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Master's Thesis

用戶設備啟動非授權新空中介面技術網路與多播廣播服務

UE-initiated New Radio Unlicensed Band network with MBS

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本論文係鄭宇翔君 (R11921054) 在國立臺灣大學電機工程學系完成之碩士學位論文，於民國 113 年 12 月 17 日承下列考試委員審查通過及口試及格，特此證明。

The undersigned, appointed by the Department of Electrical Engineering, National Taiwan University on 17 December 2024 have examined a Master's Thesis entitled above presented by Yu-Hsiang Cheng (R11921054) candidate and hereby certify that it is worthy of acceptance.

口試委員 Oral examination committee:

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摘要

隨著 5G 頻寬日益稀缺，尋找額外頻寬或提高使用效率已成為關鍵課題。為了應對這一挑戰，相關標準組織提出了新型無授權頻段（NR-U）來擴展 5G 頻寬，並引入多播與廣播服務（MBS）以提升頻寬利用效率。本文首次提出將 NR-U 與 MBS 結合的方案，並提供一套分析模型進行驗證。透過精密設計結合這兩個元素，我們的最佳解法在 20 個無線網路接取點的環境中，效能相較於現有技術提升達 7.27 倍。此外，我們的方法完全符合標準規範，效能也提升至現有技術的 3.92 倍。我們根據站點間距與頻率等參數進行多項模擬，並得出多項具有啟發性的結果。

關鍵字： 非授權頻帶、新空中介面技術、多播廣播服務、用戶設備啟動、非授權新空中介面技術

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Abstract

With the increasing scarcity of 5G bandwidth, finding additional bandwidth or improving usage efficiency has become critical. The 3GPP proposed the New Radio Unlicensed (NR-U) band to expand 5G bandwidth and introduced Multicast and Broadcast Service (MBS) to enhance bandwidth utilization efficiency. This paper is the first to propose the integration of NR-U and MBS, along with an analytical model for validation. Through a sophisticated design combining these two elements, our optimal solution outperforms the state-of-the-art (SOTA) by a factor of 7.27 in an environment with 20 Wi-Fi APs. Furthermore, our fully 3GPP standard-compliant method achieves 3.92 times the performance of the SOTA. We conducted various simulations based on parameters such as inter-site distance (ISD) and frequency, deriving several insightful results.

Keywords: Unlicensed band, New radio, MBS, UE-initiated,NR-U

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Contents

doi: 10.6342/NTU202404732

doi: 10.6342/NTU202404732

List of Figures

doi: 10.6342/NTU202404732

doi: 10.6342/NTU202404732

List of Tables

doi: 10.6342/NTU202404732

Chapter 1. Introduction

In modern society, nearly everyone owns a smartphone, and using them to watch videos online is very common. According to [1], video streaming consumes 75% of the wireless spectrum for transmission. Smartphones typically use 5G networks to access video content. As screen resolutions improve, the demand for high-resolution video content increases. The growing video traffic is illustrated in 1.1. Consequently, the 5G network is experiencing a spectrum shortage. Additionally, with the maturation of virtual reality (VR) technology, VR is expected to become popular in the near future, exacerbating the spectrum scarcity issue due to its significantly larger data requirements compared to video content.

This paper aims to address the aforementioned problems: spectrum scarcity. The 3rd Generation Partnership Project (3GPP) introduced New Radio Unlicensed (NR-U) to tackle these issues. NR-U allows 5G networks to access unlicensed bands, which are spectrums available for use without a license, provided that users follow specific standards. The most well-known technology operating in unlicensed bands is Wireless Fidelity (Wi-Fi). Accessing unlicensed bands can alleviate the spectrum scarcity problem.

However, NR-U must adhere to specific rules when accessing unlicensed bands, requiring it to contend for channel access with Wi-Fi. Consequently, NR-U throughput may be affected by Wi-Fi access points (AP). To address this issue, we utilized a mechanism established by 3GPP called user equipment (UE)-initiated NR-U. UE-initiated NR-U increases access opportunities by allowing user equipment (UEs), which are generally more numerous than BSs, to contend for channel access.

We then combine 3GPP NR-U with Multicast and Broadcast Service (MBS) to max-

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imize throughput using novel methods. MBS focuses on more efficient spectrum usage. MBS does this by enabling multicast and broadcast data transmission to multiple users who all need the same data.

We introduce two advanced methods: UE-initiated SFN and modulation and coding scheme optimization (MCS-opt), both of which outperform existing baselines and state-of-the-art (SOTA) solutions. UE-initiated SFN combines UE-initiated NR-U with a single frequency network (SFN). Both UE-initiated SFN and SOTA use SFN to improve throughput. UE-initiated SFN uses UE-initiated NR-U to improve the throughput further. It achieves up to 7.27 times better throughput than SOTA. However, SFN is not included in the 3GPP MBS standard.

MCS-opt, while only 4.92 times better than the SOTA, its MBS part follows the 3GPP MBS standard. It is easier to implement in the real world than UE-initiated SFN and the SOTA.

The main contributions of our work are as follows:

1. To the best of our knowledge, this is the first work to study and analyze the integration of the 3GPP UE-initiated NR-U and MBS systems.

2. Designed two outstanding methods to maximize throughput: UE-initiated NR-U SFN and MCS-opt. The effectiveness of these proposed methods was demonstrated, with UE-initiated NR-U SFN outperforming the SOTA in all scenarios and MCS-opt surpassing the SOTA in most typical conditions. The issue of network congestion was significantly alleviated.

3. First, a fully-listened simulation and analysis will be followed by a partially-listened simulation and analysis. The results showed that the performance of both simulations was nearly identical, confirming the validity of the fully-listened assumption. Future researchers can build upon my study, making it easier to carry out further research advancements.

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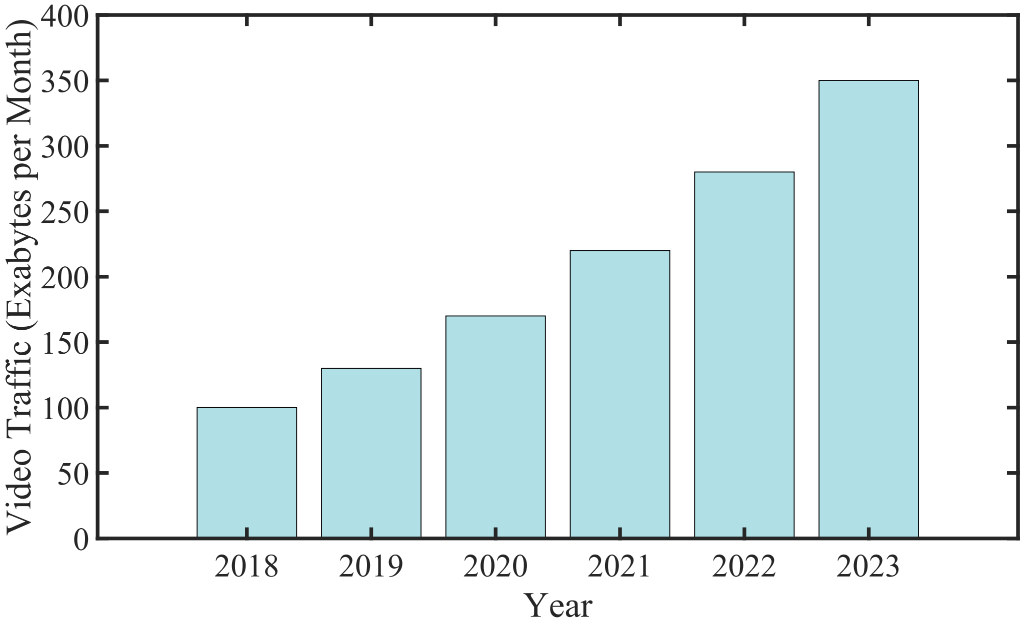

Figure 1.1: Increase of video traffic in recent years [1]. In recent years, the number of viewers of online videos has increased. The video resolution also becomes a concern of viewers.

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Chapter 2. Related Work

The current NR-U [2] is based on Long Term Evolution-Licensed Assisted Access (LTE-LAA). In Release 13, 3GPP standardized LTE-LAA, leading to numerous studies [3–6] focusing on coexistence and fairness between LTE-LAA and Wi-Fi. Pei et al. [3] used an analytical model to demonstrate that LTE small cell scenarios can negatively impact Wi-Fi in terms of throughput and delay. Mehrnoush et al. [4] also investigated similar scenarios, extending their research to the relationship between the energy detection (ED) threshold and throughput. Additionally, Mehrnoush et al. [5] examined the effects of transmit opportunity (TXOP), defer time, and contention window size on throughput. In contrast, Bitar et al. [6] explored coexistence in both homogeneous and heterogeneous networks. Most of these studies employed Markov chain models for analysis, following the pioneering work in [7].

In Release 16, 3GPP shifted focus to NR-U. Naik et al. [8] presented the first comprehensive survey on NR-U coexistence with other technologies, such as 802.11 and Wireless Gigabit. The study addressed key parameters like listen-before-talk (LBT) and maximum channel occupancy time (MCOT). Hirzallah et al. [9], similar to [8], considered scenarios where packet arrivals follow a Poisson process and provided simulation results for both uplink and downlink transmissions. While these studies offered valuable insights, they were limited to simulation-based approaches without mathematical analysis.

Subsequent works [10–16] incorporated mathematical models to better analyze coexistence. Bao et al. [10] optimized power and time allocation to maximize throughput. Lien et al. [11] focused on vehicle-to-everything (V2X), addressing challenges like high density and collision probabilities in NR-U. Chen et al. [12] discussed scheduling mecha-

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nisms to improve energy efficiency, critical for battery-operated unlicensed band devices. Daraseliya et al. [13] was the first to analyze NR-U coexistence with Wireless Gigabit, addressing fairness issues caused by reservation signals. Similarly, [14–16] examined coexistence using analytical and simulation-based approaches. Ren et al. [17] further extended Markov chain analysis for a wide range of coexistence studies.

Most of these studies assumed a ”fully-listened” scenario, ignoring the hidden node problem, a persistent challenge in unlicensed bands. For example, [18] and [19] proposed solutions to mitigate hidden node issues in Wi-Fi by improving signaling responses and optimizing transmission timing. Similarly, Huang et al. [20] introduced ”listen before receive” to address hidden nodes in LTE-LAA. Hung et al. [21] provided a mathematical analysis of Wi-Fi with hidden nodes, though the time parameters differ from NR-U. Ren et al. [22] analyzed coexistence between NR-U and Wi-Fi, including hidden nodes, but their BS-initiated access methods only considered collisions between BSs and APs. In contrast, our UE-initiated analysis accounts for collisions between BSs and UEs.

Rather than focusing on coexistence between LTE-LAA, NR-U, and Wi-Fi, we adopt analytical methods to evaluate the performance of our proposed methods. Few studies explore NR-U and MBS simultaneously. Prasad et al. [23] discussed unlicensed technologies and enhanced Multimedia Broadcast Multicast Service (eMBMS), using LBT and SFN to boost throughput. Instead of relying on a single backoff counter, we employ UE-initiated NR-U to improve channel access chances. Additionally, as SFN is not permitted in the 3GPP MBS standard [24], we developed a method that aligns more closely with these standards while outperforming the SOTA in most scenarios.

Regarding MBS and SFN, Liu et al. [25] addressed the partitioning problem for SFN areas and provided an overview of Multimedia Broadcast Multicast Service (MBMS), including reconfiguration mechanisms, path loss models, and the relationship between SINR and modulation and coding schemes (MCS). MBS is conceptually similar to MBMS, and our study builds upon this foundation to enhance NR-U performance.

doi: 10.6342/NTU202404732

Table 2.1: Comparison of Related Work on the Unlicensed Band and MBS

Paper	**Year**	**Content**	**Scenario**	**Analytical method**	**Simulation**	**MBS**
[18], [19]	2007, 2009	Proposed methods to address hidden node issues in Wi-Fi by enhancing signaling mechanisms and optimizing transmission scheduling.	Fully-listened	Yes	Yes	No
[21]	2010	Conducted a mathematical analysis of Wi-Fi systems with hidden nodes.	Fully-listened	Yes	Yes	No
[3]	2017	Developed an analytical model to assess the impact of LTE-LAA on Wi-Fi networks.	Fully-listened	Yes	No	No
[23]	2018	Discussed unlicensed technologies and enhanced eMBMS, employing LBT and SFN to improve throughput.	Fully-listened and Partially-listened	No	Yes	Yes
[4]	2018	Explored the relationship between energy detection (ED) thresholds and throughput in LTE-LAA systems.	Fully-listened	Yes	No	No
[5]	2018	Investigated the effects of TXOP, defer time, and contention window size on throughput.	Fully-listened	Yes	No	No
[6]	2018	Examined coexistence scenarios involving both homogeneous and heterogeneous networks.	Fully-listened	Yes	No	No
[8]	2020	Studied partitioning issues in SFN areas and reviewed MBMS, including mechanisms and configurations.	Partially-listened	Yes (only MBMS)	Yes	Yes
[8]	2020	Provided a comprehensive survey on NR-U coexistence with other technologies like 802.11 and Wireless Gigabit.	Fully-listened	No	Yes	No
[9]	2020	Examined NR-U scenarios where packet arrivals follow a Poisson process and provided simulation results for uplink and downlink transmissions.	Fully-listened	No	Yes	No
[10]	2021	Optimized power and time allocation strategies to maximize throughput.	Fully-listened	Yes	No	No
[11]	2021	Focused on vehicle-to-everything (V2X) networks, addressing challenges such as high density and collision probabilities in NR-U systems.	Fully-listened	Yes	Yes	No

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doi: 10.6342/NTU202404732

Paper	Year	Content	Scenario	Analytical method	Simulation	MBS
[12]	2021	Proposed scheduling algorithms to improve energy efficiency in battery-dependent unlicensed band devices.	Fully-listened	Yes	No	No
[13]	2021	Investigated NR-U coexistence with Wireless Gigabit, highlighting fairness concerns caused by reservation signals.	Fully-listened	Yes	No	No
[14]	2021	Conducted analytical studies of NR-U coexistence with Wireless Gigabit to address fairness issues.	Fully-listened	Yes	No	No
[14, 15]	2021	Utilized analytical and simulation-based approaches to evaluate coexistence challenges.	Fully-listened	Yes	No	No
[20]	2021	Introduced a ”listen before receive” mechanism to mitigate hidden node issues in LTE-LAA systems.	Fully-listened	Yes	Yes	No
[16]	2022	Employed analytical and simulation methods to investigate coexistence problems.	Fully-listened	Yes	No	No
[17]	2021	Extended Markov chain analysis to study coexistence in various scenarios.	Fully-listened	Yes	Yes	No
[22]	2023	Analyzed coexistence between NR-U and Wi-Fi, incorporating hidden nodes but focusing on BS-initiated access methods.	Partially-listened	Yes	Yes	No

doi: 10.6342/NTU202404732

Chapter 3. Background

3.1 3GPP Standards

3.1.1 NR-U (BS-initiated NR-U)

In simple terms, NR-U is about NR using Wi-Fi frequencies for transmission. However, to ensure fair coexistence with Wi-Fi, NR-U has some restrictions. As outlined in [2], 3GPP utilizes a mechanism called backoff to establish the standard for NR-U. Both uplink and downlink follow similar procedures. Since our MBS primarily serves downloads, we assume a downlink scenario here.

