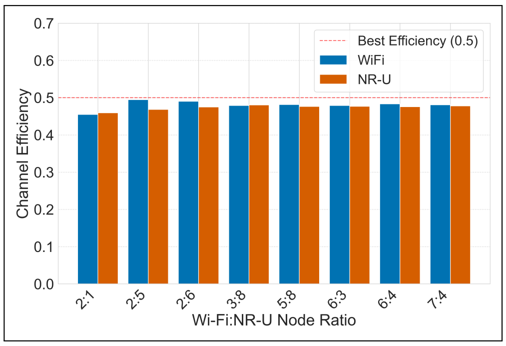
Figure 5.7: Optimal CW for 1 Wi-Fi APs and 6 NR-U gNBs

Following the selection, the process of determining a pair-specific optimal Wi-Fi CW, as detailed in Section 5.3.4 for symmetric cases, was applied individually to each of these selected asymmetric pairs. For a given pair (X Wi-Fi APs vs. Y NR-U gNBs), invoked a utility function (`find_optimal_cw`) to perform an internal Wi-Fi CW parameter sweep exclusively for that (X, Y) configuration. During this internal sweep, NR-U operated under its Optimized Gap Mode baseline (desynchronized transmissions, no random LBT backoff). The resulting Wi-Fi and NR-U channel occupancy data across the range of tested Wi-Fi CWs for that specific pair were then analyzed to identify the Wi-Fi CW value that yielded the most balanced channel occupancy. This value was deemed the optimal Wi-Fi CW for that particular asymmetric node density.

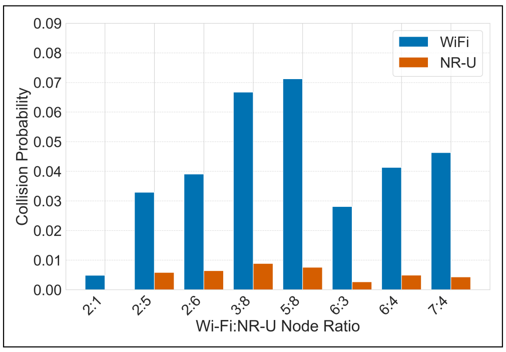
Once this pair-specific optimal Wi-Fi CW was determined, it was used to set both the `min_wifi_cw` and `max_wifi_cw` for all Wi-Fi stations in the subsequent performance evaluation simulations for that asymmetric pair. NR-U gNBs consistently operated under the Optimized Gap Mode configuration. This entire procedure—determining the pair-specific optimal Wi-Fi CW and then conducting 10 performance evaluation runs using that CW, was repeated for each of the eight randomly chosen asymmetric pairs. The aggregated performance outcomes of the Optimized Gap Mode strategy across these diverse asymmetric node configurations are presented in Figure 5.8.



(a) Channel Occupancy



(b) Channel Efficiency



(c) Collision Probability

Figure 5.8: Impact of Coexistence Strategy on Asymetric Node Distribution .

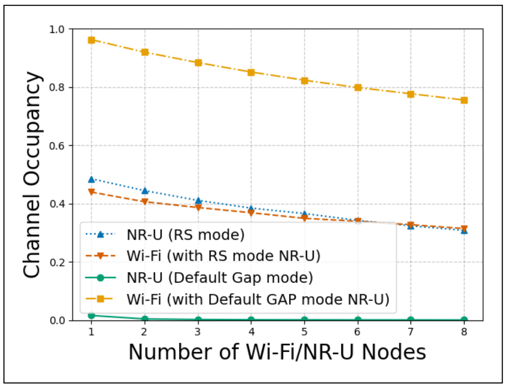
Chapter 6

Results and Performance Analysis

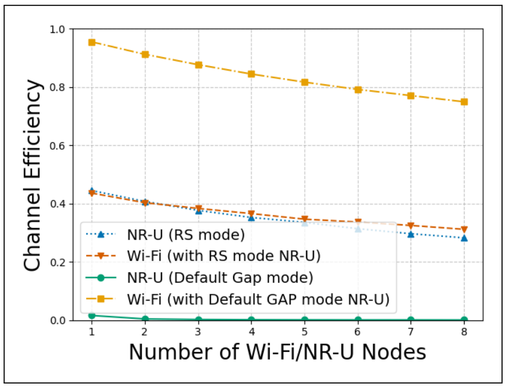
This chapter presents and analyzes the results from the simulation experiments described in Chapter 5. It systematically evaluates the performance of various coexistence mechanisms, including baseline and optimized modes, across the key metrics, providing quantitative insights into their effectiveness.

6.1 Baseline Comparison: RS Mode vs. Default Gap Mode

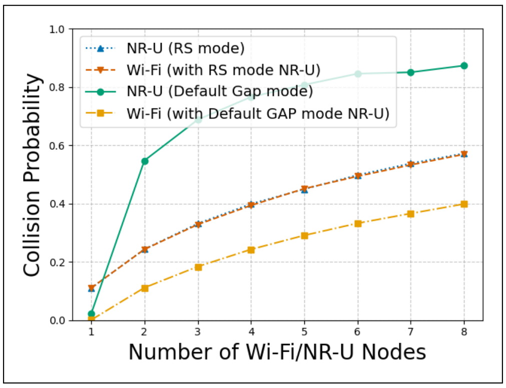
The default Gap Mode proved unsuitable for equitable coexistence from the results shown in Figure 6.1. Wi-Fi dominated channel access (occupancy $\sim$0.96 down to $\sim$0.76), effectively marginalizing NR-U, whose occupancy and efficiency dropped to near-zero levels ($\sim$0.016 to $\sim$0.0006) at higher densities. Despite minimal channel usage, NR-U suffered extremely high collision rates (up to $\sim$0.87) due to synchronized access attempts colliding with Wi-Fi. RS Mode successfully enforced fairness, granting NR-U significant channel access ($\sim$0.48 down to $\sim$0.31 occupancy). However, the reservation overhead reduced NR-U's efficiency ($\sim$0.44 to $\sim$0.28), and the synchronized nature of access led to severe collision probabilities for both technologies (rising above $\sim$0.56 at 8 nodes). While fair, RS Mode is inefficient and prone to collisions under load.



