RESOURCE ALLOCATION AND ADAPTIVE CHANNEL SCHEDULING FOR 5G NEW RADIO

Dissertation submitted in partial fulfillment of the requirement for the degree of

MASTER OF TECHNOLOGY

IN

ELECTRONICS AND COMMUNICATION ENGINEERING

By

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DECLARATION BY SCHOLAR

I hereby declare that the work reported in the M.Tech dissertation entitled **“Resource Allocation And Adaptive Channel Scheduling For 5G New Radio”** submitted at **Jaypee University of Information Technology, Waknaghat, India** is an authentic record of my work carried out under the supervision of **Dr. Shweta Pandit** and **Dr. Alok Kumar.** I have not submitted this work elsewhere for any other degree or diploma.

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This is to certify that the work in the dissertation entitled **"Resource Allocation And Adaptive Channel Scheduling For 5G New Radio"** submitted by **Shubham** is a record of an original research work carried out by him under our supervision and guidance in partial fulfillment of the requirements for the award of the degree of **Master of Technology in Electronics & Communication Engineering** in the Department of Electronics & Communication Engineering at **Jaypee University of Information Technology, Waknaghat, India**. This dissertation has not been submitted, in whole or in part, for any other degree or diploma.

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LIST OF ACRONYMS AND ABBREVIATIONS

1G	First generation of mobile networks
2G	Second generation of mobile networks
3G	Third generation of mobile networks
4G	Fourth generation of mobile networks
5G	Fifth generation of mobile networks
3GPP	Third generation partnership project
AR	Augmented reality
AMPS	Analog mobile phone system
ARFCN	Absolute radio frequency channel number
AMF	Authentication management function
AF	Application function
ACK	Acknowledgement
B-CQI	Best channel quality indicator
B5G	Beyond fifth generation of mobile networks
BWP	Bandwidth part
CDMA	Code division multiple access
CRC	Cyclic redundancy check
CP	Cyclic prefix
CRB	Common resource block
CSI-RS	Channel state information reference signal
CRS	Cell specific reference signal
CORESET	Control resource set
CCE	Control channel element
CQI	Channel quality indicator
DL	Downlink
DMRS	Demodulation reference signal
DL-SCH	Downlink shared channel
EDGE	Enhanced data rates for GSM evolution
eMBB	Enhanced mobile broadband
EPC	Evolved packet core
FR1	Frequency range 1

FR2	Frequency range 2
FDMA	Frequency division multiple access
GSM	Global system for mobile communications
GPRS	General packet radio service
gNB	Next generation base station
HARQ	Hybrid automatic repeat request
HST	High speed train
IoT	Internet of things
IP	Internet protocol
IIoT	Industrial internet of things
LTE	Long term evolution
MAC	Medium access and control
ML	Machine learning
mm Wave	Milli meter wave
mMTC	Massive machine type communication
MIMO	Multiple input multiple output
NR	New radio
NSA	Non stand alone
NEF	Network exposure function
NSSF	Network slice selection function
NACK	No acknowledgement
NOMA	Non orthogonal multiple access
OFDMA	Orthogonal frequency division multiple access
PSCH	Physical broadcast channel
PSTN	Public switching telephony network
PCF	Policy control function
PRB	Physical resource block
P cell	Primary cell
PDSCH	Physical downlink shared channel
PDCP	Packet data convergence protocol
PUSCH	Physical uplink shared channel
PUCCH	Physical uplink control channel
PHY	Physical layer

PF	Proportional fair
QoS	Quality of service
QAM	Quadrature amplitude modulation
RAT	Radio access technology
RLC	Radio link control
RE	Resource element
RB	Resource block
RACH	Random access channel
RRC	Radio resource control
RNTI	Radio network temporary identifier
RAN	Radio access network
REG	Resource element group
RR	Round robin
SCS	Subcarrier spacing
SFN	Serial frame number
SA	Standalone
SMF	Session management function
SS	Synchronized signal
S cell	Secondary cell
SUL	Supplementary uplink
TDD	Time division duplex
TDMA	Time division multiple access
URLLC	Ultra reliable low latency communication
UPF	User plane function
UE	User equipment
UDM	Unified data management
UL	Uplink
UL SCH	Uplink shared channel
UMTS	Universal mobile telecommunications system.
VR	Virtual reality
V2V	Vehicle to vehicle
WiMAX	Worldwide interoperability for microwave access

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ABSTRACT

The arrival of 5G technology represents a major shift in connectivity, bringing new possibilities across various applications, including enhanced mobile broadband (eMBB), ultra-reliable low latency communications (URLLC), and massive machine type communication (mMTC). The evolution of mobile networks from the first generation (1G) to the fifth generation (5G) has revolutionized how we communicate. 1G introduced us to analog voice communication, while 2G brought digital voice and text messaging. Smartphones and mobile applications were made possible with the introduction of 3G, which allowed for mobile internet access. 4G further increased data rates, enabling better mobile browsing and streaming of high-definition videos. Now, 5G technology takes connectivity to an entirely new level, offering unprecedented speed, capacity, and low latency. This new generation is designed to support a vast array of applications, from high-speed internet access and real-time gaming to advanced IoT solutions and autonomous vehicles. With 5G, users can experience seamless connectivity, whether they are in densely populated urban areas or on the move in remote locations.

A critical aspect of 5G networks is the efficient allocation of resources and scheduling to ensure optimal performance. Scheduling in 5G involves determining how network resources such as bandwidth and time slots are distributed among users and applications. Effective scheduling is crucial for meeting the diverse requirements of different 5G applications, ranging from high-throughput needs of eMBB to the low-latency demands of URLLC. In our study, we introduce a novel 5G new radio scheduler specifically designed to meet the demands of eMBB applications, ensuring consistent connectivity for cell edge users. Our study provides a range of promising advancements in 5G scheduling strategies, demonstrating improvements in network performance and spectral efficiency. By focusing on key metrics such as throughput, goodput, and spectral efficiency, as well as fairness in resource sharing, our research shows that the proposed scheduler can significantly enhance the overall performance of 5G networks. This work is a significant step towards realizing the full potential of 5G technology in delivering robust and reliable connectivity solutions to the evolving needs of today's communication landscape.

CHAPTER 1

INTRODUCTION

The arrival of 5G networks offers extremely low latency, wide device connectivity, and enhanced user experiences, which is the result of the rapid evolution of mobile communication technology. These networks have the potential to drastically alter how we connect to and interact with the digital world. 5G networks are built to withstand the demands of a world society that is becoming more interconnected. The effective use of complex MAC scheduling algorithms and radio resource management are essential to the success of 5G NR technology. These elements are crucial in order to guarantee that 5G networks are capable of supporting a large number of applications, including driverless vehicles, smart cities, AR, VR, and the internet of things.

The development of a novel scheduling method for adaptive MAC scheduling and resource allocation in 5G NR networks is the focus of this study. The study aims to maximize network performance, enhance resource usage, and provide equitable and consistent resource allocation to user equipment's with varying quality of service requirements. The following sections outline the specific focus areas and objectives of this research, providing a roadmap for the subsequent chapters.

1.1 Introduction to 5G NR

5G NR serves as the worldwide standard for a unified and enhanced 5G wireless air interface. It marks a substantial leap forward from earlier mobile network generations, laying the groundwork for numerous new services and applications. To grasp the context and capabilities of 5G NR, it is essential to explore several key subsections.

1.1.1 Evolution from previous generations

The progression of wireless communication from 1G to 5G, showcases an extraordinary journey characterized by notable technological innovations [1]. 5G offers unparalleled data speeds, extremely low latency, and extensive device connectivity. This fifth generation of wireless technology is poised to revolutionize industries with applications like autonomous vehicles [2], augmented reality [3], and the IoT, pushing the boundaries of what's possible in wireless communication and connectivity [4]. Difference between wireless technologies is given in table 1.1.