Each base station (BS) has an integer called a backoff counter. Initially, the backoff counter is randomly selected from a range between 0 and a parameter called the minimum contention window minus one, as shown in 3.1. The BS will then start counting down. If a BS detects that another BS is transmitting, its countdown will be paused. The channel must remain idle for a defer time before the counter can resume counting down. The station will send an ACK after a time period of T_f following the success of data transmission. The mechanism is similar to Wi-Fi.

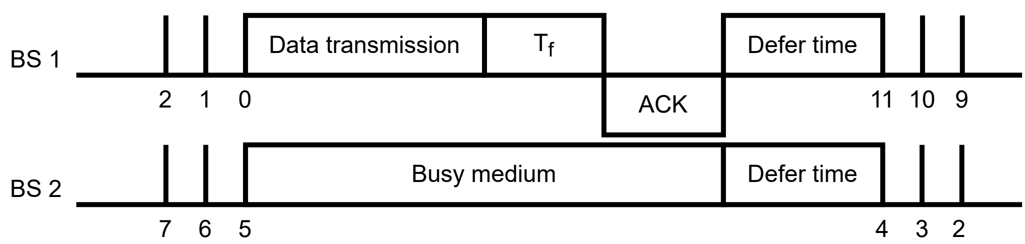

Figure 3.1: NR-U BS access unlicensed band procedure. If the channel is idle for defer time, the backoff counter will continue counting down. When it counts to zero. It starts transmitting.

doi: 10.6342/NTU202404732

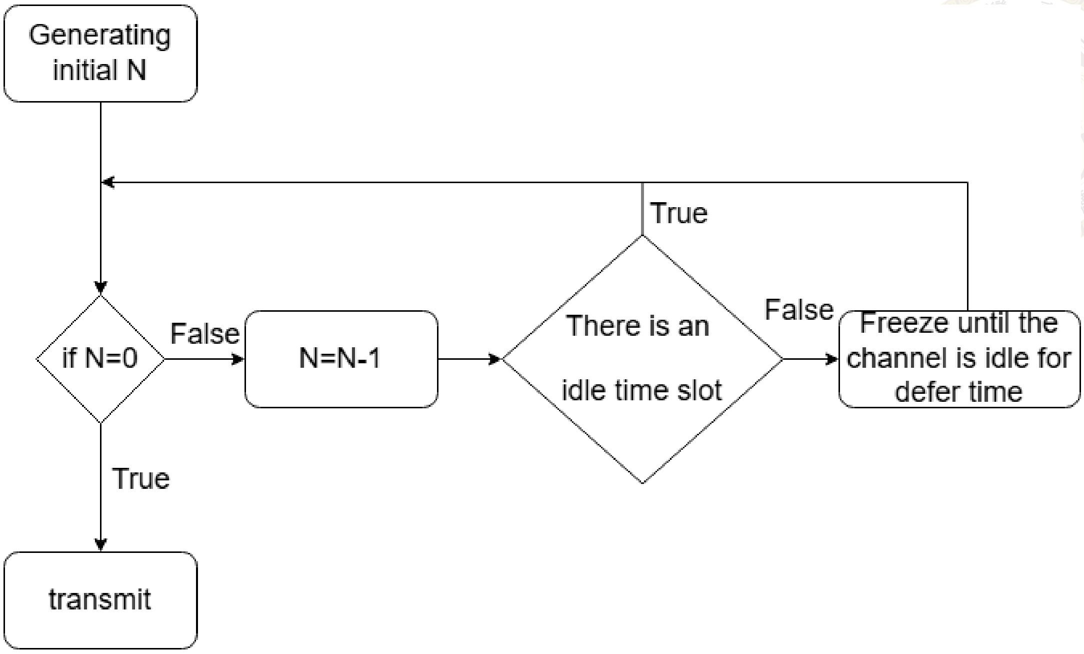

Figure 3.2: Flowchart of NR-U base station accessing the unlicensed band

3.2 is the flow chart of NR-U BS. After determining the backoff counter, the BS checks if the counter equals zero. If it does, the BS stops counting down and starts transmission. Otherwise, it decreases the counter by one. The BS then checks if the channel is idle in the current time slot. If the channel is idle, the BS checks again if the backoff counter equals zero. If the channel is busy, the BS freezes the counter until the channel is idle for the defer time. The channel is considered busy if the Signal-to-Interference-plus-Noise Ratio (SINR) in decibels (dB) exceeds the energy detection(ED) threshold. Conversely, the channel is considered idle if the SINR is below the ED threshold.

The initial backoff counter value is chosen from 0 to the current contention window minus one—the size of the contention window changes based on the occurrence of collisions. The minimum contention window is used when the BS has not experienced any collisions. As shown in (3.1), CW_i represents the contention window for a BS that has experienced i collisions. The contention window will not double if the number of collisions reaches the maximum contention window. If the number of collisions exceeds the maximum, the contention window resets to the minimum value.

doi: 10.6342/NTU202404732

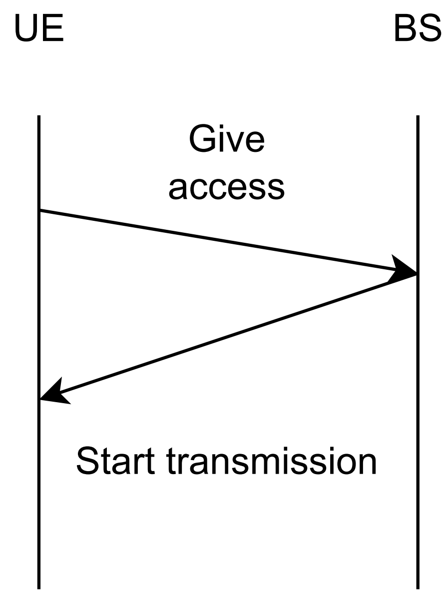

Figure 3.3: Ue-initiated signal flow. The UE gives access to BS. After receiving access, BS starts to transmission

$$CW_i = \begin{cases} 2^i CW_{min} & i <= m \\ 2^m CW_{min} & other \end{cases} \tag{3.1}$$

3.1.2 UE-initiated NR-U

UE-initiated NR-U is also specified in the 3GPP standard. Its mechanism closely resembles that of classic NR-U. As described in the previous subsection, each BS has its own backoff counter. In UE-initiated NR-U, however, each UE is assigned a backoff counter instead of the BS. The backoff counters of UEs operate in the same manner as those of BSs. When a UE's backoff counter counts down to zero, it grants the access opportunity to the BS rather than to itself. If the access granting process is successful, the BS begins transmitting data, as shown in 3.3. There are several rules that must be followed. For instance, if UE1 grants access to BS1, BS1 must start a transmission that includes UE1. This transmission can be unicast, multicast, or broadcast. Additionally, unicast transmissions that include user data planes can only be sent to UE1.

doi: 10.6342/NTU202404732

3.1.3 Multicast Broadcast Service (MBS)

Under normal conditions, data is transferred from one device to another in a one-to-one manner, with only the two devices being aware of the content. This approach can lead to inefficiencies when multiple devices need the same data, as the data must be transmitted multiple times. To address this, 3GPP introduced MBS (Multicast Broadcast Single Frequency Network) in 5G. Instead of the traditional one-to-one method, MBS transmits data one-to-many or one-to-all, known as multicast and broadcast, respectively.

MBS provides efficient data delivery across various scenarios, such as live video streaming, large-scale meetings, and online gaming. Additionally, MBS uses unicast to retransmit data that was not successfully transmitted in the initial broadcast, ensuring reliable delivery.

3.2 Single frequency network (SFN)

In traditional wireless networks, improving the receiver's SINR is typically achieved by increasing the transmitter's power. However, SFN improves SINR by synchronizing transmitters to transmit the same signal, causing the signals to add constructively. This method has three main advantages:

1. Maximizing spectrum utilization in situations where the spectrum is limited.
2. Ensuring that when a single BS is unable to transmit due to buildings or natural obstacles, other BSs can still maintain signal reception for the receivers.
3. Reducing costs; as mentioned earlier, instead of building a single expensive high-power BS, several low-cost low-power BSs can achieve the same transmission effect.

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Chapter 4. System Model

4.1 Scenario

We consider two scenarios in this work. The first one is the cell scenario. In this scenario, the BS is located at the center of each cell. Each cell is of the same size and contains only one BS. There are 19 cells arranged in a honeycomb structure. UEs are uniformly scattered in the field, meaning they are evenly distributed along both the x-axis and y-axis. We assume that every UE remains fixed during the simulation period without loss of generality. Additionally, the number of UEs remains constant, not increasing or decreasing over time. APs are also uniformly scattered across the field, with devices contending for channel access. The path loss equation is given by (4.1), where d represents the distance between the BS and UE, f_c is the central frequency, and h is the average height of buildings.

$$\begin{aligned} pl = 20\log_{10}\left(\frac{40\pi d f_c}{3}\right) + \min(0.03h^{1.72}, 10)\log_{10}(d) \\ - \min(0.044h^{1.72}, 14.77) + 0.002\log_{10}(hd) \end{aligned} \tag{4.1}$$

4.2 Fully-listened and partially-listened

In studies of unlicensed bands (such as Wi-Fi), researchers often adopt a fully-listened assumption to simplify the model for simulation and mathematical analysis, as seen in [7] and [17]. The fully-listened assumption disregards the hidden node problem by assum-

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ing that every device can detect the signals from all other devices. In most cases, this assumption does not introduce significant deviation. Additionally, mathematical analyses generally rely on [7] as a foundation, with some necessary adjustments. However, although this assumption is widely used, some researchers also consider the partially-listened scenario. Partially-listened assumes that devices cannot detect signals from all other devices, only from some, which makes the hidden node problem more likely to occur during data transmission. This approach is indeed more realistic but also complicates research. In this paper, we will first consider the fully-listened scenario, and in later chapters, we will address the partially-listened case, ultimately comparing the similarities and differences between the two.

4.3 BS state

In NR-U, if we observe a single BS, we can identify three possible events: idle, collision, and success. Idle indicates that the BS is merely counting down with no activity. Collision occurs when two or more nearby BSs transmit simultaneously, causing signal interference that ultimately results in a failed data transmission. Success refers to the case where only the observed BS is transmitting at that moment, with no other BSs competing for the channel, allowing the message to be successfully received by the receiver. Wi-Fi shares the exact mechanism as NR-U but with slight differences in parameters, so certain events in the system need to be handled separately, as shown below. For actual values, see 8.2.

1. Idle (t_{idle}):

   There is no node transmitting. It is as long as one time slot because the condition of the next time slot cannot be predicted.

2. Successful NR-U transmission (t_{us}):

   Only one NR-U BS is transmitting through the channel. It only takes one time slot for the UE to tell BS that it just got access. However, BS takes t_{gap} to transfer from receiving to transmitting according to [2]. The periods mentioned above are

doi: 10.6342/NTU202404732

all included in t_{cot}. So the transmission time is only $t_{cot} - t_{gap} - s_t$. The other nodes then wait for t_d to start counting down again.

3. Collided NR-U transmission (t_{uc}):

   The UE still spends one time slot to give BS access. However, the BS does not get the signal from UE, so other nodes will start counting down after T_d.

4. Successful Wi-Fi transmission (t_{ws}):

   There is only one Wi-Fi AP transmitting in the channel. Wi-Fi AP takes t_{rts} to send the RTS signal first. After t_{sifs}, UE takes t_{cts} to send the CTS signal. After another t_{sifs}, the header and payload are transmitted by BS, which takes t_{headw} and $tplw$. After another t_{sifs}, the UE will transmit the ACK signal, which takes t_{ack}. Waiting for t_{difs}, other backoff counters of nodes can start counting down again.

5. Collided Wi-Fi transmission (t_{wc}):

   There is more than one AP transmitting at the same time. The Wi-Fi AP first sends the RTS signal. However, the UE can not receive the signal, so after t_{difs}, the other nodes will start to count down again.

6. Collided transmission of NR-U BS and Wi-Fi AP (t_{uwc}):

   There are NR-U BS and Wi-Fi transmitting at the same time. The time cost of this event will be the larger period of t_{uc} and t_{wc}.

4.4 UE-initiated NR-U with MBS

As in the title of our paper, the objective of our research is to integrate UE-initiated NR-U with MBS. However, the integration process is more complex than just putting the components together; it requires careful harmonization.