(a) Channel Occupancy



(b) Channel Efficiency

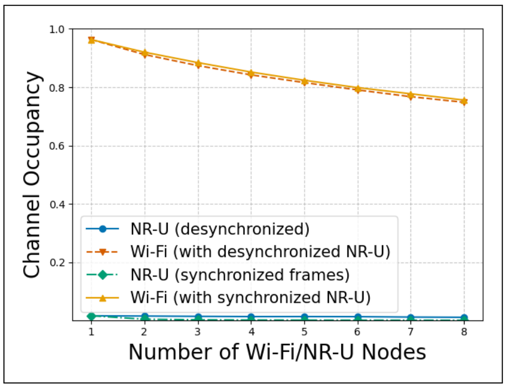


(c) Collision Probability

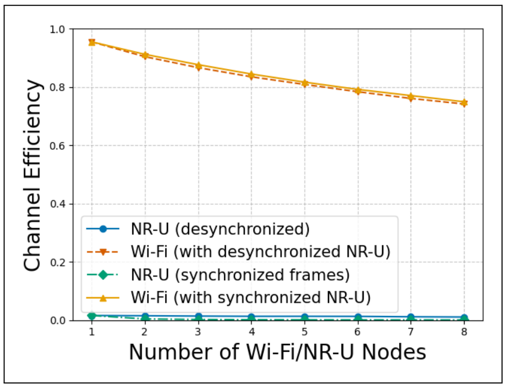
Figure 6.1: NR-U RS Mode vs. Default Gap Mode Coexistence Performance

6.2 Impact of NR-U gNB Desynchronization

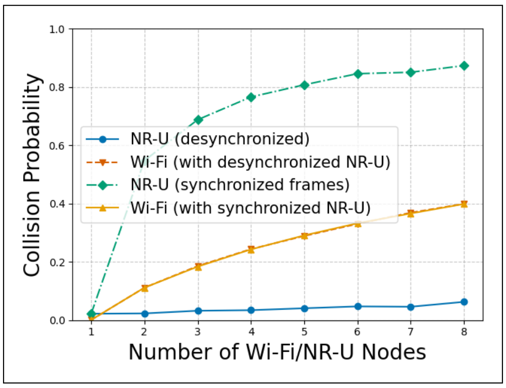
Introducing the random desynchronization offsets to gNB transmissions significantly benefited NR-U without notably impacting Wi-Fi's dominant performance as shown in Figure 6.2. Desynchronization stabilized NR-U's low occupancy and efficiency (∼0.01), preventing the collapse observed in the synchronized case. Most importantly, it drastically reduced NR-U's collision probability from a peak of ∼0.87 down to ∼0.06. Wi-Fi collisions remained largely unchanged, increasing with density to ∼0.40. Desynchronization is crucial for NR-U's basic viability in Gap Mode but insufficient for achieving fairness.



(a) Channel Occupancy



(b) Channel Efficiency

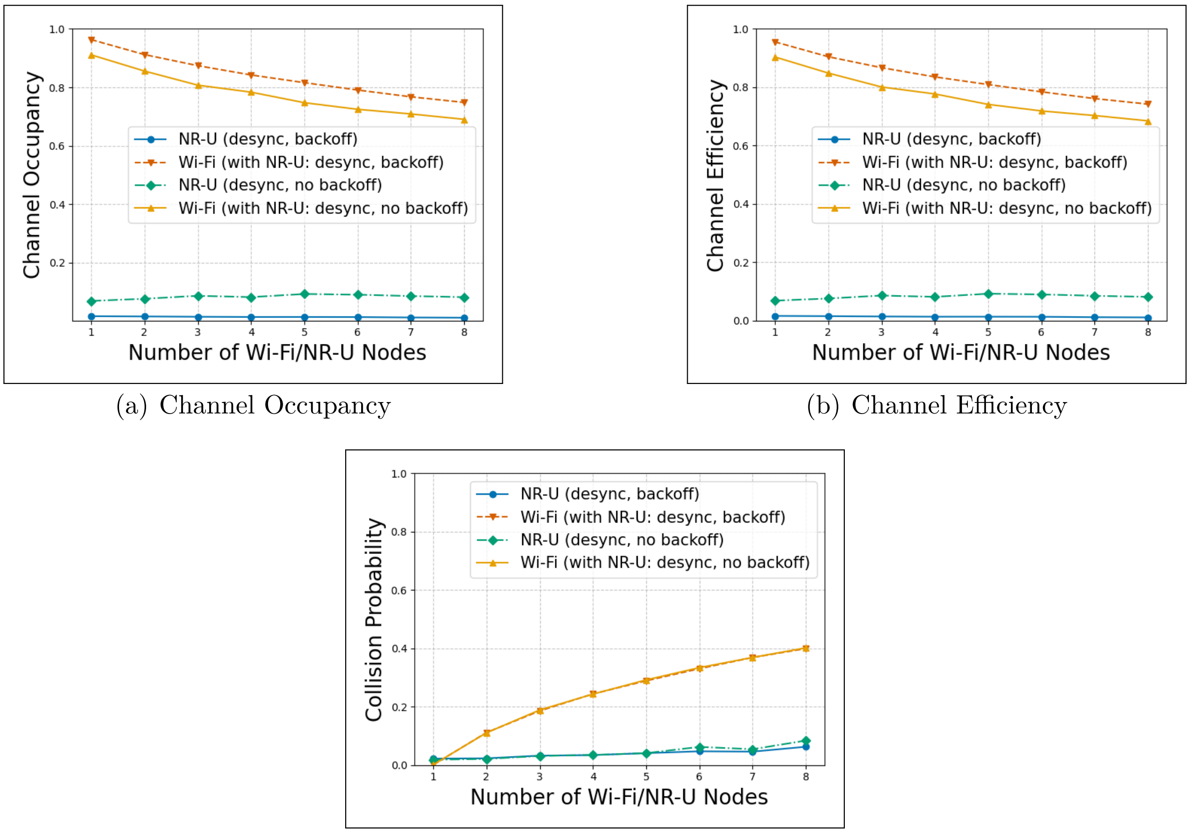


(c) Collision Probability

Figure 6.2: Gap Mode Performance: Before and After NR-U Desynchronization.