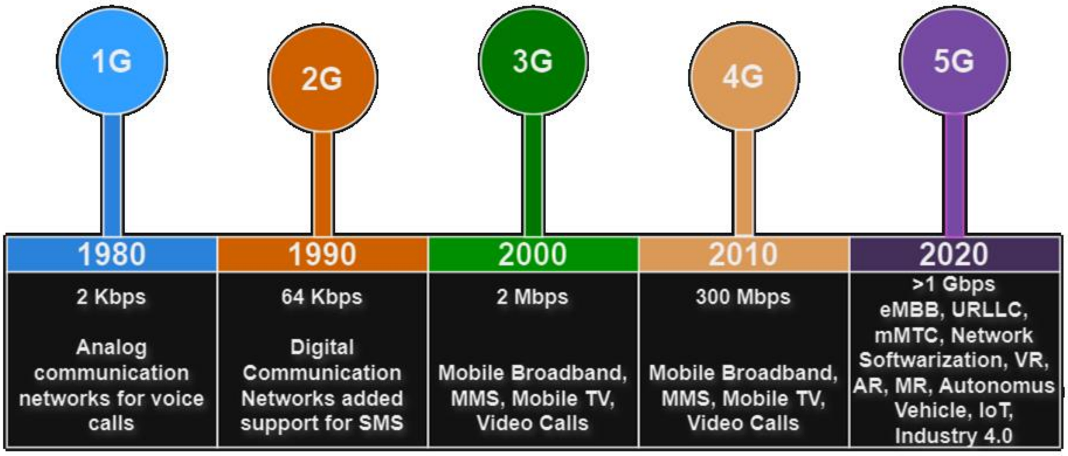


Figure 1.1: Evolution of cellular technologies over the years

Table 1.1: Difference between different cellular generations over the years [5]

Features	1G	2G	3G	4G	5G
Data Rate	Upto 2Kbps	14.4 to 64Kbps	Upto 2Mbps	200Mbps to1Gbps	10 Gbps to100 Gbps
Standards	AMPS	GSM, GPRS, EDGE	UMTS, CDMA 2000	LTE , WiMAX	5G NR
Technology	Analog cellular technology	Digital cellular technology	CDMA, IP	Unified IP, Broadband Integration	Unified IP, Enhanced Broadband
Service	Voice calls	Voice, SMS, Data	High quality voice/ data, multimedia	High- speed data, wearable devices.	AI-enhanced Wearable's, Ultra-fast data
Multi-plexing	FDMA	TDMA/ CDMA	CDMA	OFDMA	OFDMA, NOMA
Switching	Circuit	Circuit/ Packet	Packet	Packet	Hybrid Switching
Core Network	PSTN	PSTN	Packet-switched Network	All-IP Network	Next-gen IP Network

1.1.2 Key features of 5G

5G is based on an international standard, guaranteeing seamless interoperability and compatibility across various regions and network providers. This regulation facilitates the widespread adoption of 5G technology on a global scale. With telecommunications companies, governments and industries investing heavily in the infrastructure necessary to unlock the full potential of this transformative technology. As 5G continues to roll out, it is anticipated to significantly influence multiple sectors such as healthcare, transportation, education, and entertainment. Key enabling services in 5G [6], are shown in figure 1.2.

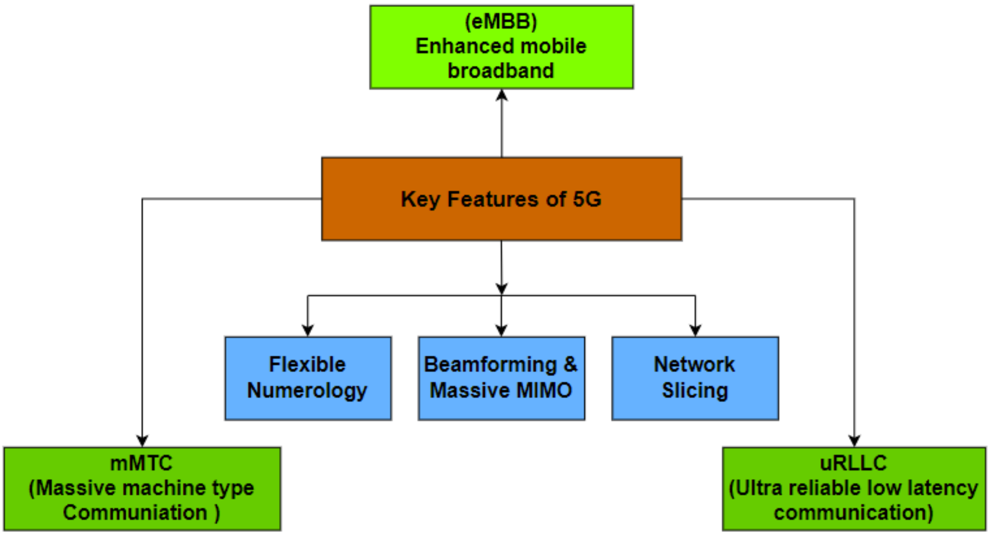


Figure 1.2: Key features of 5G

(1) Enhanced mobile broadband

A key objective of 5G is to deliver data speeds significantly higher than those of previous generations. 5G networks strive to achieve peak data rates of up to 20 gigabits per second. This substantial increase in speed facilitates faster downloads and uploads, thereby improving overall network performance for users.

(2) Ultra reliable low latency communication

One of the key objective of 5G is to significantly reduce latency, the delay between initiating a data transfer and the actual data transfer. With ultra-low latency often as low as one millisecond, 5G is essential for applications demanding real-time responsiveness, such as AR, VR, self- driving vehicles, and online gaming [7].

(3) Massive machine type communication

5G is designed to accommodate an immense volume of connected devices concurrently with the capability to support approximately 1 million devices per square kilometre. This aspect is particularly important as the number of IoT devices continues to grow. With increased capacity and improved efficiency, 5G networks can handle diverse use cases, from smart homes and cities to industrial IoT [8] applications, providing connectivity for a vast array of devices.

(4) Flexible numerology

Numerology in the context of 5G NR refers to the set of parameters that define the structure of the physical layer, specifically including cyclic prefix length and subcarrier spacing with symbol duration. In contrast to LTE [9], which employs a single SCS of 15 kHz, 5G NR facilitates the use of various SCS. Each numerology is identified by a parameter (often denoted as μ). For instance, the numerology with 15 kHz SCS when μ = 0, as shown in table 1.2. Other subcarrier spacing's also denoted as **(**Δf**)** are obtained by scaling this base value by powers of 2, resulting in a flexible and adaptable system that can efficiently cater to a variety of usage scenarios and deployment situations. This adaptability in numerology allows 5G to optimize performance for different types of traffic and network conditions, which is a significant improvement over the fixed numerology of LTE.