As shown in 4.1, the most basic form of integration works as follows. Using the backoff mechanism described above, the UE gains access and transfers this access to the BS. Upon receiving it, the BS notifies the control node via a wired network about the granted access. Based on the information collected on the status of each device, the control

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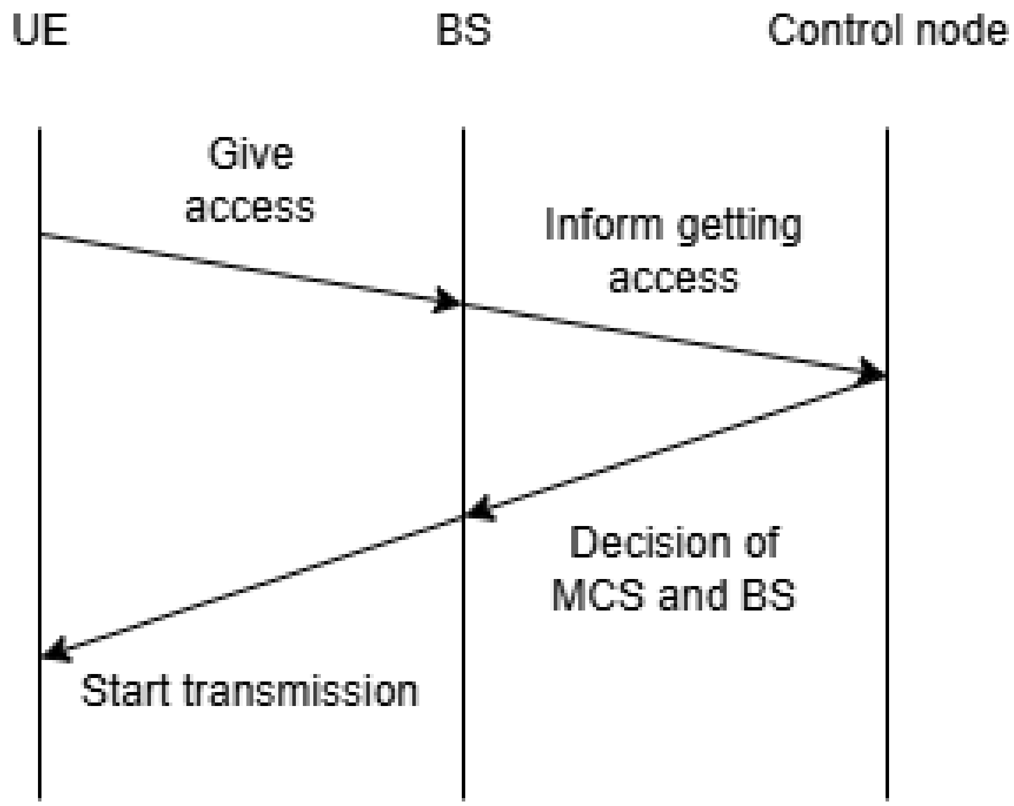

Figure 4.1: Signal flow of UE-initiated NR-U with MBS

node then determines the optimal MCS combination and designates which BS or BSs should start transmitting.

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Chapter 5. Problem formulation

As mentioned in the 1, video content consumes a significant amount of spectrum, leading to a scarcity of available spectrum. Our objective is to maximize the utilization of the spectrum. In this paper, we define spectrum utilization as the throughput of a fixed-size spectrum (20 MHz). Let t_i represent the throughput of the received data for UE i. N_{UE} denotes the number of UEs in the network. The overall network throughput T is given by:

$$T = \sum_{i=1}^{N_{UE}} t_i \tag{5.1}$$

In addition to maximizing network throughput, we aim for our solution to comply with the standards set by 3GPP and other relevant authorities. This compliance ensures that our solution can be easily applied to real systems and maintains fairness with other current wireless technologies like Wi-Fi.

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Chapter 6. Proposed solutions and state of the art

6.1 MCS-opt

Our first proposed method is more aligned with the existing 3GPP standards, as current MBS services do not include SFN. As for the details, generally speaking, the number of UEs is much larger than the number of BSs. This feature is the key to our proposed solution. There is a mechanism called UE-initiated NR-U that is published in the standard of 3GPP [2] that we mentioned many times. Instead of BSs contending for channel access, this mechanism uses UEs to contend for the channel. Since they all share the exact backoff mechanism, more backoff counters mean more access opportunities. More access opportunities mean the ability to transmit more data.

As shown in 4.1, the UE gains access through the backoff mechanism and, upon obtaining access, hands it over to the nearest BS, which then reports it to the control node. At this point, the control node needs to make two critical decisions: first, which MCS level to use, and second, which BS or BSs should handle the transmission.

As shown in 6.1, we simplify the selection to two available BSs and two MCS options without compromising generality. Selecting a different BS impacts the number of UEs covered, as, in the real world, UEs are not evenly distributed but rather clustered in dense and sparse areas. Regarding MCS, choosing a fast MCS (with a higher transmission rate) indeed increases the transmission rate, but since it requires a better SINR, it ultimately covers fewer UEs. In contrast, a slow MCS, which has a relatively lower transmission rate,

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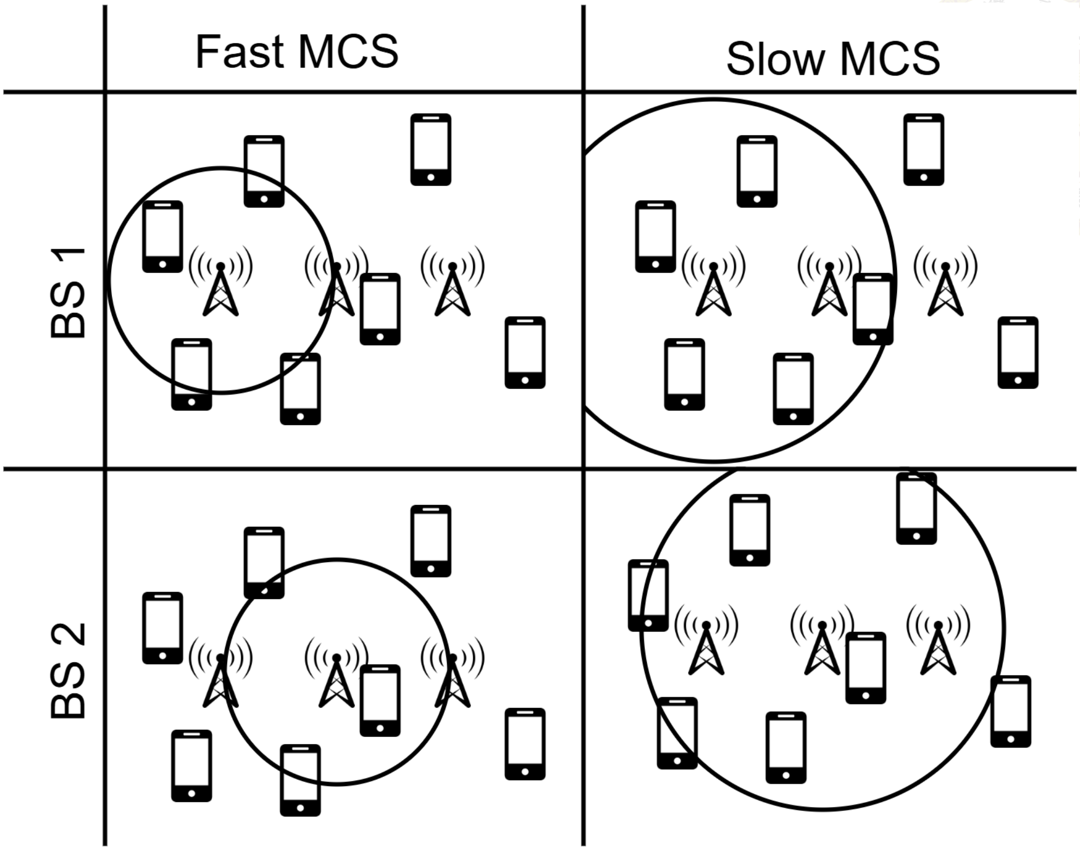

Figure 6.1: The choices of MCS and BS that the system has. Different combinations will have different results.

only requires a lower SINR and thus can cover a more significant number of UEs.

Determining how to choose between these options is the focus of our exploration. Our idea is to have each BS regularly report the signal conditions of both the UE and itself, enabling the control node to estimate the distribution map indirectly. In the articles we referenced, there are 16 MCS levels. By multiplying the number of UEs each MCS level can cover by its transmission rate, we can calculate the throughput achievable with each MCS level. We repeat this process for each accessible BS and define n_b as the number of BSs. This results in $16n_b$ choices, from which we select the one that yields the maximum throughput as our MBS approach. The time complexity is $O(n)$, which is manageable for the control node.

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6.2 UE-initiated SFN

Forming an SFN (Single Frequency Network) in the unlicensed band was introduced in [23]. Rather than using traditional NR-U, we adopt UE-initiated NR-U as introduced in [2], assigning each UE a backoff counter. When a counter reaches zero, the UE sends access to the nearest BS, which then informs the control node. The control node subsequently triggers all BSs with access to form an SFN. This approach improves SINR for UEs, allowing for data transmission at higher MCS levels. Additionally, as outlined in [23], the system selects an MCS level suitable for all UEs in the network.

Although this method theoretically achieves excellent performance, SFN is not permitted under the MBS standard defined by 3GPP, limiting its feasibility compared to the MCS-opt approach.

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Chapter 7. Analytical evaluation

7.1 Fully-listened

Table 7.1: Mathematical Notations for NR-U

Notation	Description
τ	The probability that the node transmits in a random time slot
mu	The maximum collision times a node can suffer
p	The probability that the node collides with other nodes
$b_{0,0}$	The stationary probability of the node staying in the state where collision times equal zero and the backoff counter is zero
n	Number of nodes
p_{idle}	The probability that the system's channel is idle
p_{ws}	The probability that one Wi-Fi AP successfully transmits
p_{ns}	The probability that one NR-U BS successfully transmits
p_{wf}	The probability that Wi-Fi APs collide
p_{nf}	The probability that NR-U BSs collide
p_{nwf}	The probability that NR-U BSs and Wi-Fi APs collide
ϵ	The ratio of time that the transmission is really happening without counting headers
σ	System throughput of NR
s_t	Slot time
s	The speed rate of NR BS

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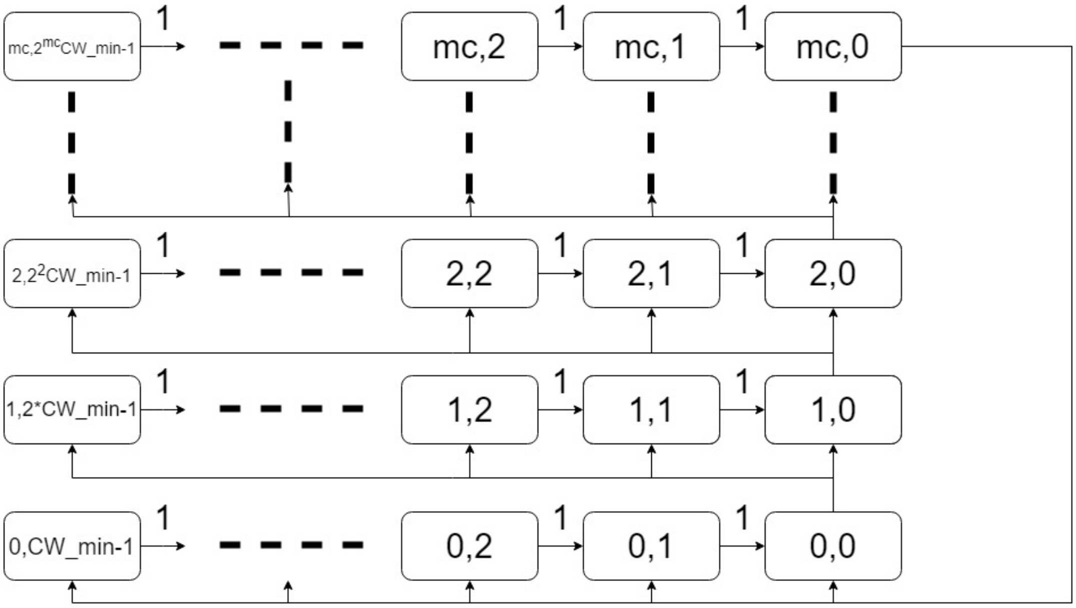

Figure 7.1: Markov Chain for NR-U. The main difference from traditional Wi-Fi is that after collisions reach the maximum collision times and another collision occurs, the contention window will not remain at its maximum value but will return to the minimum value.

$$b_{0,0} = \frac{2(1-p)(1-2p)}{((1-2p)(1-p^{mu+1}) + (1-2p^{mu+1})(1-p)cw_{min})} \tag{7.1}$$

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Table 7.2: Mathematical Notations for MBS

Notation	Description
l	Maximum modulation and coding scheme
$p_{L,b,l}$	The probability that any UE has the maximum modulation and coding scheme l to BS b
$c_{b,l}$	The CDF of $p_{L,b,l}$
$p_{n,b,l}$	The probability that any UE has the maximum modulation and coding scheme l to the nearest BS b
$s(l)$	Speed rate of the maximum modulation and coding scheme l
β	The coefficient of BS b used to calculate η
η	Analytical system throughput of the nearest method
n_{bs}	The number of BSs in the system
$p_{f,b,l}$	The probability that any UE has the maximum modulation and coding scheme l to the farthest BS b
γ	The coefficient of BS b used to calculate ζ
ζ	Analytical system throughput of the farthest method
l_b	Maximum MCS that the initiating UE has to BS b
$n_{c,b,l}$	The number of UEs covered by MBS when the MBS BS is b and the MCS is l
$\sigma_{b,l}$	The MBS throughput when the MBS BS is b and the MCS is l
ν	The maximum of $\sigma_{b,l}$
$\omega_{b,i}$	The power received by UE i from BS b
ω_i	The power received by UE i from all BSs in the network
ω_m	The smallest ω_i
ψ_i	SINR for UE i
χ_i	Speed rate of UE i

7.1.1 BS-initiated NR-U

In [17], a Markov chain similar to that in [7] is used to analyze the performance of NR-U. The main difference lies in the behavior of the contention window. In [7], when the maximum number of collisions is reached, the contention window remains at its maximum if collisions continue. However, in [17], which reflects modern Wi-Fi and NR-U, the

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contention window resets to its minimum size once a device collides after it reaches the maximum collision count. In the following analysis, we will first attempt to determine τ, according to [17], the probability of a device beginning transmission, regardless of whether the transmission is successful. We will then find the collision probability p during transmission. Using these two equations, we solve for τ and then calculate the probabilities of different events occurring based on τ. Finally, by multiplying the probabilities by the duration of each event, we obtain the expected values.

First ,by citing [17], we can get (7.2) to (7.12).

Define τ as the probability that the node starts transmission.

$$\tau = \frac{1 - p^{mu+1}}{(1-p)} b_{0,0} \tag{7.2}$$

Define p as the probability that the transmission collides.

$$p = 1 - (1-\tau)^{n-1} \tag{7.3}$$

By simplifying 7.3, we can get 7.4.

$$\tau = 1 - (1-p)^{\frac{1}{n-1}} \tag{7.4}$$

Now, we can find solutions from the above equations. We can get (7.5) to (7.9).