6.3 Impact of Disabling NR-U Backoff

Building upon desynchronization, disabling NR-U's random backoff (allowing immediate transmission post-gap if the channel is clear) enhanced NR-U's channel access as shown in Figure 6.3. This increased NR-U's occupancy and efficiency approximately five- to seven-fold (reaching ∼0.08 at 8 nodes) compared to the desynchronized-only scenario. This improvement came at the direct expense of Wi-Fi's channel share, reducing its occupancy range from ∼0.96-0.75 down to ∼0.91-0.69. Notably, this modification had minimal effect on collision rates; NR-U collisions remained low (less than 8%), and Wi-Fi collisions still climbed to ∼40%. with Wi-Fi, whose share decreased to a similar level. Crucially, adapting the Wi-Fi CW slashed Wi-Fi's collision probability from ∼40% down to below 8%, while NR-U collisions remained minimal (less than 5%). This demonstrates that managing Wi-Fi's contention is vital for achieving simultaneous fairness and low collision rates.



(a) Channel Occupancy

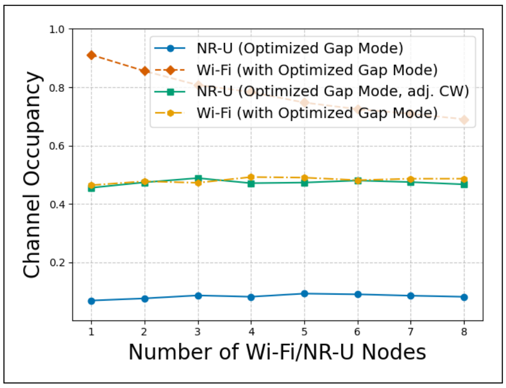
(b) Channel Efficiency

(c) Collision Probability

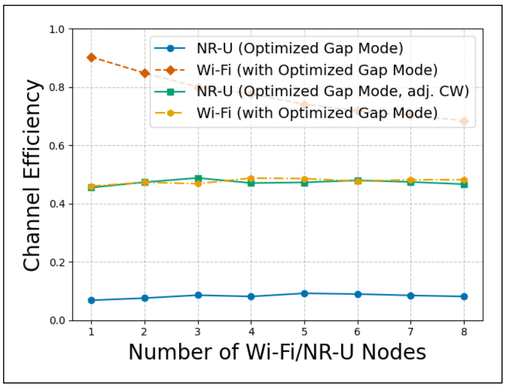
Figure 6.3: Gap Mode Performance: Before and After Disabling NR-U Backoff

6.4 Impact of Dynamic Wi-Fi CWAdjustment

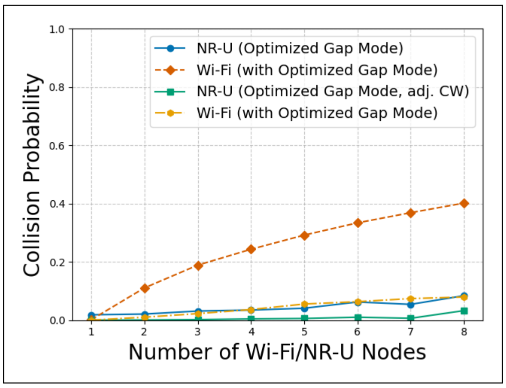
The final optimization involved dynamically adjusting Wi-Fi's CWbased on node density, applied within the desynchronized, no-NR-U-backoff framework. This yielded the Optimized Gap Mode. The adjustment dramatically balanced channel access, NR-U occupancy and efficiency surged to a stable ∼45-48%, achieving parity with Wi-Fi, whose share decreased to a similar level. Crucially, adapting the Wi-Fi CW slashed Wi-Fi's collision probability from ∼40% down to below 8%, while NR-U collisions remained minimal (less than 5%). This demonstrates that managing Wi-Fi's contention is vital for achieving simultaneous fairness and low collision rates as shown in Figure 6.4.