Table 1. 2: Numerology Table

Numerology (μ)	$\Delta f = 2^{\mu} .15$[kHz]	Cyclic Prefix
0	15	Normal
1	30	Normal
2	60	Normal / Extended
3	120	Normal
4	240	Normal
5	480	Normal

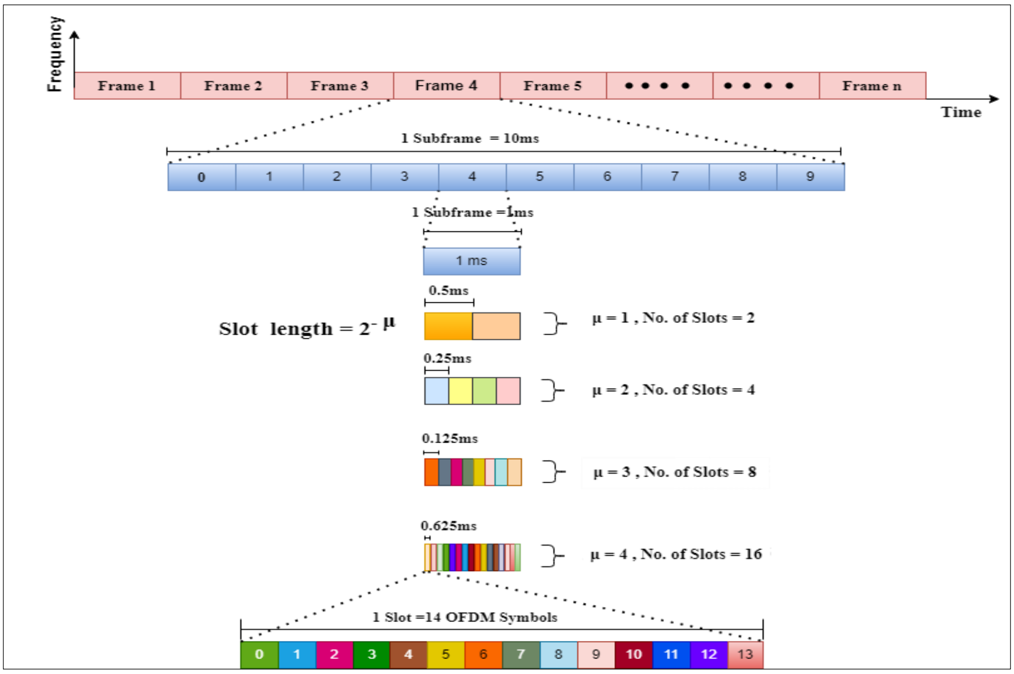


Figure 1.3: Frame structure

NR transmissions are described into frames spanning 10 milliseconds, each subsequently partitioned into 10 equidistant subframes, each with a duration of 1 millisecond. Moreover, these subframes are further subdivided into slots, each containing 14 OFDM symbols . The numerology determines how long a slot lasts in milliseconds, shown in figure 1.3. In 5G NR, frames are identified by the serial frame number (SFN), with the SFN period set to 1024 frames. Each frame lasts for 10 milliseconds, resulting in an SFN period of 10,240 milliseconds or 10.24 seconds. This repetition every 10.24 seconds ensures synchronization and coherence in the network, facilitating efficient communication and management of transmission cycles and scheduling mechanisms [10].

(5) Beamforming and massive MIMO

As the name suggests, beamforming in 5G [11], involves creating a focused beam of RF energy, similar to a flashlight beam. It acts as a traffic signalling system for 5G base stations, identifying the most efficient route to deliver data to specific users while reducing interference for others. In the 5G context, beamforming is used for spatial filtering and interference rejection, enhancing the radio environment by concentrating interference to small areas and minimizing its impact on receivers. This technique significantly boosts 5G network performance by providing high spectral efficiency, increasing capacity, improving link performance, and extending coverage areas. A key component of 5G beamforming is the use of massive MIMO antennas as shown in figure1.4. The new radio's design takes into account a diversity of placement scenarios, from huge cells with sub-1 GHz carrier frequencies to mm-wave deployments with substantial spectrum allotments. It is neither feasible nor efficient to use the same numerology in each of these cases [12].

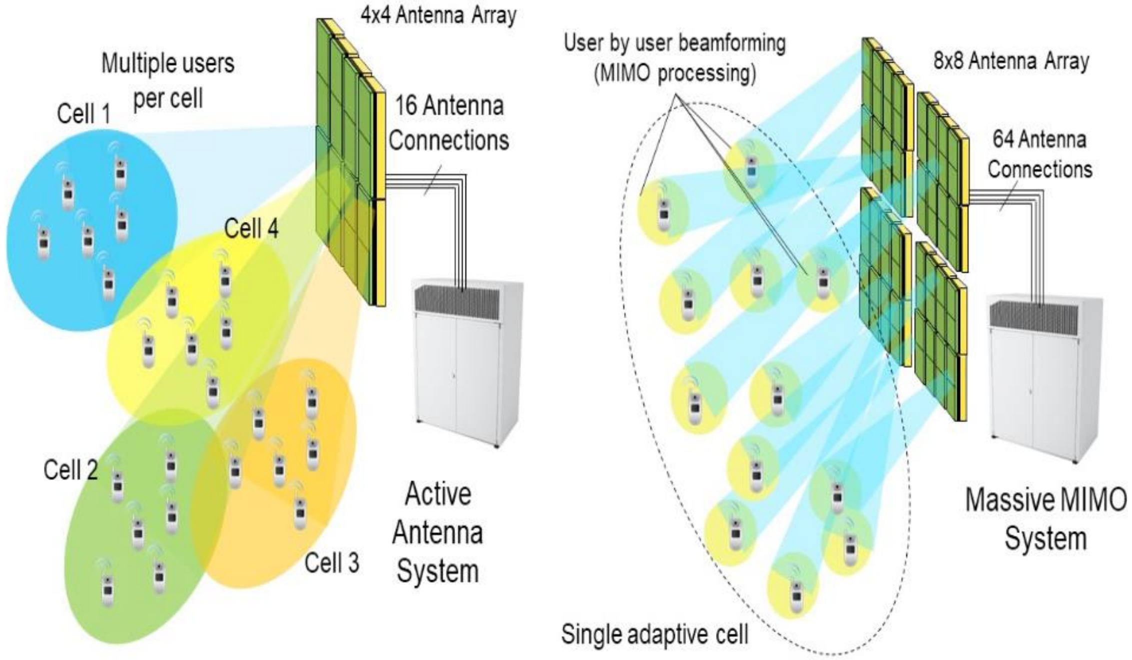


Figure 1.4: Beamforming and massive MIMO

Since bigger cell sizes are frequently used in lower range of carrier frequencies, which are typically below 1 GHz. A cyclic prefix can accommodate the expected delay spread, which typically ranges a few microseconds. Therefore, a subcarrier spacing similar to LTE or slightly higher, around 15 to 30 kHz, is required. Conversely, phase noise and other issues become increasingly noticeable when carrier frequencies approach the mmWave region, requiring even greater subcarrier spacing's. Additionally, cell sizes tend to be smaller at higher frequencies due to more demanding propagation conditions, although beamforming techniques are extensively used to mitigate delay spread. Therefore, shorter cyclic prefixes and larger subcarrier spacing's are more suited for these kinds of deployments.

Massive MIMO employs a more number of antennas to simultaneously serve multiple users, enhancing the effectiveness of beamforming. This allows 5G networks to handle more connections and deliver higher data rates, making massive MIMO a critical technology for realizing the benefits of beamforming in 5G. The adoption of massive MIMO and beamforming in 5G networks also facilitates better utilization of the available spectrum. By dynamically adjusting the direction and shape of the beams, 5G systems can more effectively manage spectral resources, reducing waste and improving overall network efficiency. This capability is especially important in dense urban environments where spectrum is a limited and valuable resource.

Moreover, the implementation of beamforming and massive MIMO in 5G supports advanced applications such as AR, VR, and self- driving vehicle. High data rates and low latency are needed for these applications, and these can be effectively provided by the focused and high-capacity communication channels created through beamforming and massive MIMO. As 5G continues to evolve, these technological advancements will be essential to bringing about a new era of creativity and connectivity.

(6) Network slicing

Network slicing in 5G involves creating customized virtual networks with distinct functionalities. Every slice comprises the service-based architecture's essential functionality combined to meet unique requirements. For instance, a single slice might offer LTE-like mobility and be used for mobile broadband applications while another slice may target a particular non-mobile, latency sensitive industrial automation application [13]. Even though their radio networks and physical cores are identical, these slices appear as independent networks from the end-user application viewpoint. This idea is similar to setting up several virtual computers on one physical machine. Furthermore, edge computing can incorporate within a network slice, so that end-user application run close to the core network edge to provide minimal latency.