The probability that there is no AP transmitting is p_{idle}. This condition is also called idle. As for p_{ws}, it is the probability that an AP succeeds in transmitting. The probability that there is a successful transmission started by an NR-U BS is P_{ns}. The probability that there is a collision between APs is P_{wf}. The meaning of p_{uf} is similar to P_{wf}. Here, we must assume there is no AP transmitting. There will be only six events for the channel, so we can get p_{nwf} by using the other five probabilities to subtract one. We can now get (7.10). p_{nwf} represents the probability of a collision between NR-U and Wi-Fi devices.

$$p_{idle} = (1-\tau_n)^{n_n}(1-\tau_w)^{n_w} \tag{7.5}$$

doi: 10.6342/NTU202404732

$$t_{interval} = p_{idle}s_t + p_{ns}t_{ns} + p_{ws}t_{ws} + p_{nf}t_{nf} + p_{wf}t_{wf} + p_{uwf}t_{uwf}; \tag{7.11}$$

$$p_{ws} = n_w\tau_w(1-\tau_w)^{n_w-1}(1-\tau_n)^{n_n} \tag{7.6}$$

$$p_{ns} = n_n\tau_n(1-\tau_n)^{n_n-1}(1-\tau_w)^{n_w} \tag{7.7}$$

$$p_{wf} = (1-\tau_n)^{n_n}(1-(1-\tau_w)^{n_w} - n_w\tau_w(1-\tau_w)^{n_w-1}) \tag{7.8}$$

$$p_{uf} = (1-\tau_w)^{n_w}(1-(1-\tau_n)^{n_n} - n_n\tau_n(1-\tau_n)^{n_n-1}) \tag{7.9}$$

$$p_{nwf} = 1 - p_{idle} - p_{ws} - p_{ns} - p_{wf} - p_{nf} \tag{7.10}$$

We multiply the probabilities with the time period written in 8.2. As a result, we can get (7.11). It also means the average interval of the system. The ratio of time that the transmission is really happening without counting headers is (7.12).(7.13) stands for the throughput of the NR-U BS. We define S_r as the transmission rate of the BS.

$$\epsilon = \frac{p_{ns}t_{cot}}{t_{interval}} \tag{7.12}$$

$$\sigma = S_r\frac{p_{ns}t_{cot}}{t_{interval}} \tag{7.13}$$

7.1.2 UE-initiated NR-U

For UE-initiated NR-U, since the UE needs to send a start signal to the BS first, the transmission collision time for NR-U will be different. Define $\hat{t_{uc}}$ as the duration of an unsuccessful UE-initiated NR-U transmission. It takes s_t to transmit the start signal to the BS. We define t_{gap} as the time the BS takes to switch to transmission mode after receiving the signal. The BS then begins transmitting data back to the UE that granted access, taking an additional s_t transmission time. If the UE does not receive the data within $\hat{t_{uc}}$, it will regard the transmission as failed and restart the countdown.

$$\hat{t_{uc}} = s_t + t_{defer} + s_t \tag{7.14}$$

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$$\beta = \sum_{l=1}^{l} \sum_{k=1}^{n} p_{n,b,l} c_{b,l}^{n-k} (1 - c_{b,l})^{k-1} C_{n-k}^{n-k+k-1} (n + 1 - k) s(l) \tag{7.15}$$

As for why the successful transmission time for UE-initiated NR-U does not change, it is because although transmitting the start signal takes s_t, and switching the BS from receive mode to transmit mode takes t_{gap}, these times are all included in t_{cot}, so they do not change.

7.1.3 MBS

Our paper proposes its own MBS analysis method. Using this analysis method, we determine the system's transmission rate. Finally, by multiplying the proportion of effective transmission time obtained from [17] by the transmission rate we derived, we obtain the throughput.

Nearest We first define UE as having max modulation and coding scheme l. This means that the UE can demodulate and decode MCS that is lower or equal to l. Define $p_{L,b,l}$ as the probability that any UE has max modulation and coding scheme l to $BS\ b$. Define $c_{b,l}$ as the cdf of $p_{L,b,l}$. We then make all UEs only connect to their nearest BS. Define $p_{n,b,l}$ as the probability that any UE has max modulation and coding scheme 1 to the nearest BSb. We assume there is a random UE scattered on the map. There are $n - k$ UEs that have better or equal modulation and coding schemes than the UE that we randomly chose. There will be $k - 1$ UEs that have worse modulation and coding schemes than it excluding itself. There can be combinations. We know signals can only be received and decoded by UEs that have better or equal SINR. In the end, we multiply it with speed rate $s(l)$. Integer k could be any number from 1 to n. 7.17 is established. Define β as the coefficient of BS b.

Define σ_n as the analysis system throughput of the method nearest. Define n_b as the

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$$\gamma = \sum_{l=1}^{l}\sum_{k=1}^{n} p_{f,b,l} c_{b,l}^{n-k}(1-c_{b,l})^{k-1} C_{n-k}^{n-k+k-1}(n+1-k)s(l) \tag{7.17}$$

number of BSs in the system. We can get 7.16.

$$\sigma_n = \sum_{b=1}^{n_b} \beta(b)\epsilon \tag{7.16}$$

Farthest We first define UE as having max modulation and coding scheme l. This means that the UE can demodulate and decode MCS that is lower than l. $p_{n,b,l}$ is the probability that any UE has max modulation and coding scheme l to BSb. $c_{b,l}$ stands for the cdf of $p_{n,b,l}$. We then make all UEs only connect to its farthest BS. $p_{f,b,l}$ is the probability that any UE has max modulation and coding scheme l to farthest BSb. We assume there is a random UE scattered on the map. There are $n-k$ UEs that have better or equal modulation and coding schemes than the UE that we randomly chose. There will be $k-1$ UEs that have worse modulation and coding schemes than it excluding itself. There can be combinations. We know signals can only be received and decoded by UEs that have better or equal SINR. In the end, we multiply it with speed rate $s(l)$. k could be any number from 1 to n. 7.17 is established. γ stands for the coefficient of $BS\ b$.

ζ stands for analysis system throughput of method farthest. n_{bs} stands for the number of BSs in the system. 7.18 is established.

$$\zeta = \sum_{b=1}^{n_{bs}} \gamma(b)\epsilon \tag{7.18}$$

MCS-opt As mentioned in section 6, the method MCS-opt chooses the best MBS combination in the possible MBS combinations. We define the initiating UE as having max MCS to BS b as l_b. $n_{c,b,l}$ as the number of MBS covered UE when the MBS BS is b and the MCS is l. $\sigma_{b,l}$ stands for the MBS throughput when the MBS BS is b and the MCS is l. 7.19 is established.

$$\sigma_{b,l} = n_{c,b,l}s(l) \quad l > l_b \tag{7.19}$$

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We need to find the maximum, and we call it ν. 7.20 is established.

$$\nu = max(\sigma_{b,l}) \tag{7.20}$$

σ stands for the system throughput as follows:

$$\sigma = \nu\epsilon \tag{7.21}$$

SFN $\omega_{b,i}$ stands for the power that is received by UE i from BS b. ω_i stands for the power that is received by UE from all BS in the network. ω_m stands for the smallest ω_i as followed

$$\omega_m = min(\sum_{b=1}^{n_{bs}} \omega_{b,i}) \tag{7.22}$$

We then get SINR written as ψ fromω_m. Finally, we use 8.3 to change ψ into speed rate χ. System throughput σ is as followed:

$$\sigma = \chi\epsilon \tag{7.23}$$

7.2 Partially-listened

In the partially-listened scenario, hidden node problem exists. We first define the initiating UE as the UE that is going to grant access to a BS and the receiving BS as the BS that will receive this access from the initiating UE. Essentially, two types of nodes are present. One type is the sensible UE, which is within the sensing range of both the initiating UE and the receiving BS. The other type is the hidden node, which lies within the sensing range of the receiving BS only and is outside the sensing range of the initiating UE.

Define N_s as the number of sensible nodes. Define N_h as the number of hidden nodes. We can get 7.24 from 7.2. Define τ_s as the probability that a sensible node transmits in any time slot.

$$\tau_s = \frac{1 - p^{mu+1}}{1 - p} b_{0,0} \tag{7.24}$$

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Define τ_h as the probability that a hidden node transmits in any time slot according to [22].

$$\tau_h = \left(\frac{1 - p^{mu+1}}{1 - p} + \sum_{i=0}^{mu} \frac{(2cw_i - v)(v - 1)p^i}{2cw_i}\right) b_{0,0} \tag{7.25}$$

Define p as the probability that a collision occurs when the UE is transmitting access.

$$p = 1 - (1 - \tau_s)^{N_s}(1 - \tau_h)^{N_h} \tag{7.26}$$

We can now determine the probability of the channel being idle. If all hidden nodes and sensible nodes, including the node we are calculating, are not transmitting, the channel is idle.

$$p_{idle} = (1 - \tau_s)^{N_s}(1 - \tau_h)^{N_u} \tag{7.27}$$

For a successful transmission, the chosen node must be transmitting, and all sensible nodes, excluding the chosen node, and hidden nodes must not transmit.

$$p_s = \tau_s(1 - \tau_s)^{N_s - 1}(1 - \tau_h)^{N_h} \tag{7.28}$$

Define p_{os} as the success transmission probability of other UEs that can be sensed by the chosen UE.

$$p_{os} = (N_s - 1)\tau(1 - \tau)^{N_s - 1}(1 - \tau_h)^{N_h} \tag{7.29}$$

The collision probability is 1 minus all other probabilities.

$$p_c = 1 - p_s - p_{idle} - p_{os} \tag{7.30}$$

Define Ω_i as the number of times that node i can successfully access in simulation time S. Define s_t as the slot time length.

$$\Omega_i = \frac{p_s t_{us} S}{(p_s t_{us} + p_{os} t_{us} + p_c t_{uc} + p_{idle} s_t) t_{us}} \tag{7.31}$$

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Define Ω as the number of times that all nodes of the NR-U system access successfully.

$$\Omega = \sum_{i=1}^{N_{UE}} \Omega_i \tag{7.32}$$

Define r_u as the speed rate of NR-U. Define n_{am} as the average number of UEs within the sensing range of a BS. Multiply r_u, n_{am}, and the number of times the system can successfully access to get the system throughput. Define σ_h as the system throughput.

$$\sigma_i = \frac{r_u n_{am} \Omega_i}{S} \tag{7.33}$$

$$\sigma = \sum_{i=1}^{N_{UE}} \sigma_i \tag{7.34}$$

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Chapter 8. Simulation Results and Discussion

8.1 Simulation settings

The system is composed of UEs, APs, and BSs. The default set parameters are shown in 8.1. The devices will contend for the channel using backoff mechanism. As discussed in the 1, spectrum resources are becoming scarce. Therefore, we assume that the devices will operate with a full buffer. Once the transmission is completed, the devices will release the channel, and the next round of contention will begin.

Table 8.1: Default parameters of the system

Parameters	Value
Radius of cells	300m
Number of BS	19
Number of UE	100
BS transmission power	30dBm
Noise Power	-92dBm
f_c	2.4GHz
h	5m
Speed rate of Wi-Fi (r_w)	54Mbps
BS distribution	Cellular Network
UE distribution	Uniform

8.1.1 Modulation and Coding Scheme

When the BS transmits, it might use different modulation and coding methods. We summarize these as modulation and coding schemes. Using a compact modulation and

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Table 8.2: Time parameters

Time parameters	Value (μs)	Description
s_t	9	Length of a time slot
t_{pusch}	s_t	Time reserved for PUSCH
t_{gap}	16	Time gap between uplink and downlink
t_f	16	Silent period
t_{cot}	8000	Channel occupancy time for NR-U
t_{plw}	3008	Channel occupancy time for Wi-Fi
t_d	$t_f + 2s_t$	Defer time
t_{rts}	(160+224)/r_w	Length of ready to send signal
t_{sifs}	16	Length of short interframe space
t_{difs}	34	Length of DCF interframe space
t_{cts}	(112+224)/r_w	Length of clear to send signal
t_{headw}	(192+224)/r_w	Length of Wi-Fi header
t_{ack}	t_{cts}	Length of ACK message
t_{us}	$t_{cot} + t_d$	Length of successful transmission of NR-U
t_{ws}	$t_{rts} + 3t_{sifs} + t_{cts} + t_{headw}$ $+t_{plw} + t_{ack} + t_{difs} + s_t$	Length of successful transmission of Wi-Fi
t_{uc}	$t_{cot} + t_{defer}$	Length of collision transmission of NR-U
$\hat{t_{uc}}$	$s_t + t_{defer}$	Length of collision transmission of UE-initiated NR-U
t_{wc}	$t_{rts} + t_{difs} + s_t$	Length of collision transmission of Wi-Fi
t_{uwc}	$max(t_{uc}, t_{wc})$	Length of collision transmission of NR-u and Wi-Fi

coding scheme can provide a better data rate. However, a compact modulation and coding scheme means that once there is any interference with the transmission, the UE might have difficulty demodulating and decoding the signal. Therefore, we must decide on the modulation and coding scheme based on the SINR that the UE is experiencing. According to [25], we can obtain 8.3 for the modulation and coding schemes. Additionally, the UE can demodulate and decode signals that have a higher SINR than the minimum required.

8.2 Fully-listened

8.2.1 Baseline

Nearest BS In this method, we assume that the system is UE-initiated. After gaining access to the channel, the UE grants it to the nearest BS, which then begins MBS. The MCS is set so that the UE that granted access can just demodulate and decode. All other UEs with an equal or better MCS level can also receive the data.

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Table 8.3: Modulation and coding scheme: SINR to speed rate

Speed rate (Mbps)	SINR (dB)
10.369	29
9.68	27
8.717	24.9
7.777	23.1
7.161	21.5
6.333	19.5
5.463	17.45
4.651	16.1
3.823	13.9
3.369	11.8
2.68	10
2.067	8
1.228	5.1
0.527	4.05
0.213	2
0	0

Farthest BS In this method, we assume that the system is UE-initiated. After gaining access to the channel, the UE grants it to the nearest BS. The BS informs the control node that it has obtained access. The control node then initiates MBS from the BS that is furthest from the UE that granted access. It is important to note that the UE must be able to detect the signal from this BS. The MCS is set so that the UE that granted access can just demodulate and decode. Additionally, all other UEs with an equal or better MCS level can receive the data.

SOTA This method, introduced in [23], represents the state-of-the-art in mobile network unlicensed bands with multicast and broadcast. It follows traditional NR-U, specifically BS-initiated NR-U. When the BS's backoff counter reaches zero, it activates all BSs with access to form an SFN (Single Frequency Network), allowing BSs to transmit data using a higher MCS level. According to [23], the system selects an MCS level that can serve all UEs in the network. Intuitively, this method should deliver excellent performance. However, as mentioned earlier, SFN is not permitted in the MBS standard defined by 3GPP.

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8.2.2 Comparison between Methods

In 8.1, we can see that the method nearest BS has worse performance compared to the method farthest BS. This is because the nearest BS method excludes too many UEs. Although the bottleneck user has a transmission rate, it can contribute little throughput to the system.