(a) Channel Occupancy



(b) Channel Efficiency

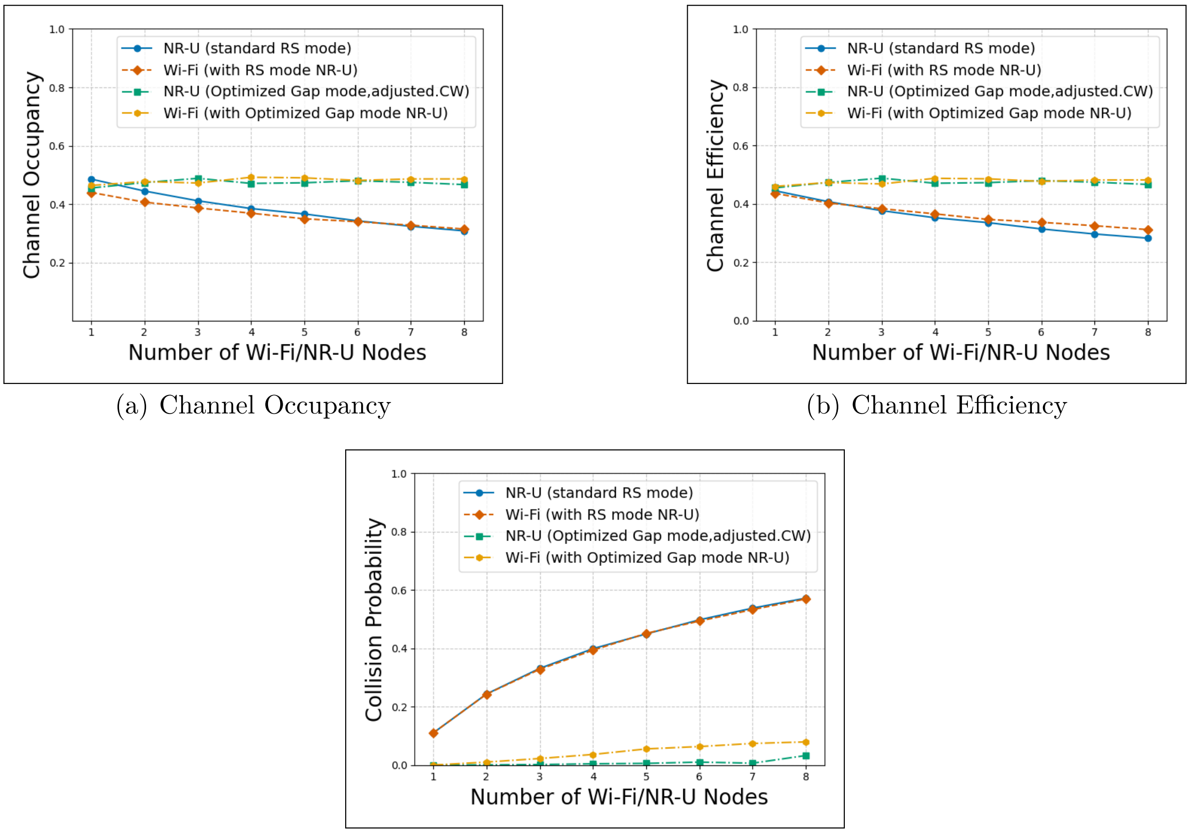


(c) Collision Probability

Figure 6.4: Optimized Gap Mode Performance: Before and After Dynamic Wi-Fi CWAdjustment

6.5 Performance: Optimized Gap Mode vs. RS Mode

Comparing the Optimized Gap Mode (plus adjusted Wi-Fi CW) against the baseline RS Mode highlights the former's advantages in Figure 6.5. While both achieve fairness initially, RS Mode's occupancy and efficiency degrade significantly with node density (∼31% each at 8 nodes). Optimized Gap Mode (plus adjusted Wi-Fi CW) maintains higher, stable, and balanced occupancy and efficiency for both technologies (∼47% each at 8 nodes). The most significant difference lies in collision probability where RS Mode suffers escalating collisions (∼ 56%), whereas Optimized Gap Mode maintains low collision rates for both NR-U (less than 5%) and Wi-Fi (less than 8%). Optimized Gap Mode offers superior scalability, efficiency, and collision performance.



(a) Channel Occupancy

(b) Channel Efficiency

(c) Collision Probability

Figure 6.5: Optimized Gap Mode vs. RS Mode Performance.

6.6 Fairness Evaluation: Jain's Index

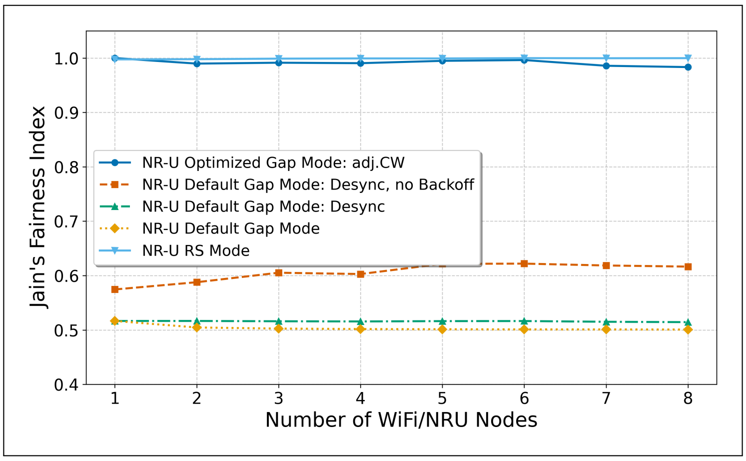


Figure 6.6: Jain's Fairness Index (Jain's Fairness Index (JFI)) Across Coexistence Modes.

JFI, measuring channel time equity, confirmed the Optimized Gap Mode's (plus adjusted Wi-Fi contention window) success, achieving near-perfect fairness (JFI > 0.97) comparable to RS Mode (JFI $\approx$0.99). In contrast, intermediate Gap Mode variations exhibited poor fairness: default synchronized ($\sim$0.50), desynchronized only ($\sim$0.51), and desynchronized with no NR-U backoff (∼0.57-0.62). Only the fully optimized configuration or RS Mode provided equitable access by this metric (Figure 6.6).

6.7 Fairness and Utilization: Joint Airtime Metric

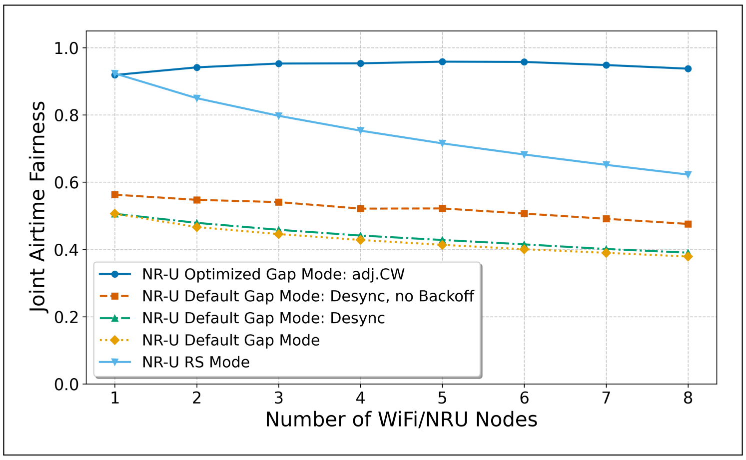


Figure 6.7: Joint Airtime Fairness Across Coexistence Modes.