1.1.3 Spectrum utilization

5G wireless technology operates across a broad variety of frequencies, including mmWave bands and sub-6 GHz bands. 5G can provide a combination of fast data rates, reduced latency, and expanded capacity because it uses new frequency bands. The primary frequency bands linked to 5G [14] are listed below:

- FR1 (Bands at sub-6 GHz): Low-Band (Sub-1 GHz): This refers to frequency ranges 600 MHz and 700 MHz and other lower than 1 GHz. Although low-band spectrum may have lower data speeds than higher frequencies, it allows better penetration and coverage across obstructions.
- Mid-Band (1 GHz - 6 GHz): This covers frequency ranges from 2.5 GHz and 3.5 GHz bands, which are in the range of 1 GHz and 6 GHz. As compared to low-band, mid-band offers greater data rates while striking a fair balance between capacity and coverage.
- FR2 (mmWave bands)*:* Frequency ranges over 24 GHz, including as 28 GHz, 39 GHz, and 60 GHz, are included in the high-band (24 GHz - 100 GHz) category. mmWave bands have a very high data rate and capacity but have limited coverage and are susceptible to signal blockage by obstacles. The allocation of specific frequency bands for 5G can vary by country and region. Regulatory authorities around the world manage and allocate spectrum for 5G deployment.

It's important to note that different frequency bands serve different purposes within the 5G network, and network operators often deploy a combination of these bands to optimize coverage and capacity. The 5G infrastructure is designed to use dynamic spectrum sharing, allowing for efficient use of available frequencies based on demand and network conditions.

1.2 Network architecture

Along with the 3GPP NR access technology development, The RAN is handles all radio-related aspects of the network, which includes scheduling, radio resource management, coding, retransmission protocols, and various multi-antenna methods. The 5G core network handles tasks required to provide a full network which is not limited to radio access. This covers things like end-to-end connection setup, charging functionality, and authentication [15]. It is advantageous to handle these tasks independently rather than combining them into the RAN. It makes it possible for the same core network to support many radio-access technologies. However, the NR radio-access network can also be linked to the EPC, a traditional LTE core network. This is actually the case while utilizing NR in non-standalone mode, since LTE and EPC handle paging and connection establishment.

The service-based architecture, network slicing capability, and control-plane/user-plane separation of the 5G core network set it apart from the EPC (see figure 1.5). The 5G core is built on a service-oriented architecture. This suggests that rather than concentrating on nodes, the requirement is on the features and services offered by the core network. This makes sense considering that the essential tasks of today's core networks are often powered by generic computer hardware and are frequently heavily virtualized.

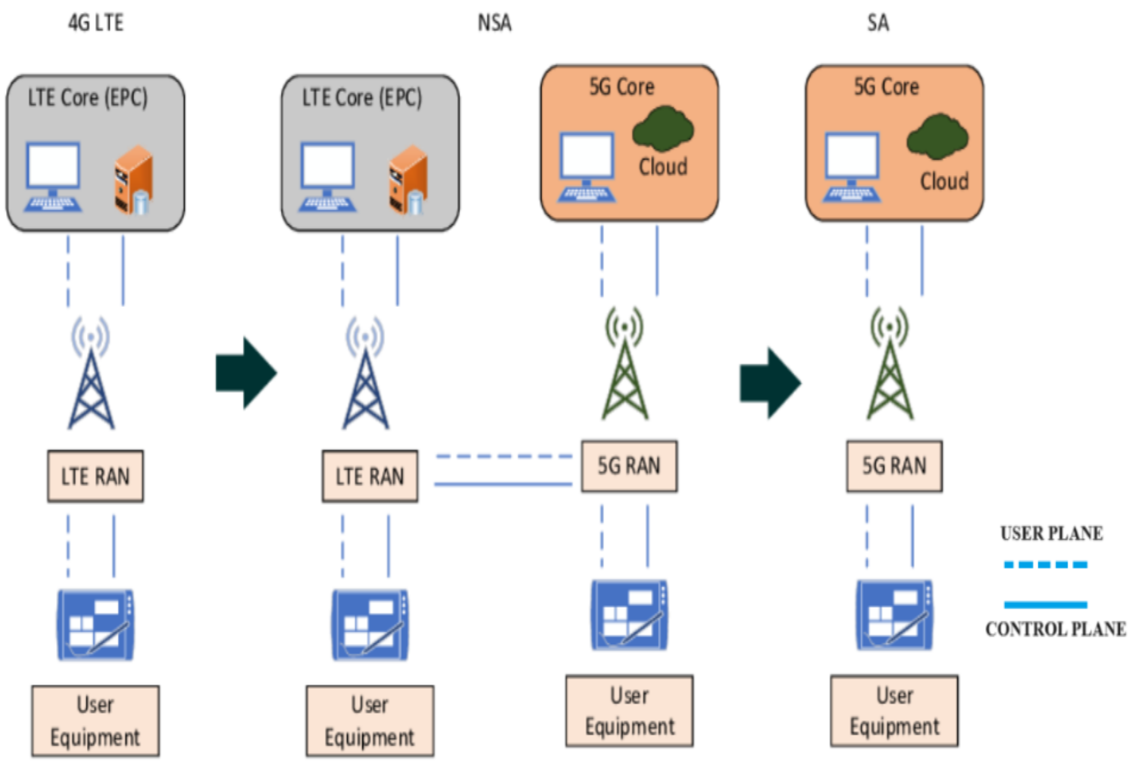


Figure 1.5: NSA vs. SA architecture

The 5G core is illustrated in figure 1.6, which uses a service-based diagram that emphasizes features and services. Furthermore, another reference-point description is available that highlights the point-to-point interaction between functions [16]. Between the RAN and other networks, such the internet, the UPF serves as a gateway.

Traffic metering, packet filtering, packet forwarding and routing, packet inspection, and QoS management are among its responsibilities. It also serves as an anchor point for (inter-RAT) mobility when necessary. There are multiple components to the control-plane functions. The IP address assignment of UE, control over policy enforcement, and general session management tasks are all handled by the SMF.

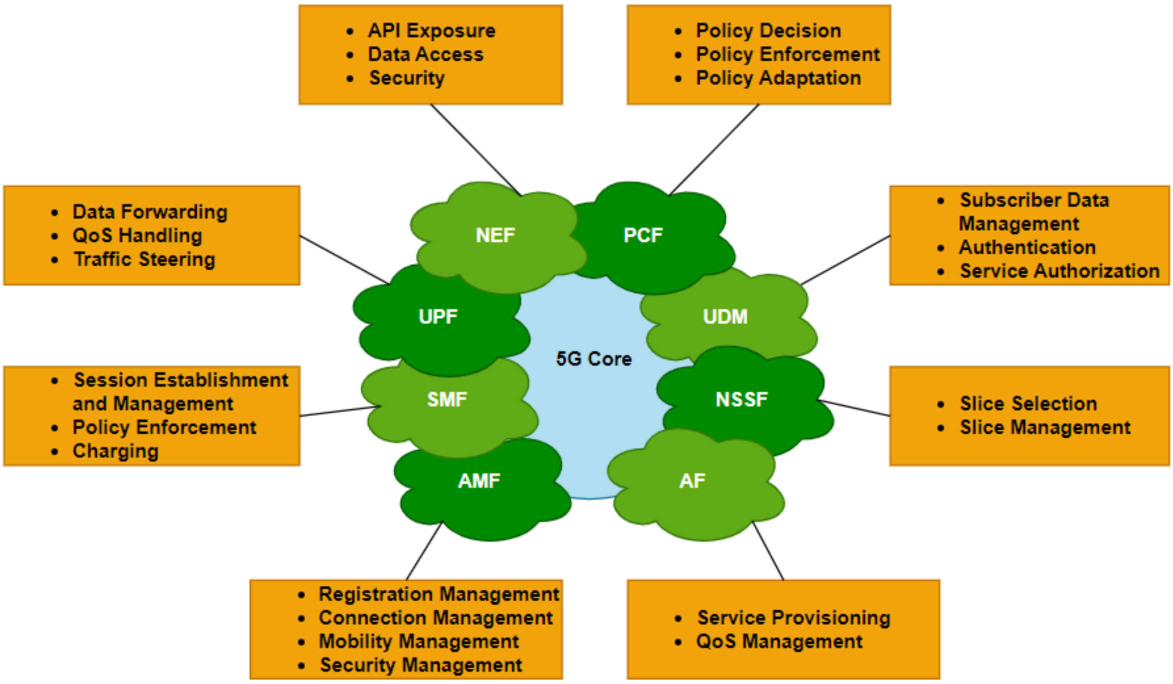


Figure 1.6: 5G core network

(1) Access and mobility management function (AMF): The AMF handles connection and mobility management tasks. Its key functions include:

- Registration Management: Managing UE registration and deregistration.
- Connection Management: Establishing and releasing signalling connections.
- Mobility Management: Managing handovers and mobility events as UEs move between cells or networks.
- Security Management: Handling authentication and maintaining security contexts for UEs.

(2) Session management function (SMF): SMF oversees session management, including the establishment, modification, and termination of sessions. Its responsibilities include:

- Session Establishment and Management: Allocating IP addresses and managing session parameters.
- Policy Enforcement: Applying policies related to QoS and traffic routing.
- Charging: Collecting data for billing and charging purposes.

(3) User plane function (UPF): UPF is a key element that handles user data traffic, performing functions such as:

- Data Forwarding: It involves routing of user data packets from the external data networks to the RAN.
- QoS Handling: Ensures that data packets meet the QoS requirements specified by the SMF.
- Traffic Steering: Directing traffic based on policies, enabling network slicing and edge computing.

(4) Network exposure function (NEF): The NEF provides secure and controlled exposure of network capabilities to third-party applications and services. It facilitates:

- API Exposure: Allowing external applications to interact with the network via standardized APIs.
- Data Access: Enabling applications to access network data for analytics and service optimization.
- Security: Ensuring that exposed network capabilities are accessed securely and comply with privacy regulations.

(5) Policy control function (PCF): The PCF is handles policy management, including definition and enforcement of network policies. Its functions include:

- Policy Decision: Determining policies related to QoS, charging, and access control.
- Policy Enforcement: Communicating with other network functions to ensure policies are applied consistently.
- Policy Adaptation: Adapting policies based on real-time network conditions and service requirements.

(6) Unified data management (UDM): The UDM manages subscription data and validation credentials. Its main tasks include:

- Subscriber Data Management: Storing and retrieving user profiles and subscription information.
- Authentication: Supporting user authentication processes to verify user identities.
- Service Authorization: Authorizing users to access specific network services based on their subscriptions.

(7) Network slice selection function (NSSF): The NSSF allows the network to be partitioned into multiple virtual slices tailored for specific services or customers. Its functions include:

- Slice Selection: Identifying the appropriate network slice for a particular service or user.

- Slice Management: Coordinating resources and policies across different network slices to ensure optimal performance.

(8) Application function (AF): The AF communicates with the 5G Core to deliver application-level services and modify network behaviour. Its responsibilities include:

- Service Provisioning: Enabling third-party services to request network resources and policies.
- QoS Management: Collaborating with the PCF and other functions to ensure application QoS requirements are met.

1.3 Scheduling and resource allocation

Scheduling and resource allocation are fundamental processes in 5G NR networks, ensuring that network resources are utilized efficiently and effectively to fulfil the varied needs of different services and applications. The process of scheduling involves figuring out the timing and order in which resources are assigned to users and applications, focusing on optimizing throughput, latency, fairness, and overall network performance. It involves making real-time decisions about how resources such as time slots and frequency bands are allocated to users based on current network conditions and user demands.

Resource allocation, meanwhile, involves the broader task of distributing available network resources, including spectrum, power, and antennas, among multiple users and services. This process ensures that each user and application receives the necessary resources to function optimally. Techniques such as FDMA, TDMA, and OFDMA/NOMA [17], are employed to partition and assign resources efficiently.

Effective scheduling and resource allocation are crucial for handling the complex and dynamic nature of 5G networks, which must support an extensive range of services from high-bandwidth eMBB to URLLC applications [18]. These procedures need to scale with the growing number of linked devices, handle interference, and adjust to changing network circumstances. Advanced algorithms that can dynamically respond to real-time network changes are essential for maintaining the performance and reliability of 5G NR networks, particularly at the cell edges where connectivity challenges are more pronounced. Chapter 2 will provide a more detailed look at scheduling and resource allocation in 5G NR networks.

1.4 Problem statement

In the context of eMBB and URLLC networks, ensuring connectivity for cell edge users poses a significant challenge. While eMBB demands high data rates and broad coverage, URLLC requires ultra-reliable and low-latency connections, often at the cell periphery where signal strength is weaker. Traditional scheduling algorithms may struggle to meet the stringent connectivity requirements of cell edge users in such diverse environments. Therefore, the development of scheduling algorithms that can guarantee connectivity for cell edge users, particularly in the intersection of eMBB and URLLC services, is important. Ensuring connectivity for cell edge users in eMBB and URLLC networks presents several challenges:

(1) Coverage and signal strength
Cell edge users often experience weaker signal strength and may struggle to maintain connectivity, especially in areas with high interference or obstacles. Traditional scheduling algorithms may prioritize users with stronger signals, leading to reduced connectivity for those at the cell periphery.

(2) Diverse service requirements
eMBB and URLLC services have contrasting requirements, with eMBB demanding high data rates and broad coverage, while URLLC requires ultra-reliable and low-latency connections. Balancing these diverse service requirements to ensure connectivity for cell edge users poses a complex optimization problem.

(3) Interference and resource allocation
In dense network deployments, interference between neighbouring cells can degrade the connectivity experience for cell edge users. Effective scheduling algorithms must manage interference and optimize resource allocation to prioritize connectivity for users at the cell periphery without compromising network performance.

(4) Dynamic network conditions
The dynamic nature of wireless networks, with fluctuating user demand, mobility patterns, and environmental factors, further complicates the task of ensuring connectivity for cell edge users. Scheduling algorithms must adapt in real-time to changing network conditions to maintain reliable connectivity for all users.

While existing scheduling algorithms have made significant strides in addressing these challenges, there is still room for improvement. Our aim is to develop a more efficient scheduling algorithm that can guarantee connectivity for cell edge users while optimizing resource utilization and network performance. By leveraging advanced techniques and algorithms, our goal is to enhance the reliability and efficiency of 5G NR networks, particularly in challenging environments where connectivity at the cell edge is critical for delivering high-quality services to users.

1.5 Objectives

- To develop and implement novel adaptive scheduling algorithm for cell edge users in eMBB and URLLC networks and comparison of the proposed algorithm's performance with existing scheduling techniques.
- To investigate the impact of the proposed algorithm on the overall throughput, goodput and spectral efficiency of the 5G NR network, aiming to maximize the utilization of available spectrum resources.
- To provide fair resource allocation using proposed algorithm.

1.6 Organisation

This dissertation is organized into six chapters, starting with Chapter 1, Introduction. The introduction provides a basic understanding of 5G networks, including their features, benefits, and key components, as well as an overview of scheduling and resource allocation challenges.

Chapter 2 offers a detailed overview of scheduling, explaining the fundamental concepts, techniques, and issues related to scheduling and resource allocation in 5G NR networks.