The performance of the farthest BS method is better than that of the nearest BS method. The reason for this result is similar to that of the nearest BS method. Although the transmission rate of the MBS is limited due to the long distance between the BS and the initiating UE, the large number of covered UEs compensates for this drawback.

The MCS-opt method performs better than the nearest BS and farthest BS methods in any condition because it always considers all combinations. Additionally, there are only $16n_b$ combinations, so the time complexity is acceptable.

It is intuitive that UE-initiated SFN has the best performance. UE-initiated access gives it more chances than SOTA. Once it has access, it activates all BSs that have access to form an SFN. Even though it needs to serve all the UEs in the system, meaning the UE with the worst SINR in the network will be the bottleneck user, the MCS of system transmission will still be fine. This is because SFN provides considerable improvement to SINR.

The method Rival SFN has several features worth discussing. First, it performs almost identically to the UE-initiated SFN method when there is no AP. This is because, without APs, only the NR-U nodes are accessing the channel, resulting in the same performance for both BS-initiated and UE-initiated approaches. However, when the number of APs increases to one, the system throughput drops sharply from around 1000 to about 600. This decline occurs because the number of contending nodes has increased, and Wi-Fi now shares part of the channel access opportunities. As the number of APs continues to grow, the system throughput of NR-U decreases correspondingly, which is expected behavior for any unlicensed system. We can now proceed to compare this SOTA method with other methods on a case-by-case basis.

As mentioned above, the SOTA method has no chance of outperforming the UE-

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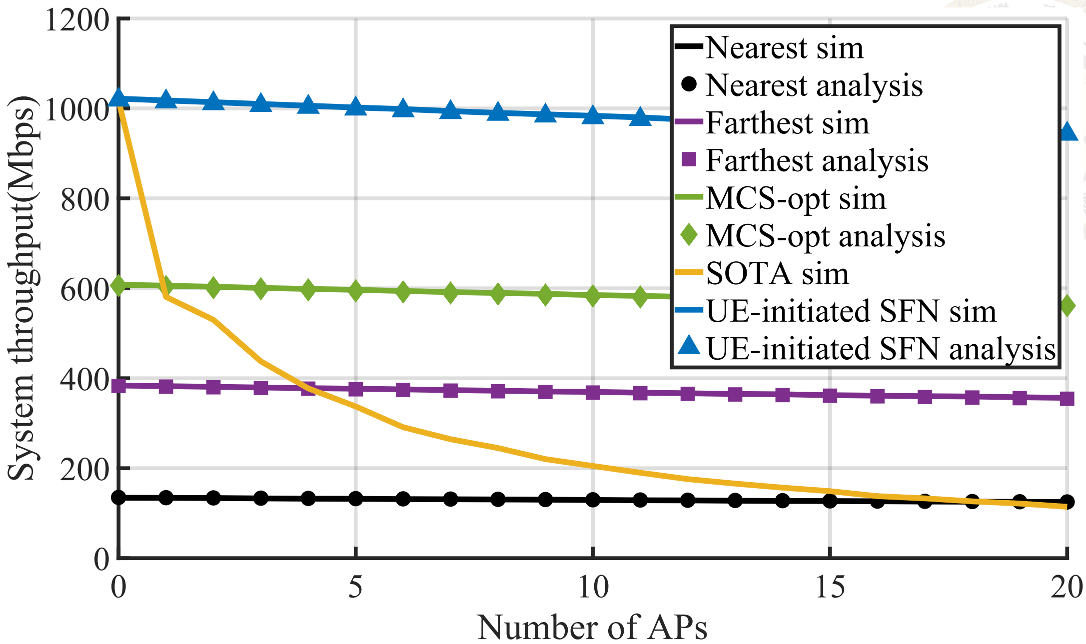

Figure 8.1: 2.4GHz Comparison between methods of different initiating mechanisms and MBS strategies

initiated SFN method because SOTA has fewer contending nodes than UE-initiated SFN and is thus more susceptible to interference, which easily lowers its performance. Compared to the MCS-opt method, SOTA starts to fall behind once there is more than one contending AP. It is reasonable to consider the MCS-opt method as outstanding since it closely aligns with current standards and surpasses the SOTA method under most conditions. Moreover, setting up a communication system in an area without any other unlicensed technologies is impractical, so it is reasonable to conclude that the MCS-opt method generally performs better than the Rival SFN method in real-world wireless networks. The Rival SFN method even falls behind the farthest BS method when there are more than five active APs. Finally, it performs almost the same as the nearest BS method when the number of APs reaches seventeen, indicating that SOTA's performance deteriorates significantly when numerous APs are present.

In conclusion, the farthest BS method generally outperforms the nearest BS method due to its higher number of MBS-covered UEs. The MCS-opt method offers both low time complexity and better performance compared to these two methods. In real-world scenarios, MCS-opt theoretically outperforms SOTA. The UE-initiated SFN method demonstrates strong resistance to interference from Wi-Fi APs.

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8.2.3 Central Frequency

The 5GHz band is another unlicensed band that is frequently used. Generally speaking, people use the 5GHz band for its wider spectrum. Compared to the 2.4GHz band, the higher frequency of the 5GHz band makes it easier to provide more spectrum. However, in this paper, we only consider contending for a fixed-size spectrum because we want to focus on the impact of path loss on system throughput.

In 8.2, we can see that all methods perform worse than in 8.1. The nearest BS method has decreased by about 61 percent. The farthest BS method decreased by about 46 percent. The reason the nearest BS method suffers more loss than the farthest BS method is clear: the nearest BS method covers very few UEs for each MBS, with its advantage being a high transmission rate for each covered UE. However, the high path loss caused by higher frequency easily diminishes this transmission rate. In the case of the farthest BS method, its advantage lies in covering many UEs during MBS, and since the speed rate is already low, worse SINR only causes a slight loss. For the MCS-opt method, the decrease is about 43 percent. The percentage decrease in system throughput for the MCS-opt method is less than for the nearest BS and farthest BS methods, but the high path loss still remains a concern.

The UE-initiated SFN method still achieves the best system performance among all methods. However, there is a slight performance decrease due to the high path loss associated with high central frequencies. This decrease is minimal thanks to the SFN, which enhances SINR for all UEs. In the 2.4GHz band, the SINR of the UE-initiated SFN method already exceeds the requirements for 16-level MCS, the highest MCS level. Therefore, the SINR of its UEs remains very high overall.

As usual, the SOTA method has nearly the same system throughput as the UE-initiated SFN method when there are no APs. As the number of APs increases, its system throughput decreases similarly to the behavior observed at 2.4GHz. It starts to fall behind the MCS-opt method when there are 5 APs contending for the channel and loses to the farthest BS method when there are ten contending APs. Despite this, it consistently outperforms the nearest BS method.

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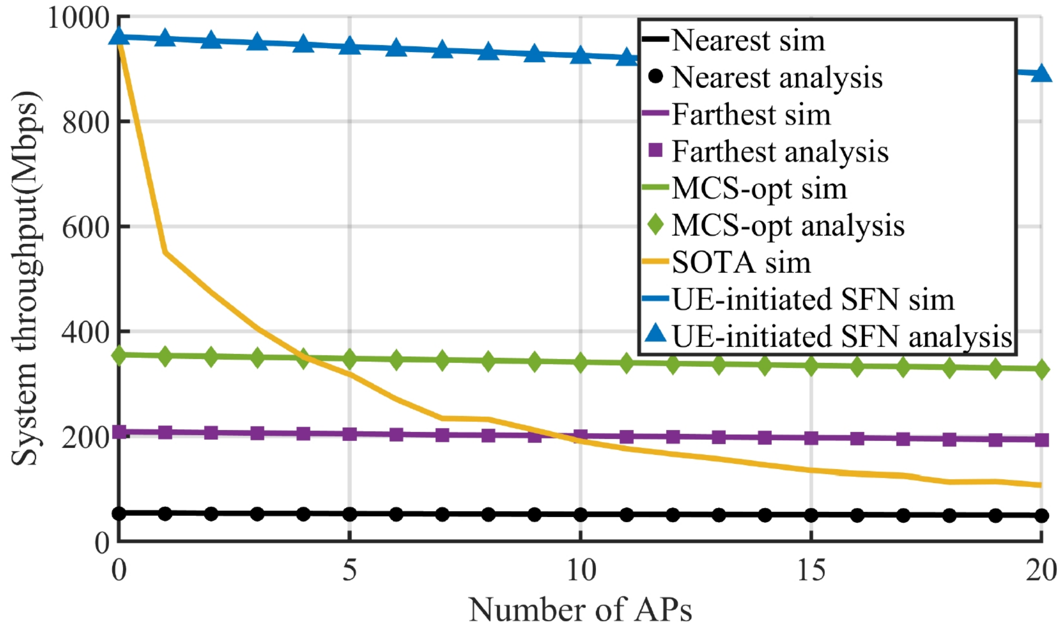

Figure 8.2: 5GHz Comparison between methods of different initiating mechanisms and multicast strategies

In conclusion, the MCS-opt method is still the best method compared to the nearest BS and farthest BS methods. SFN provides better resistance against high path loss caused by high central frequency because its SINR is much higher than the minimum required. However, the decrease in system throughput is inevitable.

8.2.4 Inter-site distance (ISD)

Inter-site distance (ISD) equals 100 meters In 8.3, we can observe that the nearest BS method, the farthest BS method, and the MCS-opt method all perform better when the ISD is 100m compared to when the ISD is 300m. However, there is no improvement in either SFN method. At an ISD of 300m, the SFN has already enabled the bottleneck user to achieve sufficient SINR to receive transmissions from BSs at the highest MCS level, so the increased SINR resulting from lower path loss no longer enhances system throughput. Nevertheless, the increase in contending APs continues to have a significant impact on SOTA.

As for the nearest BS method, the improvement is 424 percent. The improvement of this method is the highest compared with other methods. There are two main reasons. The

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first one is the SINR improvement for the bottleneck user. The MBS can proceed with a higher level of MCS. However, this reason alone will not account for such a significant improvement. The second reason is the main reason. The MBS covers many more UEs than before. The decrease in ISD can also be explained by the higher density of UEs. The MCS chosen by this method can include many more UEs than before.

Compared with the nearest BS method, the farthest BS method shows only a 102 percent improvement. This is because it already performs exceptionally well when ISD equals 300m, and with an ISD of 100m, its coverage area is already extensive, making it challenging to increase the number of covered UEs further.

As for the MCS-opt method, we can see that its system throughput has also improved. The reason for the improvement is similar to the nearest BS method and farthest BS method. It can now cover more UEs because the density of UEs has increased. Additionally, the level of the bottleneck user's MCS is also increased. Furthermore, it almost has the same performance as the method UE-initiated SFN.

The SINR of the UE-initiated SFN is already sufficient when the ISD equals 300m, even exceeding the SINR required for the highest MCS. Therefore, further reduction in path loss does not bring any improvement. Meanwhile, SOTA continues to be affected by interference from APs.

If the network is small enough, SFN does not offer a significant advantage over other methods. Choosing the MCS-opt method achieves performance close to that of UE-initiated SFN, making it an excellent choice, mainly because its mechanism is more compatible with existing standards.

Inter-site distance (ISD) equals 500 meters In 8.4, the system throughput of the three MBS methods (nearest BS method, farthest BS method, and MCS-opt) has all decreased. The nearest BS method decreases by around 53 percent, the farthest BS method by about 31 percent and the MCS-opt method by approximately 31 percent. The nearest BS method still shows the most considerable change. This is due to a similar reason as its significant increase when the ISD is 100m: the number of covered UEs decreases sharply as the ISD increases, and the MCS used by the BS is also lower compared to the scenario when the

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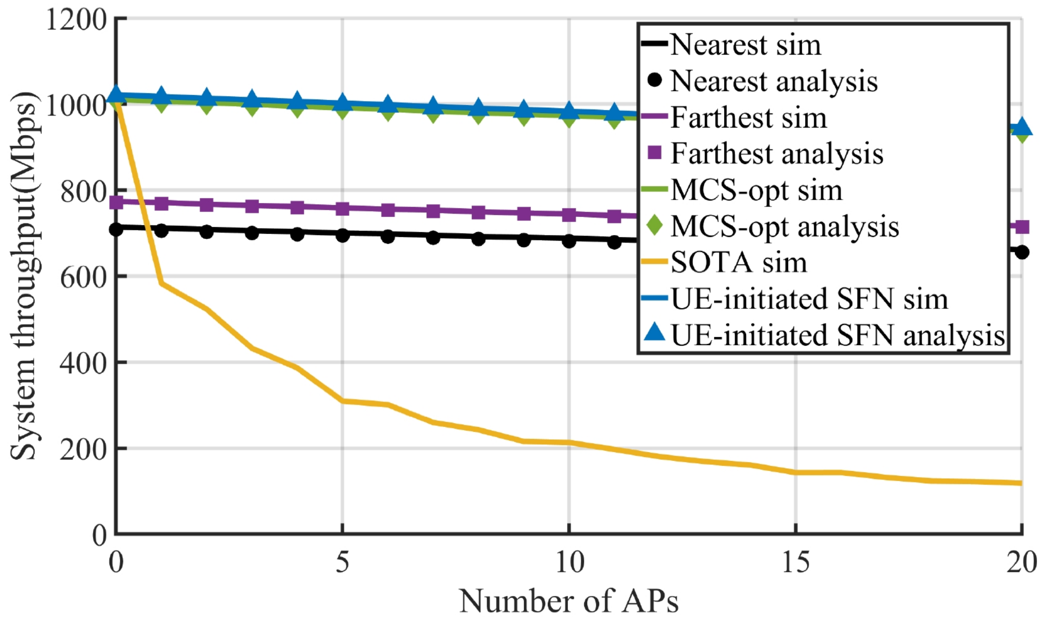

Figure 8.3: ISD equals 100. Comparison between methods of different initiating mechanisms and multicast strategies

ISD is 300m.

As for the two SFN methods, the system throughput remains unchanged. This is because the SINR of UEs already exceeds the required SINR for the highest MCS level by a substantial margin when the ISD is 300m. There needs to be more than the increased path loss to lower the UE's SINR below the requirement for the SINR of the highest MCS level.

We can draw a brief conclusion that SFN demonstrates strong resilience against extreme conditions, such as high path loss. Moreover, our designed UE-initiated SFN outperforms the SOTA. Among the other three methods, MCS-opt still takes the lead.