The Joint Airtime Fairness metric, incorporating both equity and overall channel utilization, further underscored the Optimized Gap Mode's effectiveness (Figure 6.7). It consistently maintained the highest scores across all node densities (average ∼0.92-0.95), indicating both fair sharing and efficient spectrum use. Although RS Mode started with high fairness (∼0.92), its score dropped sharply under load (to ∼0.62 at 8 nodes) due to inefficiency and collisions. Other Gap Mode variants performed poorly. The Optimized Gap Mode uniquely balances high fairness with high utilization, proving the most effective strategy overall, particularly as network density increases.

6.8 Fairness Analysis in Asymmetric Scenarios

The Jain's Fairness Index (JFI) consistently registered values indicative of highly equitable channel occupancy sharing (Figure 6.8)). For the majority of the simulation runs across various AP to gNB ratios, such as 2:6, 7:4, 2:1, 3:8, 2:5, 6:4, and 5:8, the JFI values were predominantly above 0.98, frequently exceeding 0.99. For instance, in the 7 APs vs. 4 gNBs scenario, showed JFI values of ∼0.999. Even in scenarios with a more significant imbalance, like 2 APs vs. 6 gNBs or 5 APs vs. 8 gNBs, JFI values generally remained high, though occasional runs dipped to approximately 0.963 or 0.946 respectively. The Joint Airtime Fairness metric, also showed values that closely tracked the JFI, typically

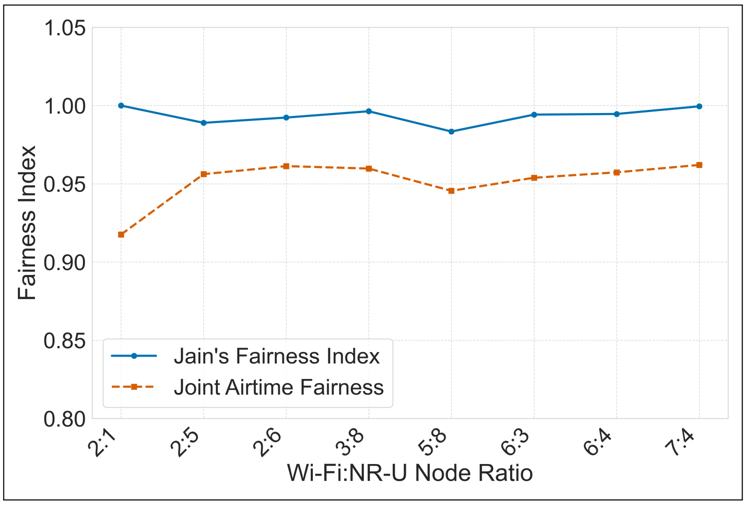


Figure 6.8: Fairness Across Asymetric Node Distribution.

remaining above 0.93 and often exceeding 0.95. The raw channel occupancy figures for Wi-Fi and NR-U in many of these asymmetric runs hovered around the 0.40 to 0.55 range for each technology, often appearing close to each other despite the differing number of nodes (see Figure 5.8(a)). For example, in several runs of the 2 APs vs. 6 gNBs configuration, Wi-Fi channel occupancy was observed between approximately 0.44 and 0.57, while NR-U occupancy was between 0.38 and 0.53.

Chapter 7

Discussion of Findings

This chapter interprets the findings in greater depth. It discusses the performance of each coexistence mechanism, explores observed trade-offs, evaluates the implications of the results, and acknowledges the study's limitations, offering a critical perspective on the research outcomes.

7.1 Coexistence Strategy Performance Evaluation

7.1.1 Default Gap Mode Performance

The performance of the default Gap Mode (Figure 6.1) starkly illustrated its unsuitability for fair coexistence. Wi-Fi's aggressive DCF mechanism, combined with the synchronized nature of NR-U's channel access attempts following the gap period, led to near-complete marginalization of NR-U. Wi-Fi nodes consistently captured the channel, resulting in high channel occupancy ($\sim$76-96%) and efficiency for Wi-Fi, while NR-U struggled to gain access (occupancy $< 1.6\%$, efficiency near zero at higher densities). Critically, despite its low channel usage, NR-U experienced extremely high collision rates (up to $\sim$87%), primarily due to multiple gNBs attempting access simultaneously after their synchronized gaps, often colliding with ongoing Wi-Fi transmissions that started during the gap. This confirms that simple, synchronized gap-based access without further coordination is detrimental to NR-U performance and fails to achieve equitable spectrum sharing.

7.1.2 Reservation Signal (RS) Mode Performance

In contrast, the RS Mode demonstrated a significantly fairer distribution of channel resources (Figure 6.1, Figure 6.6). By explicitly reserving the channel post-LBT until the next slot boundary, NR-U secured substantial airtime (occupancy ∼31-48%). This resulted in near-perfect fairness indices (JFI ∼0.99). However, this fairness came at a considerable cost. The non-data-bearing RS signal introduced significant overhead, reducing NR-U's channel efficiency (∼28-44%) compared to its occupancy. More importantly, the reliance on synchronization, while enabling fairness among NR-U nodes, created severe contention points, leading to high collision probabilities for both Wi-Fi and NR-U (greater than 56% at 8 nodes, Figure 6.1(c)). This indicates that while RS Mode enforces fairness, it is inefficient and does not scale well in denser deployments due to escalating collision rates, echoing concerns raised in [33].