Chapter 3 presents a comprehensive literature survey, reviewing existing research on scheduling algorithms and resource allocation methods. It identifies gaps in current approaches and highlights areas for potential improvement.

Chapter 4 describes the methodology used in developing and implementing the proposed adaptive scheduling algorithms. This includes the design, implementation, and evaluation frameworks utilized in this research.

Chapter 5 discusses the results obtained from extensive simulations and experiments. It compares the performance of the proposed algorithms with existing techniques and analyses their effectiveness in enhancing connectivity and spectral efficiency.

Finally dissertation is concluded in Chapter 6, which provides a summary of the main conclusions, and recommendations for future direction.

CHAPTER 2

OVERVIEW TO SCHEDULING

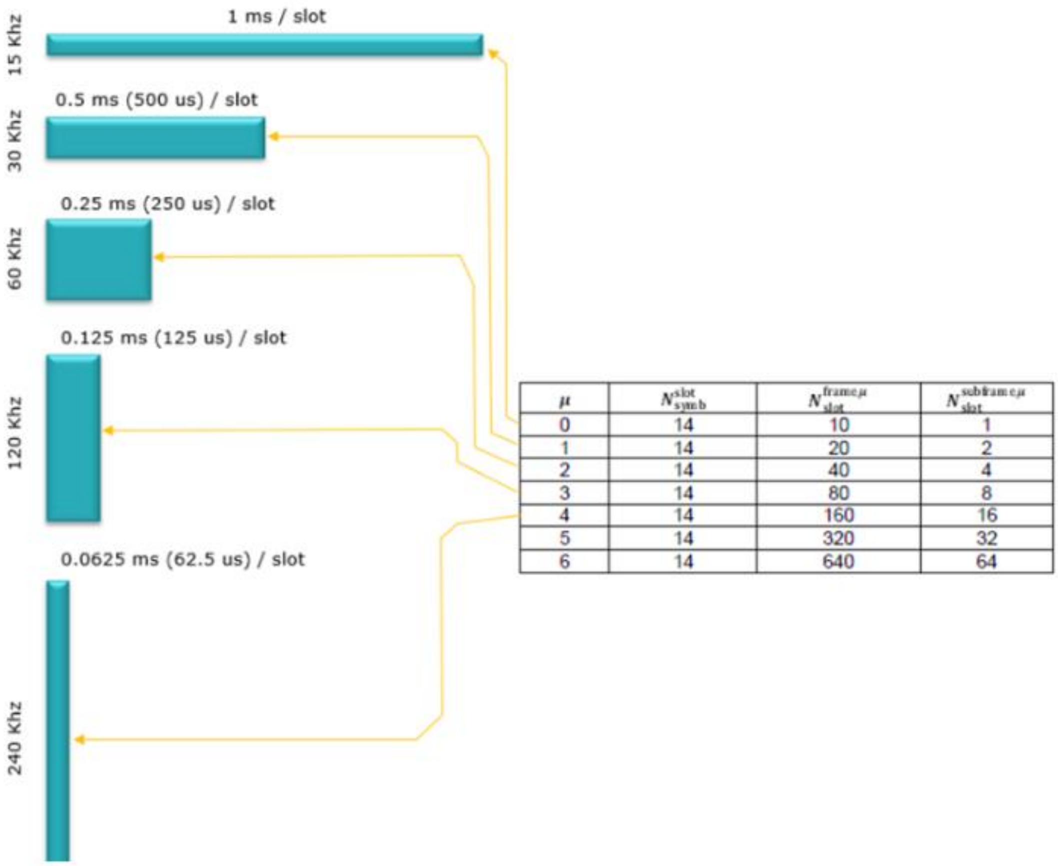
Scheduling in 5G New Radio (NR) networks is a critical function that directly impacts the network's performance, efficiency, and user experience. The primary objective of scheduling is to manage and allocate network resources effectively to meet diverse service requirements such as eMBB, URLLC, and mMTC. In 5G NR, scheduling decisions are made by the base station (gNB) and involve dynamically assigning time-frequency resources to users. These decisions are influenced by various factors, including channel conditions, QoS requirements, and traffic demands. The scheduling process in 5G NR is more complex compared to previous generations due to the introduction of new features like flexible frame structures, multiple numerologies, and beamforming capabilities.

The goal of efficient scheduling is to optimize network throughput while lowering latency and guaranteeing user fairness. Additionally, it is essential to sustaining the network's stability and dependability, particularly in situations with varying service requirements or heavy traffic. The subsequent sections of this chapter will explore the various technical components and mechanisms that lays the foundation of the scheduling process in 5G NR. These include the frame structure, numerology, bandwidth parts, frequency bands, beam management, control resource sets, downlink control information, channel state information framework, and uplink control information. Additionally, the roles of key protocol layers such as MAC, RLC, and PDCP in the scheduling process will be examined.

2.1 Frame structure

As discussed in chapter 1, the frame structure in 5G NR is designed to be highly flexible to accommodate a variety of services. This flexibility is achieved through a hierarchical organization of frames, sub frames, slots, and mini-slots, allowing the network to efficiently allocate resources and optimize performance.

The numerology affects how long a slot lasts, as figure 2.1 illustrates. In general, the slot duration gets shorter as the subcarrier spacing is larger. This pattern is a result of the fundamental properties of OFDM. Despite the changes in numerology, the duration of a radio frame (10ms) and a subframe (1ms) remains unchanged. To accommodate the physical differences among numerologies, the number of slots within a subframe is adjusted accordingly. Slots with a normal CP consistently contain 14 symbols, while those with an extended CP contain 12 symbols [4].



μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16
5	14	320	32
6	14	640	64

Figure 2.1: Frequency domain structure

2.1.1 Resource grid

An organized framework called the resource grid is used to arrange time-frequency resources for data transmission. It contains OFDM symbols in the time domain and subcarriers in the frequency domain. The grid is divided into PRBs shown in figure 2.2 and 2.3, each containing 12 subcarriers and spanning one slot duration [19].

The Resource element (RE), which maps data, control information, and reference signals, is the smallest unit in the grid. The structure of the resource grid adapts to different numerologies, which affects the spacing and duration of slots. This flexibility allows for efficient scheduling of various traffic types and supports features like carrier aggregation and beamforming, ensuring optimized network performance.

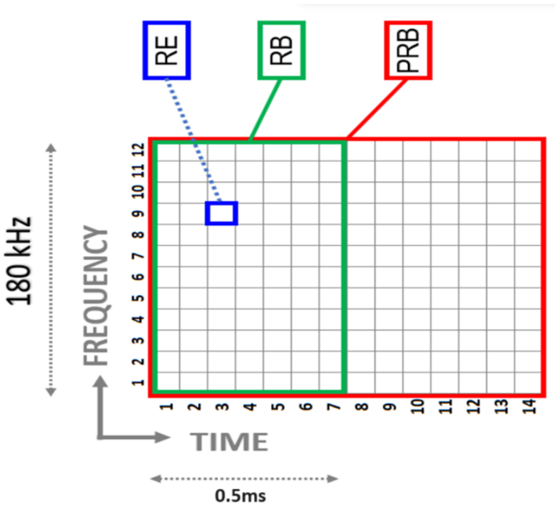


Figure 2.2: Physical resource block

At first appearance, the resource grid of NR appears to be constructed similarly to that of LTE. However, the physical characteristics, NR varies according on the numerology employed, affecting things like subcarrier spacing and the quantity of OFDM symbols in a radio frame.