8.2.5 Optimization of method MCS-opt

As specified in [2], the MBS of UE-initiated NR-U must include the initiating UE. This mechanism is designed to ensure fairness, preventing situations where a UE gains frequent access without receiving any data itself. However, this rule limits the range of MCS levels available for selection. Without this restriction, we have $16n_b$ combinations to choose from. With the restriction in place, we are left with only $16(n-i)$, where i is the

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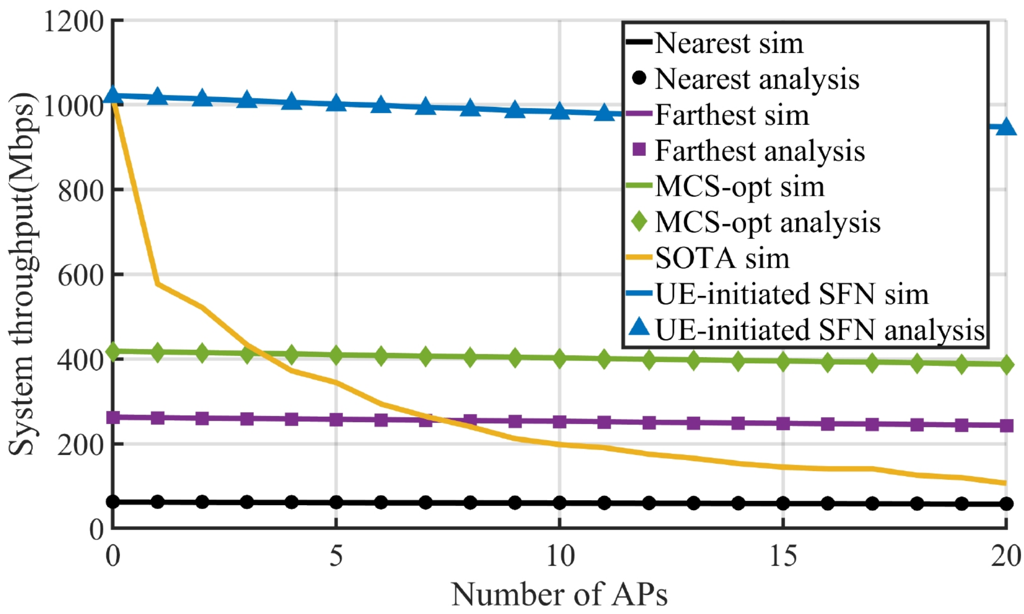

Figure 8.4: ISD equals 500. Comparison between methods of different initiating mechanisms and multicast strategies

maximum MCS level of the initiating UE, thus reducing the number of possible choices. Our objective is to determine if this rule impacts system throughput and, if so, to quantify the extent of this impact.

We use the parameters in 8.2. Unlimited opt means that the system chooses any BS and any MCS. Opt means that the system chooses BS and MCS, which must cover the initiating UE. As shown in 8.5, we can see that both methods have almost the same performance. Unlimited opt has only a bit better performance than op.

We can conclude that the 3GPP requirement sacrifices only a negligible amount of performance while achieving fairness in the system.

8.3 Partially-listened

As shown in 8.6, the transmission probability of the initiating UE gradually decreases as the number of UEs increases. This is intuitive, as with fixed bandwidth, a higher number of UEs means that each UE has fewer transmission opportunities available.

As shown in 8.7,p represents the probability of a collision occurring when the initiating UE begins to grant access to the receiving BS. This probability is influenced by the

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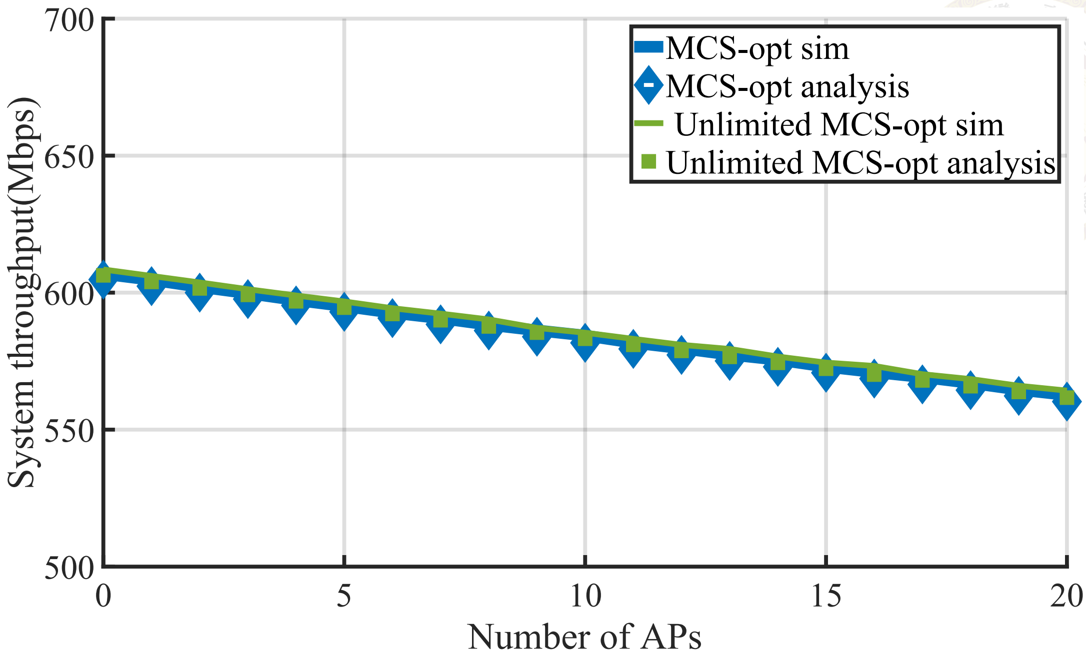

Figure 8.5: System throughput of method optimized MCS-opt and method MCS-opt

number of sensing UEs and the number of hidden UEs. Although NR-U has a backoff mechanism to avoid collisions, the probability of collisions still increases as the number of UEs grows.

By observing (7.28), we can easily see that p_s is strongly related to τ_s and τ_h. It is also influenced by the number of sensing nodes (N_s) and hidden nodes (N_h). As the number of UEs increases, τ decreases, while N_s and N_h increase, resulting in a decrease in p_s. This is intuitive: as the number of competing nodes with the exact mechanism grows, the chances of success naturally decrease. As shown in 8.9, as the number of UEs increases, p_{idle} starts to decrease because more UEs mean more nodes are attempting to access the channel. As more nodes attempt to access the channel, the probability that the channel remains idle naturally decreases.

As shown in 8.10, when the number of UEs is 1, the probability is 0. This is because we focus on a specific UE within the system for the calculation, and with no other UEs present, this results in a probability of 0. Additionally, we observe that this probability gradually increases as the number of UEs rises. This is intuitive, as the more competing UEs there are besides the designated UE, the more p_{os} will slowly increase.

As shown in 8.11, p_c represents the probability that the initiating UE fails to pass

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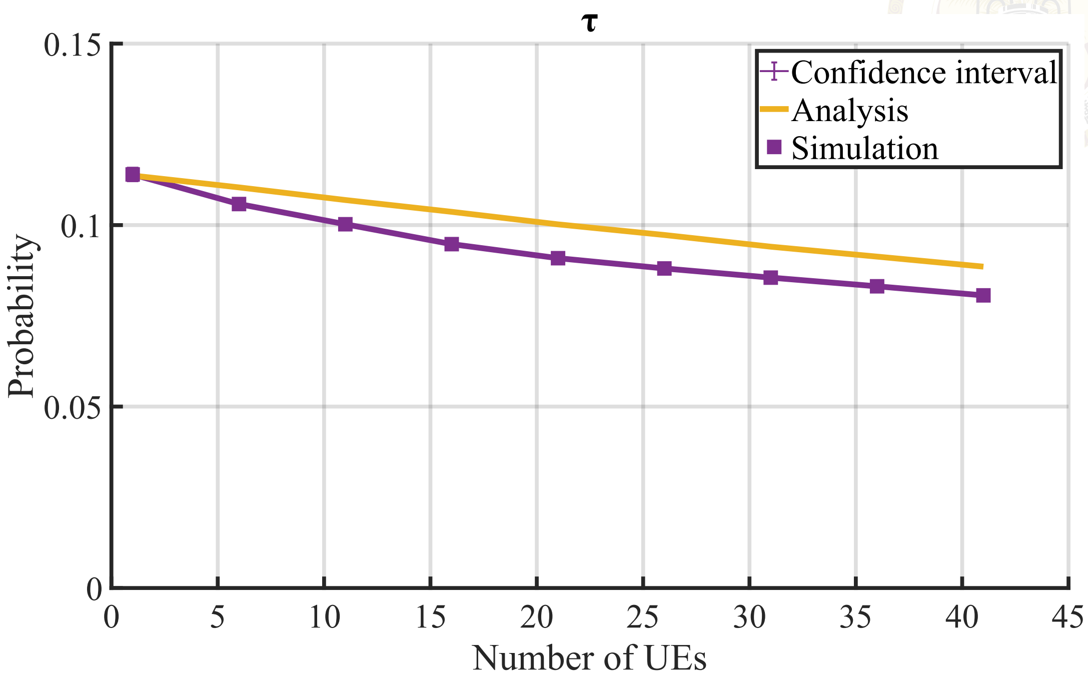

Figure 8.6: Transmission probability of initiating UE

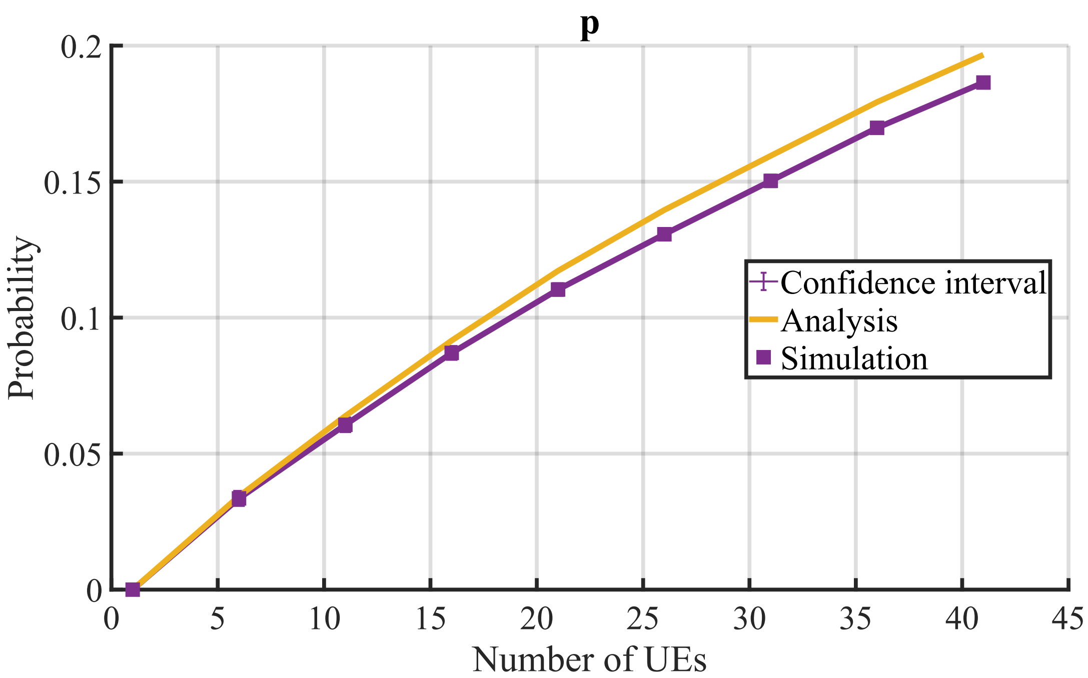

Figure 8.7: Collision probability of transmitting UE

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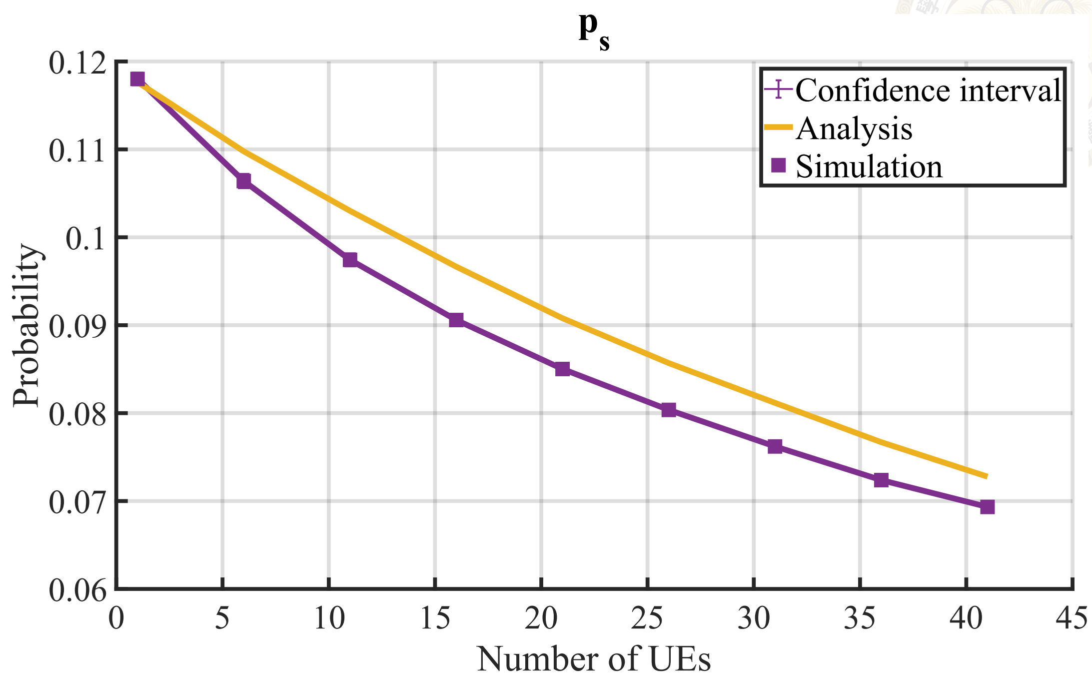

Figure 8.8: Success probability of transmission. It does not represent the proportion of time but rather the proportion of events.