7.1.3 Optimized Gap Mode Strategy Performance

The development of the Optimized Gap Mode involved a sequential enhancement process. Introducing random offsets to gNB synchronization boundaries (Figure 6.2) was a crucial first step. This staggering of LBT attempts dramatically reduced NR-U's self-collisions, with its collision probability dropping from ∼87% to below 8% (Figure 6.2(c)), preventing the catastrophic performance collapse seen in the default Gap Mode. While Wi-Fi remained dominant, this desynchronization ensured NR-U could maintain a minimal, stable presence (∼1-2% occupancy/efficiency), establishing a foundational requirement for viable Gap Mode operation, though insufficient alone for equitable coexistence.

Building on this, disabling NR-U's redundant random LBT backoff mechanism (Figure 6.3) further improved NR-U's channel access. Since NR-U nodes already observe a mandatory gap for synchronization, the additional backoff was an unnecessary impediment. Its removal allowed NR-U to contend more assertively post-gap, leading to a five- to seven-fold increase in its occupancy and efficiency (reaching ∼8% at 8 nodes, Figures 6.3(a), 6.3(b)), primarily at the expense of some of Wi-Fi's dominant channel share. Importantly, this enhancement had minimal negative impact on either NR-U's low collision rate (less than 8%) or Wi-Fi's collision trajectory, demonstrating that NR-U's backoff in this context is largely redundant.

The most significant enhancement was the dynamic adjustment of Wi-Fi's CW based on network density, applied within the desynchronized, no-NR-U-backoff framework (Figure

6.4). By strategically increasing Wi-Fi's CW, particularly in denser scenarios, its aggressive channel access was moderated, allowing NR-U to gain substantial channel access. This resulted in a transformative improvement; NR-U occupancy and efficiency surged to $\sim$45-48%, achieving near parity with Wi-Fi across all tested symmetric node densities (Figure 5.5(a)), a stark contrast to the $\sim$31% share per technology under RS Mode at 8 nodes.

This fully Optimized Gap Mode strategy consistently maintained robust and balanced performance for both technologies. Critically, unlike RS Mode which suffered escalating collisions (exceeding 56% at 8 nodes), the Optimized Gap Mode sustained low collision rates for both NR-U (less than 5%) and Wi-Fi (less than 8%) across all symmetric densities. This demonstrates superior scalability, higher overall channel utilization, and significantly better collision performance, making it a much more viable and efficient coexistence in the unlicensed.

The robustness of this dynamically adjusted Wi-Fi CW approach was further validated in asymmetric node configurations (Section 5.4). By applying a Wi-Fi CW specifically optimized for each unique imbalanced pairing of Wi-Fi APs and NR-U gNBs, the Optimized Gap Mode consistently maintained high levels of fairness (JFI predominantly >0.98, Figure 6.8). As illustrated in Figure 5.8, balanced channel occupancy (often with both technologies in the 40-50% range) was achieved even with unequal node counts, without increasing collision rates beyond the low levels seen in symmetric scenarios. This successful application to realistic asymmetric deployments underscores the practical viability and scalability of the Optimized Gap Mode strategy.

7.2 Limitations of the Study

While providing valuable insights, these findings should be considered in light of the study's limitations. The results are derived from a discrete-event simulation environment. Although parameters were chosen based on relevant IEEE and 3GPP standards, simulations cannot perfectly capture the full complexity of real-world phenomena such as intricate channel fading, diverse traffic patterns beyond the assumed fixed payload (Wi-Fi) or MCOT-based transmission (NR-U), hardware processing delays, or potential protocol implementation variations. The study focused on a specific range of node densities (1-8 per technology) with an equal number of Wi-Fi APs and NR-U gNBs; vastly different densities or asymmetric deployments might alter the quantitative results. Furthermore, the investigation centred on MAC-layer coexistence mechanisms (LBT, backoff, gaps, CW); deeper PHY-layer interactions or potential cross-layer coordination strategies were outside the scope of this work.

7.3 Significance and Implications

Despite these limitations, this study provides significant insights into NR-U and Wi-Fi coexistence. It clearly demonstrates that simplistic or static coexistence mechanisms, such as the default Gap Mode or even the fair-but-inefficient RS Mode, are inadequate, particularly as network density increases. The research strongly indicates that achieving robust, efficient, and fair coexistence necessitates adaptive strategies. The success of the Optimized Gap Mode, specifically the final step of dynamically adjusting the Wi-Fi CW based on density, highlights a practical approach. By actively managing the contention behaviour of the incumbent technology (Wi-Fi), the newer entrant (NR-U) can gain equitable channel access without resorting to inefficient reservation schemes or suffering from catastrophic collisions. This optimized approach offers superior scalability, high channel utilization ($\sim$90-95% total), and low collision rates (less than 8% for both), making it a highly promising strategy for practical deployments of 5G NR-U in shared unlicensed bands. It underscores the principle that successful coexistence often requires tuning the parameters of both competing systems, not just the new one. Looking ahead, exploring machine learning techniques to automate the dynamic CW adjustment in real-time based on sensed channel conditions could further enhance the adaptability and performance of such coexistence strategies.

Chapter 8

Conclusions

This project successfully developed and validated a coexistence strategy for 5G NR-U and Wi-Fi systems operating in shared unlicensed spectrum. Addressing the prevalent challenges of mutual interference and suboptimal performance, the research utilized an extensive literature review to inform a conceptual framework, leading to specific algorithms for spectrum sharing and interference mitigation, which were rigorously tested within a custom Python SimPy discrete-event simulator.

The evaluation of baseline mechanisms revealed significant limitations, the default Gap Mode for NR-U proved unsuitable for equitable sharing, resulting in severe marginalization of NR-U by Wi-Fi and extremely high NR-U collision rates due to synchronized contention. Conversely, while the RS Mode successfully enforced fairness through explicit channel reservation, it incurred substantial inefficiency from non-data-bearing overhead and demonstrated poor scalability with escalating collision rates for both technologies under increasing network load.

Initial evaluations revealed significant limitations in baseline mechanisms. The default NR-U Gap Mode proved unsuitable for equitable sharing, severely marginalizing NR-U and incurring high collision rates due to synchronized contention. Conversely, while NR-U RS Mode enforced fairness via channel reservation, it suffered from substantial inefficiency and poor scalability due to non-data-bearing overhead and escalating collisions under increasing network load.