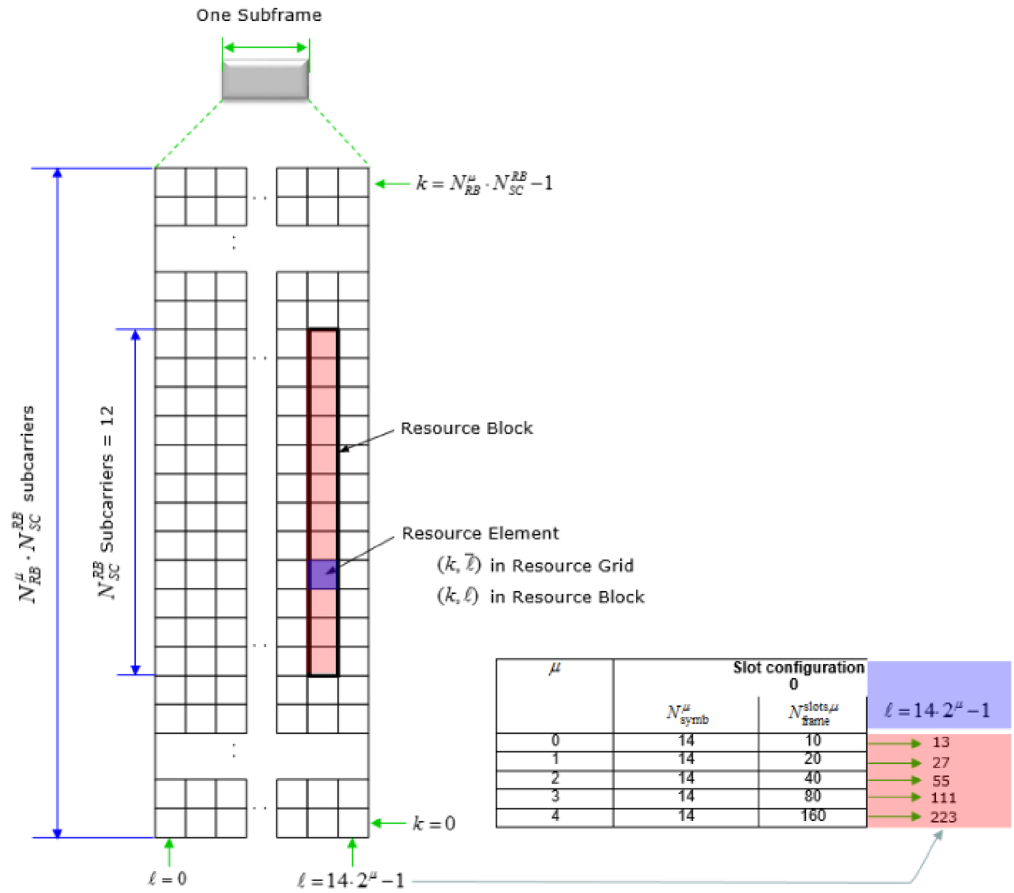


Figure 2.3: Resource grid

2.1.2 Flexible slot configurations and their impact on latency and throughput

- Flexible slot configurations dynamically adapt to varying service needs and traffic conditions.
- Mini-slots reduce scheduling intervals, ensuring low latency for critical applications like URLLC.
- Mixing numerologies within a frame optimizes resource allocation for efficiency.
- Dynamic slot allocation adjusts to real-time demands, maximizing network throughput.
- Adaptive scheduling efficiently distributes resources based on QoS requirements and network load, balancing latency and throughput effectively.

2.2 Bandwidth part (BWP)

The BWP represents a continuous set of PRB selected from a contiguous subset of the common resource blocks for a given number on a certain carrier [20]. Although the example below shows the scenario with three BWPs, it's crucial to remember that a maximum of four BWPs can be defined in the UL and DL. The resource blocks numbered within each BWP are represented by PRB. Similarly, the resource blocks numbered from one end of the carrier band through the other end are represented by the CRB (Carrier Resource Block).

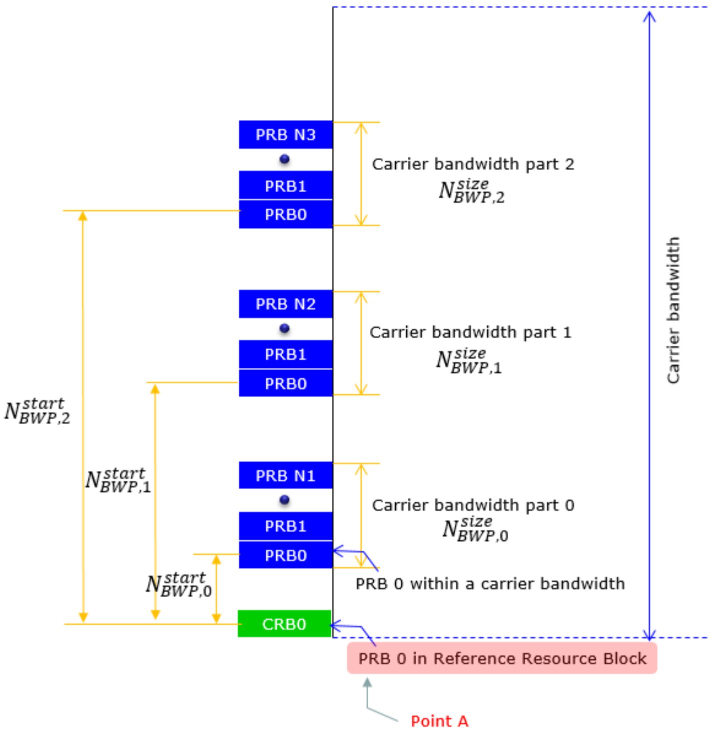


Figure 2.4: Bandwidth part

Point A as shown in figure 2.4 is a shared reference point for the resource block grids, and as mentioned in [21], higher-layer factors determine its placement.

- The frequency offset between point A and the lowest subcarrier of the lowest resource block of the SS/PBCH block, which is utilized by the UE for initial cell selection, is represented by PRB-index-DL-common for the DL of a PCell.
- The frequency offset between point A and the frequency location for the UL of a PCell in paired spectrum is given by PRB-index-UL-common, which is based on the ARFCN listed in system information block type 1 (SIB1).
- PRB-index-UL-common for the UL of a PCell in unpaired spectrum represents the frequency offset between point A and the lowest subcarrier of the lowest resource block of the SS/PBCH block, which is used by the UE for initial cell selection.
- PRB-index-DL-Dedicated, for the DL of a SCell, denotes the frequency offset in the higher-layer SCell configuration between point A and the frequency location based on ARFCN.
- In the higher-layer SCell arrangement, the frequency offset between point A and the frequency location based on ARFCN is represented by PRB-index-UL-Dedicated for the UL of a SCell.
- In the higher-layer SUL configuration, the frequency offset between point A and the frequency location based on ARFCN is represented by PRB-index-SUL-common for the SUL.

2.3 Synchronization

From the perspective of a UE, communication involves two key synchronization processes: Downlink Synchronization and Uplink Synchronization [22-26].

(a) Downlink Synchronization: This process involves the UE detecting the exact timing of the start of a radio frame and the beginning of each OFDM symbol within the frame. It accomplishes this by analysing signals known as Synchronization Signal (SS) Blocks. Downlink synchronization is critical for the UE to correctly receive and decode downlink transmissions from the network.

(b) Uplink Synchronization: In contrast, uplink synchronization focuses on the UE determining the precise timing for transmitting uplink data, such as PUSCH or (PUCCH. Given that the network (gNB) handles multiple UEs simultaneously, it's essential to align the timing of each UE's uplink transmissions with a common receiver timer in the network.

This process, known as random access channel (RACH) procedure, can be complex as it involves adjusting the timing of each UE's uplink transmissions to ensure proper synchronization with the network's receiver.

2.4 CSI-RS process

In 5G NR networks, the gNB transmits a particular reference signal called the channel status information reference signal. Its primary purpose is to assist UEs in estimating the quality of the downlink radio channel [15].