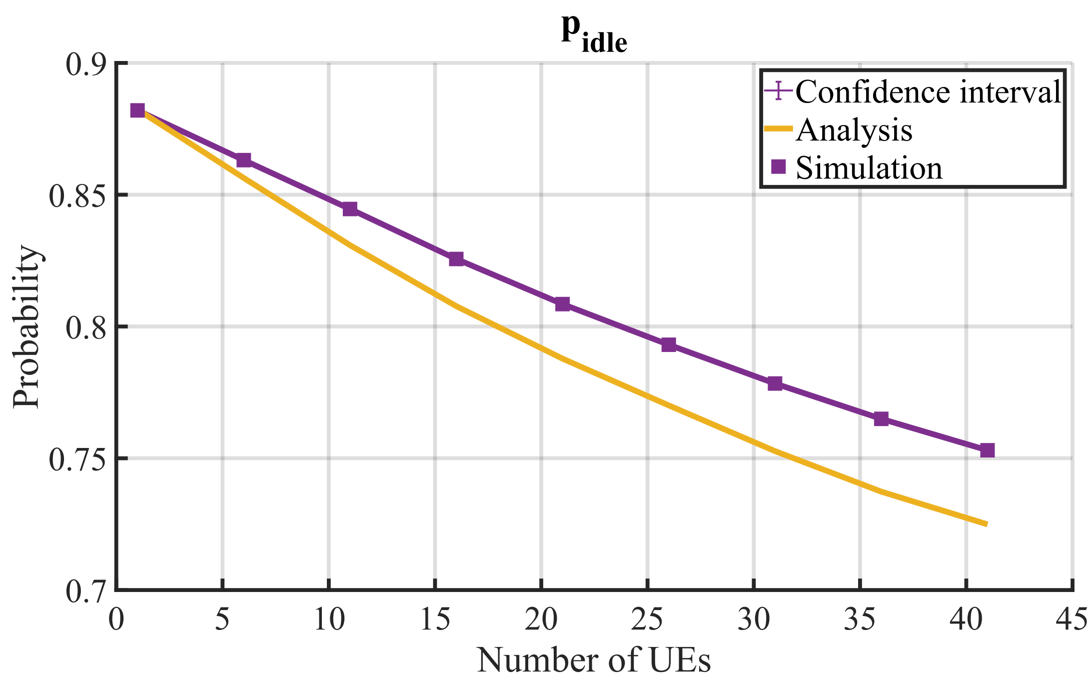

Figure 8.9: Idle event probability of the channel. It does not represent the proportion of time but rather the proportion of events.

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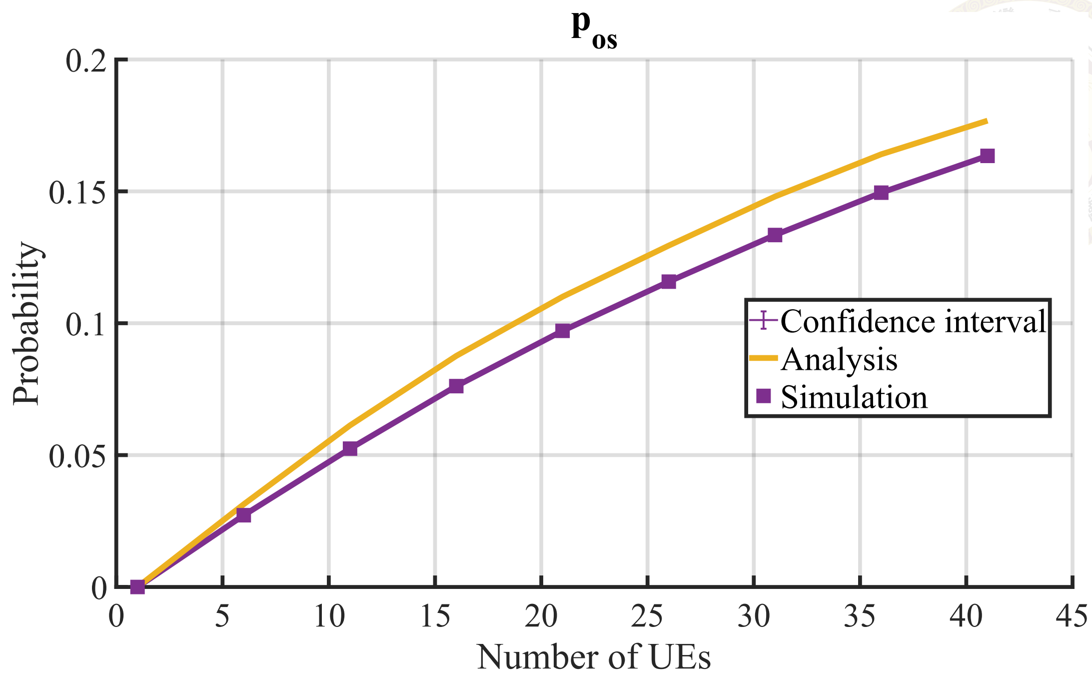

Figure 8.10: Successful transmission probability of nodes other than the designated UE. It does not represent the proportion of time but rather the proportion of events.

access to the BS. Initially, p_c rises quickly as the number of UEs increases, leading to more frequent collision opportunities. As shown in 8.9, as the number of UEs increases, p_{idle} starts to decrease because more UEs mean more nodes are attempting to access the channel. As more nodes attempt to access the channel, the probability that the channel remains idle naturally decreases.

As shown in 8.11, p_c represents the probability that the initiating UE fails to pass access to the BS. Initially, p_c rises quickly as the number of UEs increases, leading to more frequent collision opportunities. As shown in 8.12, by using (7.31) along with the probabilities discussed above, we can determine the average number of times each UE can access the channel within the simulation period. We observe that this number is monotonically decreasing. This is because we are focusing on the access times of a single UE, similar to p_s.

As shown in 8.13, throughput increases as the number of UEs rises. This increase is primarily due to two factors. First, as the number of UEs grows, the available bandwidth across the system's spatial area gradually becomes fully utilized, meaning channel utilization improves. Second, with more UEs, there are more potential target UEs for MBS transmissions, which naturally leads to an increase in throughput.

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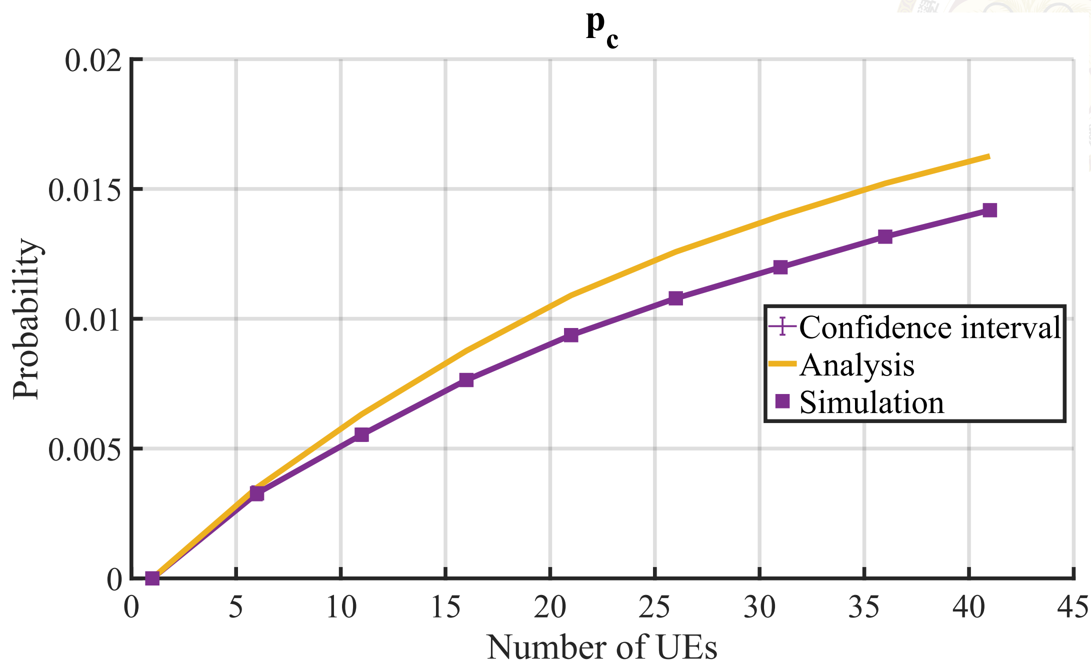

Figure 8.11: Collsion probability of transmission. The collision probability of transmission differs from p, which represents the collision probability specifically when a transmission is occurring. Here, the collision probability refers to the proportion of collision events out of all events occurring within a given time frame.

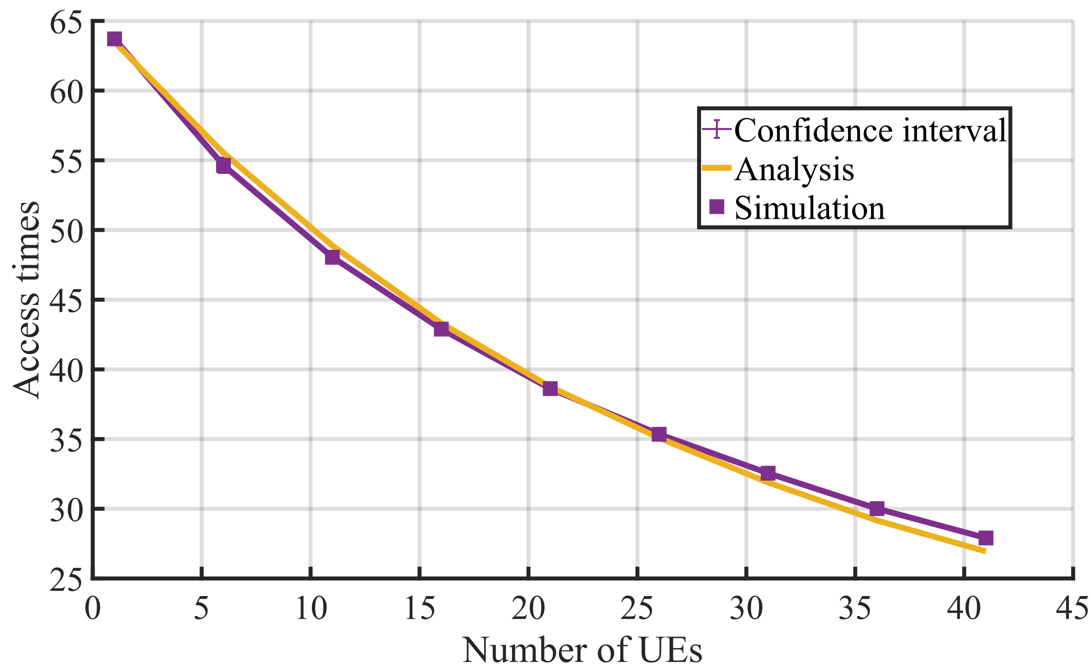

Figure 8.12: Access times of a node in certain period($10000 \mu s$)

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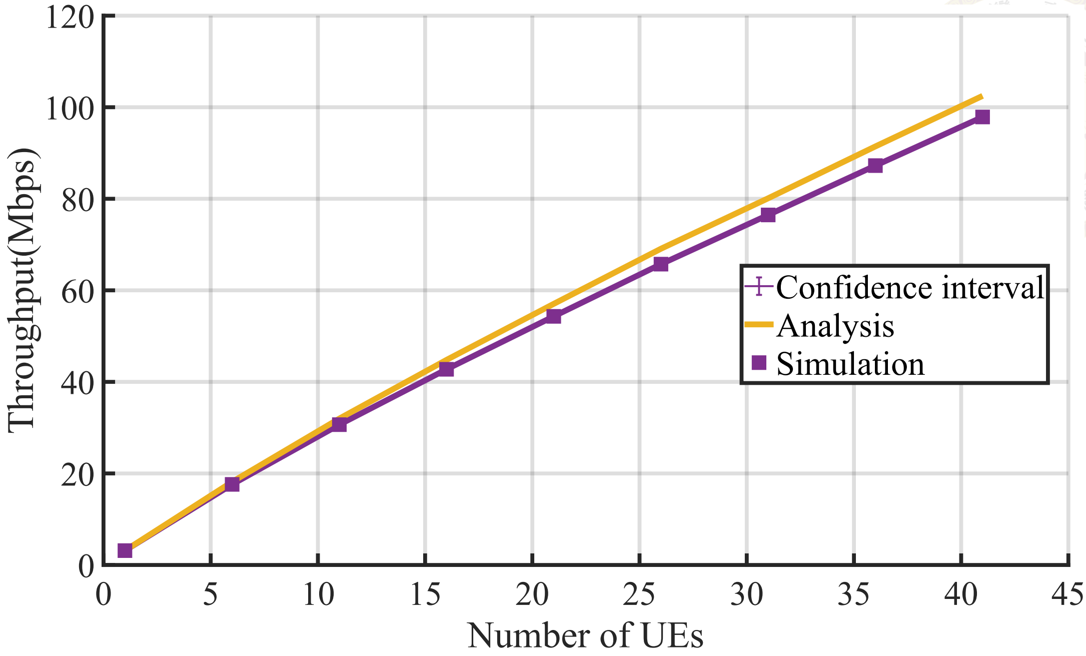

Figure 8.13: Throughput of the NR-U system

As shown in 8.14, we set the x-axis to represent the number of APs, assuming there are 100 UEs. We can clearly observe that the simulation results closely match the mathematical analysis, and the overall trend aligns with intuition: a higher number of APs gradually impacts the NR-U system's throughput due to Wi-Fi interference. However, the impact remains minimal, mainly due to the use of UE-initiated NR-U.

In summary, using the calculated probabilities, we derive access times, which then allow us to determine throughput. Although a higher number of UEs increases the collision probability (p_c), NR-U's inherent mechanisms effectively limit excessive collision rates. Additionally, the UE-initiated approach provides NR-U throughput with strong resilience against Wi-Fi interference. At the same time, the multiplicative growth in MBS transmission targets leads to an overall increase in throughput, demonstrating that our system is both practical and capable of achieving significant throughput gains.

As shown in 8.15, we will simulate the five methods previously discussed under the partially-listened assumption. First, by comparing 8.15 with 8.1, we can clearly see that the values and trends in both figures are very similar. All methods are affected by the number of APs, with SOTA being the most impacted. Next, we will provide a detailed comparison of each method.