In contrast, an "Optimized Gap Mode" strategy, centered on dynamically adjusting the Wi-Fi Contention Window (CW), emerged as a robust and superior solution. This strategy integrated three key elements: gNB transmission desynchronization to drastically reduce

NR-U self-collisions; the disabling of NR-U's redundant random LBT backoff to improve its channel access; and most critically, a dynamic, density-aware adjustment of Wi-Fi's CW to moderate its inherent access aggressiveness and balance channel sharing.

This Optimized Gap Mode demonstrably maximized performance, consistently achieving near-perfect fairness (Jain's Fairness Index > 0.97), high and balanced channel occupancy and efficiency (45-50% for each technology), and low collision rates (below 8%) for both NR-U and Wi-Fi. Crucially, its effectiveness was validated across diverse scenarios, including both symmetric and representative asymmetric node configurations.

This study therefore concludes that effective coexistence in shared unlicensed spectrum necessitates adaptive, multifaceted strategies. Specifically, managing the contention behaviour of coexisting systems, particularly by tailoring the incumbent Wi-Fi's aggressiveness to the specific network topology, is vital. The proposed Optimized Gap Mode represents a viable, efficient, and scalable approach, fulfilling the project's aim to create a robust framework for facilitating fair and maximized performance of 5G NR-U and Wi-Fi in shared unlicensed spectrum environments.

Chapter 9

Recommendations for Future Work

The current study relied on a discrete-event simulation environment using SimPy, which, while robust for controlled analysis, may not fully capture the complexities of real-world wireless environments. Future work should focus on validating the Optimized Gap Mode strategy through field testing in diverse deployment scenarios, such as urban hotspots, enterprise networks, or indoor small-cell environments. Real-world testing would account for factors like channel fading, multipath effects, hardware-specific delays, and dynamic traffic patterns, which were simplified in the simulation. Implementing the proposed algorithms on actual 5G NR-U and Wi-Fi hardware (e.g., commercial gNBs and Wi-Fi access points) could provide insights into practical performance and identify any discrepancies between simulated and real-world outcomes.

The simulation assumed fixed payload sizes for Wi-Fi (1472 bytes) and a constant MCOT for NR-U (6 ms), which standardized transmission durations but overlooked the variability of real-world traffic. Future research should explore coexistence under diverse traffic patterns, such as bursty IoT traffic, high-throughput video streaming, or latency-sensitive applications like URLLC. This could involve extending the simulation framework to model variable packet sizes, mixed access categories for Wi-Fi (e.g., Voice, Video, Best Effort), and different NR-U priority classes. Analyzing how the Optimized Gap Mode performs under heterogeneous traffic conditions would enhance its applicability to practical scenarios.

While this study investigated a set of representative asymmetric node densities (as detailed in Section 5.4), future work should explore a wider and more granular range of asymmetric configurations. This could include more extreme imbalances (e.g., 1 AP vs. 8 gNBs or vice-versa, if practical CW solutions can be found), different total numbers of nodes while maintaining asymmetry, and systematically varying the AP-to-gNB ratio. This would further test the limits and scalability of the pair-specific Wi-Fi CW optimization.

This study focused on the 5 GHz unlicensed band, a critical spectrum for both Wi-Fi and NR-U. Future work should extend the analysis to other unlicensed bands, such as the 6 GHz band (used by Wi-Fi 6E and potentially NR-U) or the 60 GHz band (used by WiGig and emerging NR-U applications). These bands present unique challenges, such as increased path loss in higher frequencies or different regulatory constraints. Adapting the Optimized Gap Mode to these bands would require recalibrating parameters like synchronization slots, CW sizes, and LBT timing to account for band-specific characteristics.

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Appendix A

Additional Files and Schematics

A.1 Core Simulation Classes

```
class WiFiStation:
    """
        Simulates a Wi-Fi station with DCF channel access mechanism
        Implements the IEEE 802.11 Distributed Coordination Function (DCF)
        with exponential backoff for channel access.
    """
    def __init__(self, env, name, channel, config=WiFiConfig()):
        self.config = config
        self.times = Times(config.data_size, config.mcs)  # Calculate timing
    parameters
        self.name = name
        self.env = env
        self.log_color = random.choice(LOG_COLORS)  # Assign random color for
    logging
        self.frame_to_send = None
        self.succeeded_transmissions_WiFi = 0  # Successful transmission counter
        self.failed_transmissions_WiFi = 0  # Failed transmission counter
        self.failed_transmissions_in_row = 0  # Consecutive failures counter
        self.min_cw = config.min_cw  # Minimum contention window
        self.max_cw = config.max_cw  # Maximum contention window
        self.channel = channel  # Shared wireless medium
        self.process = None  # Current process reference
        self.first_interrupt = False  # Interrupt flag
        self.back_off_time = 0  # Current backoff time
        self.start = 0  # Backoff start time
        self.channel.data_airtime_WiFi.update({name: 0})
        self.channel.control_airtime_WiFi.update({name: 0})
```

```
        env.process(self.start_process())  # Start the station process
```

Listing A.1: WiFiStation Class Definition

```
class NRUBaseStation:
    """
        Simulates an NR-U base station with LBT channel access
        Implements Listen-Before-Talk (LBT) with backoff for NR-U
        and accounts for synchronization slots.
    """
    def __init__(self, env, name, channel, config_nr=NRUConfig()):
        self.config_nr = config_nr
        self.name = name
        self.env = env
        self.log_color = random.choice(LOG_COLORS)
        self.transmission_to_send = None
        self.succeeded_transmissions = 0  # Successful transmission counter
        self.failed_transmissions = 0  # Failed transmission counter
        self.failed_transmissions_in_row = 0  # Consecutive failures counter
        self.min_cw = config_nr.min_cw  # Minimum contention window
        self.N = None
        self.desync = 0  # Desynchronization offset
        self.next_sync_slot_boundry = 0  # Next sync slot boundary time
        self.max_cw = config_nr.max_cw  # Maximum contention window
        self.channel = channel  # Shared wireless medium
        self.process = None  # Current process reference
        self.first_interrupt = False  # Interrupt flag
        self.back_off_time = 0  # Current backoff time
        self.time_to_next_sync_slot = 0  # Time until next sync slot
        self.waiting_backoff = False  # Backoff in progress flag
        self.start_nr = 0  # Backoff start time
        self.channel.data_airtime_NR.update({name: 0})
        self.channel.control_airtime_NR.update({name: 0})
        env.process(self.start_process())
        env.process(self.sync_slot_counter())  # Track synchronization slots
```

Listing A.2: NRUBaseStation Class

```
@dataclass()
class NRUTransmission:
    """
        Represents an NR-U transmission with associated metadata
        Tracks all relevant information about an NR-U transmission,
        including timing, source, and statistics about the transmission success.
    """
```

```
    transmission_time: int  # Total transmission time (microseconds)
    enb_name: str  # Source node name
    log_color: str  # Color for logging
    start_time_us: int  # Transmission start time (simulation microseconds)
    airtime: int  # Effective airtime usage for data (microseconds)
    rs_time: int  # Reservation signal time (microseconds)
    number_of_retransmissions: int = 0  # Number of retransmission attempts
    end_time_us: int = None  # Transmission end time (simulation microseconds)
    transmission_duration_us: int = None  # Total transmission duration (
    microseconds)
    collided: bool = False  # Collision flag
```

Listing A.3: NRUTransmission Class Definition

```
@dataclass()
class WiFiDataPacket:
    """
        Represents a Wi-Fi data packet with transmission information
        Tracks all relevant information about a Wi-Fi packet transmission,
        including timing, size, source, and statistics about retransmissions.
    """
    frame_time: int  # Time to transmit the frame (microseconds)
    station_name: str  # Source station name
    log_color: str  # Color for logging
    data_size: int  # Size of data payload (bytes)
    start_time_us: int  # Transmission start time (simulation microseconds)
    number_of_retransmissions: int = 0  # Number of retransmission attempts
    end_time_us: int = None  # Transmission end time (simulation microseconds)
    transmission_duration_us: int = None  # Total transmission duration (
    microseconds)
```

Listing A.4: WiFiDataPacket Class Definition

A.2 Key Methods and Data Structures

```
def create_nru_transmission(self):
    """
        Creates a new NR-U transmission with appropriate timing parameters
        Returns:
            NRUTransmission: A new transmission object with calculated parameters
    """
    transmission_time = self.config_nr.mcot * 1000  # Convert max channel occupancy
    time from ms to \textmu s
```

```
    rs_time = 0 if GAP_MODE_ENABLED else (self.next_sync_slot_boundry - self.env.now
    )
    airtime = transmission_time - rs_time
    return NRUTransmission(transmission_time, self.name, self.log_color, self.env.
    now, airtime, rs_time)
```

Listing A.5: NRUTransmission Instantiation via create_nru_transmission

```
def wait_back_off(self):
    """Implements Wi-Fi exponential backoff procedure"""
    # Calculate backoff time based on current retry count
    self.back_off_time = self.calculate_backoff_slots(self.
    failed_transmissions_in_row)

    while self.back_off_time > -1:
         try:
            # Request channel access lock
            with self.channel.tx_lock.request() as req:
                 yield req

            # Add DIFS wait time to backoff
            self.back_off_time += Times.t_difs
            log_transmission_event(self, f"Starting to wait backoff (with DIFS): ({
    self.back_off_time})u...")
            self.first_interrupt = True
            self.start = self.env.now
            self.channel.wifi_stations_in_backoff.append(self)

            # Wait for backoff time
            yield self.env.timeout(self.back_off_time)
            log_transmission_event(self, f"Backoff waited, sending frame...")
            self.back_off_time = -1  # Backoff complete

            self.channel.wifi_stations_in_backoff.remove(self)

            except simpy.Interrupt:
                 # Handle interruption (e.g., when channel becomes busy)
             if self.first_interrupt and self.start is not None:
                 log_transmission_event(self, "Waiting was interrupted, waiting to
    resume backoff...")
                all_waited = self.env.now - self.start
                # Calculate remaining backoff time
                if all_waited <= Times.t_difs:
                   self.back_off_time -= Times.t_difs
                else:
```

```
                slot_waited = int((all_waited - Times.t_difs) / Times.t_slot)
                self.back_off_time -= ((slot_waited * Times.t_slot) + Times.
t_difs)
                self.first_interrupt = False
```

Listing A.6: WiFiStation Class wait_back_off method

Appendix B

Addenda

B.1 Source Code Access

The full code can be found on my GitHub repository [34], I also added information of how to install the necessary dependencies to run the simulations, how to use it to performing the simulations and how to analyze the results.

B.2 Ethics Clearance Form

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UNIVERSITY OF CAPE TOWN
IYUNIVESITHI YASEKAPA · UNIVERSITEIT VAN KAAPSTAD

PRE-SCREENING QUESTIONNAIRE OUTCOME LETTER

STU-EBE-2025-PSQ001562
2025/03/13

Dear Brendon Mutema,

Your Ethics pre-screening questionnaire (PSQ) has been evaluated by your departmental ethics representative. Based on the information supplied in your PSQ, it has been determined that you do not need to make a full ethics application for the research project in question.

You may proceed with your research project titled:

Coexistence Strategy for 5G New Radio and WiFi Communication Systems

Please note that should aspect(s) of your current project change, you should submit a new PSQ in order to determine whether the changed aspects increase the ethical risks of your project. It may be the case that project changes could require a full ethics application and review process.

Regards,

Faculty Research Ethics Committee