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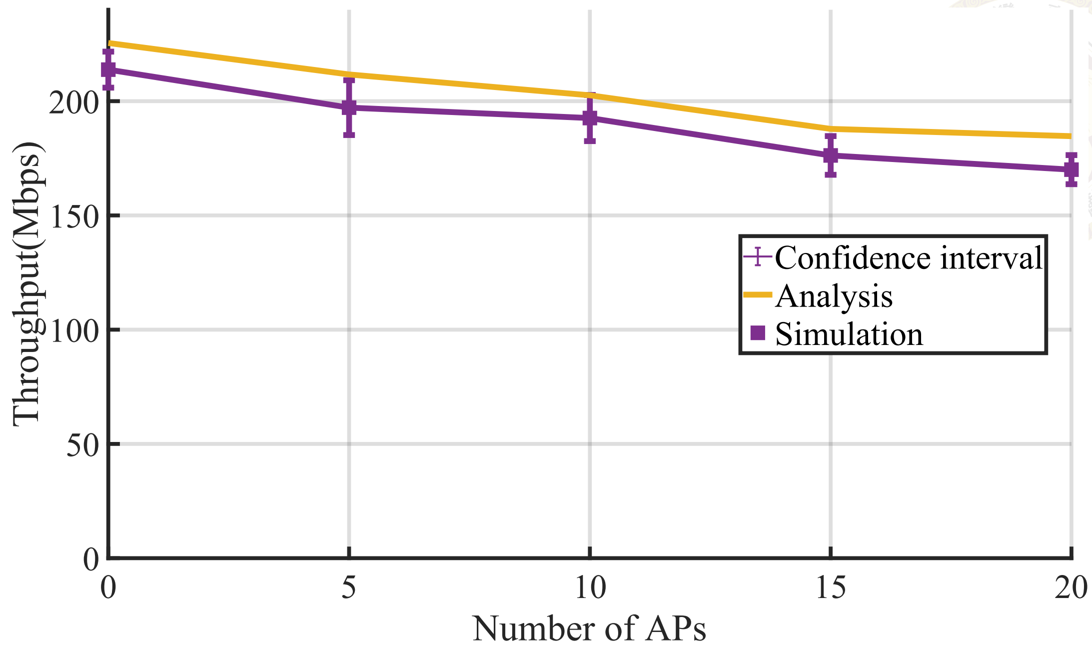

Figure 8.14: Throughput of the NR-U system when x-axis stands for number of APs

SOTA Since SOTA is BS-initiated, it involves fewer contending nodes than UE-initiated methods, thereby increasing its vulnerability to interference as the number of APs rises. This effect is evident in both fully-listened and partially-listened scenarios.

Nearest In the fully-listened scenario, only one channel is active at a time. In contrast, the partially-listened scenario functions as if there are multiple independent channels that do not interfere with each other, ultimately resulting in better performance.

Farthest Due to the limitation of the sensing range, the base station selected by the farthest method will essentially be the same as the one selected by the nearest method, leading to the same throughput in the end.

MCS-opt In the fully-listened scenario, MCS-opt typically selects a lower transmission rate to include more UEs, which generally improves throughput and ensures that almost all UEs are served. In this case, the partially-listened scenario would demonstrate a similar performance to the fully-listened scenario.

UE-initiated SFN Thanks to the strong signal power provided by the SFN, nearly all UEs achieve the optimal SINR. This ensures that the majority of UEs can receive a high-

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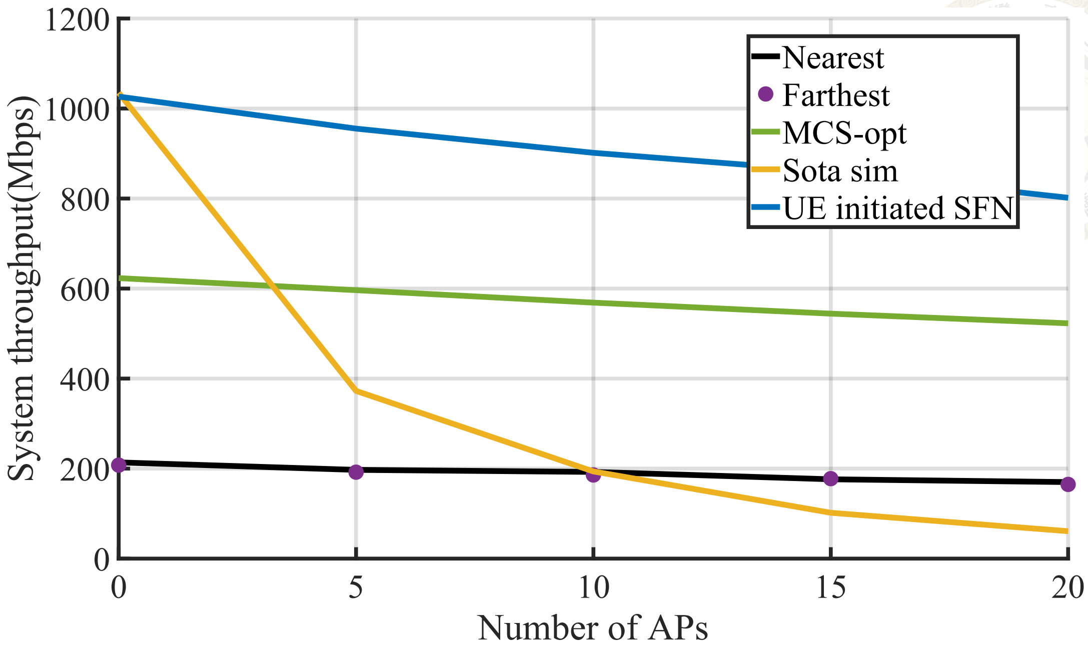

Figure 8.15: The results of the five methods in the partially-listened scenario closely resemble those in the fully-listened scenario.

quality signal, leading to a consistent system throughput. As a result, the overall throughput remains stable and similar across different scenarios since most UEs can take advantage of the improved signal strength.

Here, we can draw a brief conclusion: the five methods demonstrate highly similar performance in both fully-listened and partially-listened scenarios, indicating that the fully-listened assumption remains valid in the NR-U MBS context under discussion.

8.4 Conclusion

In this paper, we strive to leverage UE-initiated NR-U and MBS to enhance the throughput of NR systems. With network congestion increasing due to streaming media, improving system throughput has become imperative. 3GPP introduced NR-U technology to boost NR system throughput by utilizing the unlicensed band and further introduced UE-initiated NR-U in [2], a mechanism that grants greater channel access to networks with more UEs. Additionally, 3GPP introduced MBS in [26] to manage the high volume of video traffic in modern wireless networks. We are the first to combine these two mechanisms, resulting in a substantial improvement in system throughput.

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Moreover, we have not just simply combined them; we propose the MCS-opt method and the UE-initiated SFN method. Both methods show significant improvement over baselines, including the state-of-the-art. This improvement is demonstrated through simulation and analysis. MCS-opt uses a low-complexity exhaustive algorithm to identify the optimal solution among various MBS MCS options. UE-initiated NR-U SFN strengthens each UE's SINR through SFN, increasing throughput and taking advantage of the high access probability of UE-initiated NR-U.

Under the fully-listened assumption, simulations, and mathematical analyses reveal that our proposed methods vastly outperform the baselines. We also discuss the impact of different frequencies and cell radius, and our proposed methods remain exceptional under these variations, sometimes even approaching theoretical limit values. To further validate our methods, we conducted simulations and analyses under the partially-listened scenario, which produced results closely aligned with those under the fully-listened assumption. This confirms two points: first, the fully-listened assumption is highly realistic in the context of UE-initiated NR-U combined with MBS, and second, our methods are indeed applicable in real-world scenarios.

In summary, we developed the novel concept of combining UE-initiated NR-U and MBS as a means of significantly enhancing throughput—a strategy that, to our knowledge, has not been previously proposed. Beyond simple combination, we propose two highly effective designs(UE-initiated SFN, MCS-opt) for this integration. Both designs are operationally sound and deliver remarkable performance improvements. MCS-opt, in particular, achieves near-perfect compatibility with current protocols. These designs offer a promising solution to current bandwidth scarcity issues. Additionally, we evaluate these methods across a variety of scenarios, bridging the designs closer to real-world applications. We even conduct a comparison between partially-listened and fully-listened conditions—a comparison that, as far as we know, is unprecedented in UE-initiated NR-U research. This comparative foundation will serve as a valuable reference for future researchers in this domain.

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doi: 10.6342/NTU202404732

Bibliography

[1] Cisco, "Cisco annual internet report (2018–2023) white paper," https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html, 2024/6/17.

[2] 3GPP, "Physical layer procedures for shared spectrum channel access," 3rd Generation Partnership Project (3GPP), Technical Specification (TS) 37.213, 03 2024, version 18.2.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3435

[3] E. Pei, D. Meng, L. Li, and P. Zhang, "Performance analysis of listen before talk based coexistence scheme over the unlicensed spectrum in the scenario with multiple lte small bases," *IEEE Access*, vol. 5, pp. 10 364–10 368, 2017.

[4] M. Mehrnoush, V. Sathya, S. Roy, and M. Ghosh, "Analytical modeling of wi-fi and lte-laa coexistence: Throughput and impact of energy detection threshold," *IEEE/ACM Transactions on Networking*, vol. 26, no. 4, pp. 1990–2003, 2018.

[5] M. Mehrnoush, S. Roy, V. Sathya, and M. Ghosh, "On the fairness of wi-fi and lte-laa coexistence," *IEEE Transactions on Cognitive Communications and Networking*, vol. 4, no. 4, pp. 735–748, 2018.

[6] N. Bitar, M. O. Al Kalaa, S. J. Seidman, and H. H. Refai, "On the coexistence of lte-laa in the unlicensed band: Modeling and performance analysis," *IEEE Access*, vol. 6, pp. 52 668–52 681, 2018.

doi: 10.6342/NTU202404732

[7] G. Bianchi, "Performance analysis of the ieee 802.11 distributed coordination function," *IEEE Journal on selected areas in communications*, vol. 18, no. 3, pp. 535–547, 2000.

[8] G. Naik, J.-M. Park, J. Ashdown, and W. Lehr, "Next generation wi-fi and 5g nr-u in the 6 ghz bands: Opportunities and challenges," *IEEE Access*, vol. 8, pp. 153 027–153 056, 2020.

[9] M. Hirzallah, M. Krunz, B. Kecicioglu, and B. Hamzeh, "5g new radio unlicensed: Challenges and evaluation," *IEEE Transactions on Cognitive Communications and Networking*, vol. 7, no. 3, pp. 689–701, 2020.

[10] H. Bao, Y. Huo, X. Dong, and C. Huang, "Joint time and power allocation for 5g nr unlicensed systems," *IEEE Transactions on Wireless Communications*, vol. 20, no. 9, pp. 6195–6209, 2021.

[11] S.-Y. Lien and H.-L. Tsai, "3gpp v2x on unlicensed spectrum: performance analysis and optimum channel access strategies," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 9, pp. 9230–9243, 2021.

[12] Q. Chen, X. Xu, and H. Jiang, "Online green communication scheduling for sliced unlicensed heterogeneous networks," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 10, pp. 10 657–10 670, 2021.

[13] A. Daraseliya, M. Korshykov, E. Sopin, D. Moltchanov, S. Andreev, and K. Samouylov, "Coexistence analysis of 5g nr unlicensed and wigig in millimeter-wave spectrum," *IEEE Transactions on Vehicular Technology*, vol. 70, no. 11, pp. 11 721–11 735, 2021.

[14] V. Loginov, A. Troegubov, A. Lyakhov, and E. Khorov, "Enhanced collision resolution methods with mini-slot support for 5g nr-u," *IEEE Access*, vol. 9, pp. 146 137–146 152, 2021.

 doi: 10.6342/NTU202404732

[15] V. Loginov, E. Khorov, A. Lyakhov, and I. F. Akyildiz, "Cr-lbt: Listen-before-talk with collision resolution for 5g nr-u networks," *IEEE Transactions on Mobile Computing*, vol. 21, no. 9, pp. 3138–3149, 2021.

[16] M. Zając and S. Szott, "Resolving 5g nr-u contention for gap-based channel access in shared sub-7 ghz bands," *IEEE Access*, vol. 10, pp. 4031–4047, 2022.

[17] Q. Ren, J. Zheng, B. Wang, and Y. Zhang, "Performance modeling of an nr-u and wifi coexistence system with nr-u type b multi-channel access procedure," *IEEE Internet of Things Journal*, 2022.

[18] L. B. Jiang and S. C. Liew, "Improving throughput and fairness by reducing exposed and hidden nodes in 802.11 networks," *IEEE Transactions on Mobile Computing*, vol. 7, no. 1, pp. 34–49, 2007.

[19] J. Lee and I. Yeom, "Avoiding collision with hidden nodes in ieee 802.11 wireless networks," *IEEE Communications letters*, vol. 13, no. 10, pp. 743–745, 2009.

[20] C.-Y. Huang, H.-Y. Chen, C.-H. Huang, S.-T. Sheu, T.-W. Chiang, T.-L. Cheng, and C.-C. Chang, "Listen before receive (lbr) assisted network access in laa and wifi heterogeneous networks," *IEEE Access*, vol. 9, pp. 43 845–43 861, 2021.

[21] F.-Y. Hung and I. Marsic, "Performance analysis of the ieee 802.11 dcf in the presence of the hidden stations," *Computer Networks*, vol. 54, no. 15, pp. 2674–2687, 2010.

[22] Q. Ren, B. Wang, J. Zheng, and Y. Zhang, "Performance modeling of an nr-u and wifi coexistence system using the nr-u category-4 lbt procedure and wifi dcf mechanism in the presence of hidden nodes," *IEEE Transactions on Vehicular Technology*, vol. 72, no. 11, pp. 14 801–14 814, 2023.

[23] A. Prasad, P. Lunden, Z. Li, and M. A. Uusitalo, "Enhancements for enabling point-to-multipoint communication using unlicensed spectrum," in *2018 IEEE International Symposium on Broadband Multimedia Systems and Broadcasting (BMSB)*. IEEE, 2018, pp. 1–5.

doi: 10.6342/NTU202404732

[24] 3GPP, "Architectural enhancements for 5g multicast-broadcast services," 3rd Generation Partnership Project (3GPP), Technical specification (TS) 23.247, 03 2024, version 18.5.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3854

[25] H.-H. Liu and H.-Y. Wei, "Towards nr mbms: A flexible partitioning method for sfn areas," *IEEE Transactions on Broadcasting*, vol. 66, no. 2, pp. 416–427, 2020.

[26] 3GPP, "Study on channel model for frequencies from 0.5 to 100 ghz," 3rd Generation Partnership Project (3GPP), Technical report (TR) 38.901, 04 2024, version 18.0.0. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3173

doi: 10.6342/NTU202404732