- Channel Quality Estimation: CSI-RS provides UEs with vital information about the current state of the downlink radio channel. By analysing the characteristics of the received CSI-RS signals, UEs can assess factors such as signal strength, fading, interference, and other channel impairments.
- Optimization of Signal Reception: The information obtained from CSI-RS helps UEs optimize their reception of downlink signals. By understanding the channel conditions, UEs can adapt their reception strategies, such as adjusting antenna beamforming or receiver parameters, to maximize the quality of received signals.
- Support for Advanced Antenna Techniques: CSI-RS plays a crucial role in enabling advanced antenna techniques like beamforming, precoding, and MIMO. These techniques rely on accurate channel state information to optimize the transmission of signals from the base station to the UE, enhancing spectral efficiency and overall network performance.
- Configuration and Transmission: The configuration parameters of CSI-RS, including its frequency, time, and antenna port configurations, are determined by higher-layer signalling. The gNB transmits CSI-RS periodically or semi-statically, ensuring that UEs have access to up-to-date channel state information for efficient communication

2.4.1 Sequence generation and resource mapping

A pseudo random sequence is utilized in 5G NR networks to generate CSI. This sequence is scaled by a power scaling factor, multiplied by a specifically created weighting sequence in the time and frequency domains, and assigned to particular resource elements in the resource grid. Accurate CSI in 5G NR systems must be obtained using multi-step procedure as shown in figure 2.5 [27].

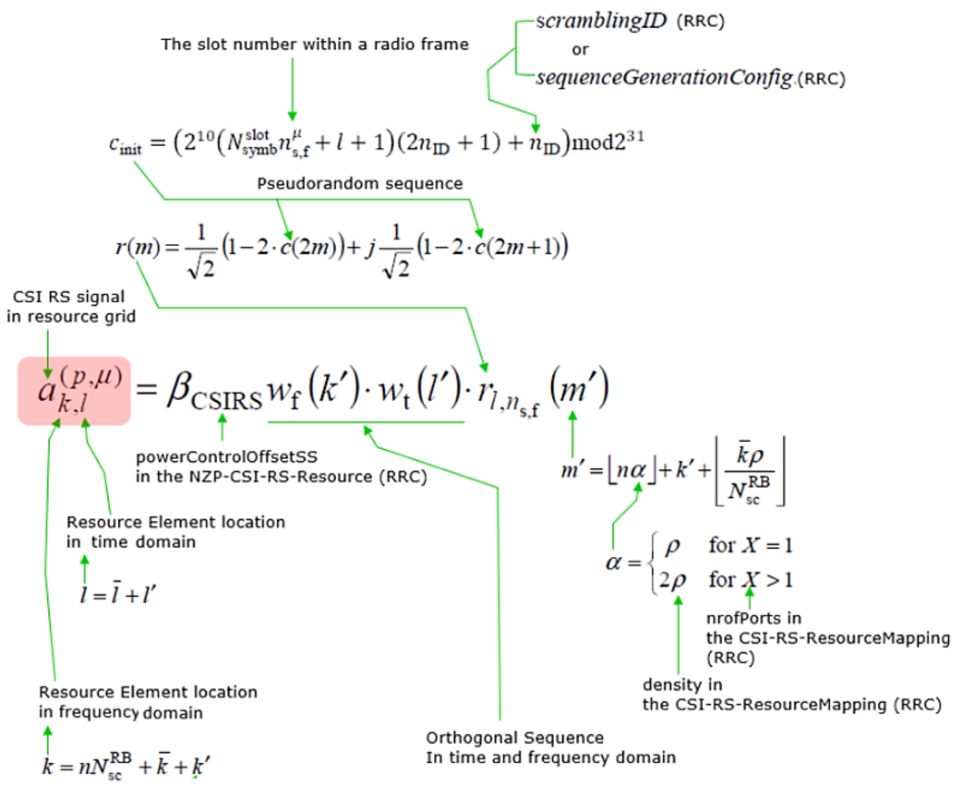
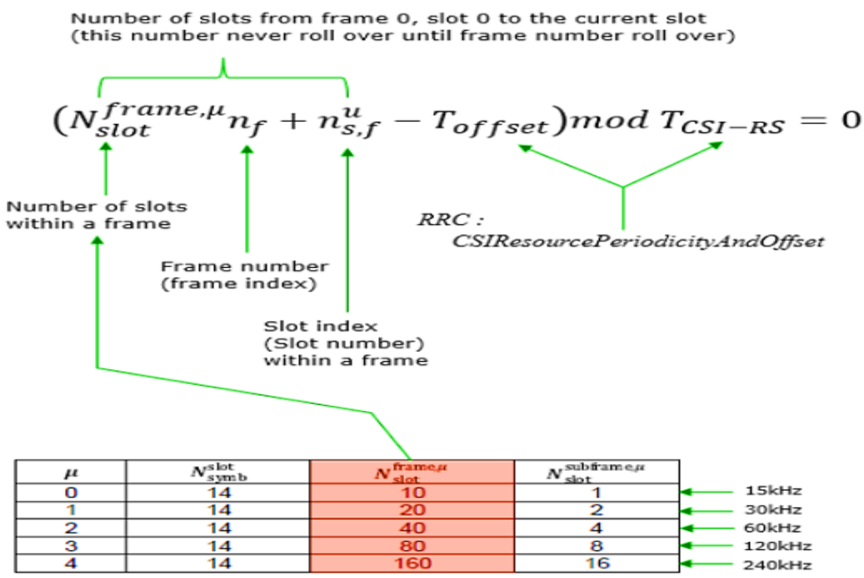


Figure 2.5: Sequence generation

2.4.2 Timing of CSI transmission

The timing of CSI transmission within a slot is determined by the radio resource control (RRC) parameter [28]. This parameter dictates the periodicity and offset of CSI transmission and is calculated using the following equation shown in figure 2.6.



μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16

Figure 2.6: Timing of CSI transmission

2.5 Channel mapping

5G networks employ various channels to facilitate efficient communication between base stations and user devices. These channels serve different purposes and play essential roles in enabling reliable data transmission and control signalling [29]. Below figure 2.7 shows the key channels utilized in 5G NR networks:

PBCH (Physical Broadcast Channel)	- Broadcasts essential system information to all UEs - Carries Master Information Block (MIB)
PDSCH (Physical Downlink Shared Channel)	- Transmits downlink user data and control information to UEs - Used for delivering data packets and control messages
PDCCH (Physical Downlink Control Channel)	- Carries downlink control information and scheduling assignments for UEs - Used for signaling downlink control information
PUSCH (Physical Uplink Shared Channel)	- Transmits uplink user data and control information from UEs to the base station - Carries uplink data packets and control messages
PUCCH (Physical Uplink Control Channel)	- Transmits uplink control information from UEs to the base station - Used for uplink control signaling and acknowledgment
PRACH (Physical Random Access Channel)	-Used by UEs to request access to the network -Initiates random access procedures for new UEs

Figure 2.7: Channels in 5G NR

The diagram given in figure 2.8 illustrates the channel mapping in 5G NR networks, from the MAC layer through the PHY layer, it is based on specifications detailed in 3GPP documents [30- 31]. This overview aims to present a general view of the channel architecture in NR without diving into the complexities of individual channel processing, which are extensive topics that are discussed in [30-31]. While the channel mapping in NR may appear similar to LTE at first glance, a closer look at the PHY layer reveals some key differences:

- Lack of CRS (Cell specific reference signal): NR does not employ CRS for reference signalling, in contrast to LTE.

- Utilization of DMRS for NR PDSCH: NR PDSCH requires demodulation reference signal (DMRS), unlike LTE PDSCH, which does not use DMRS. This difference arises because NR PDSCH needs its own reference signal (DMRS) in the absence of CRS.

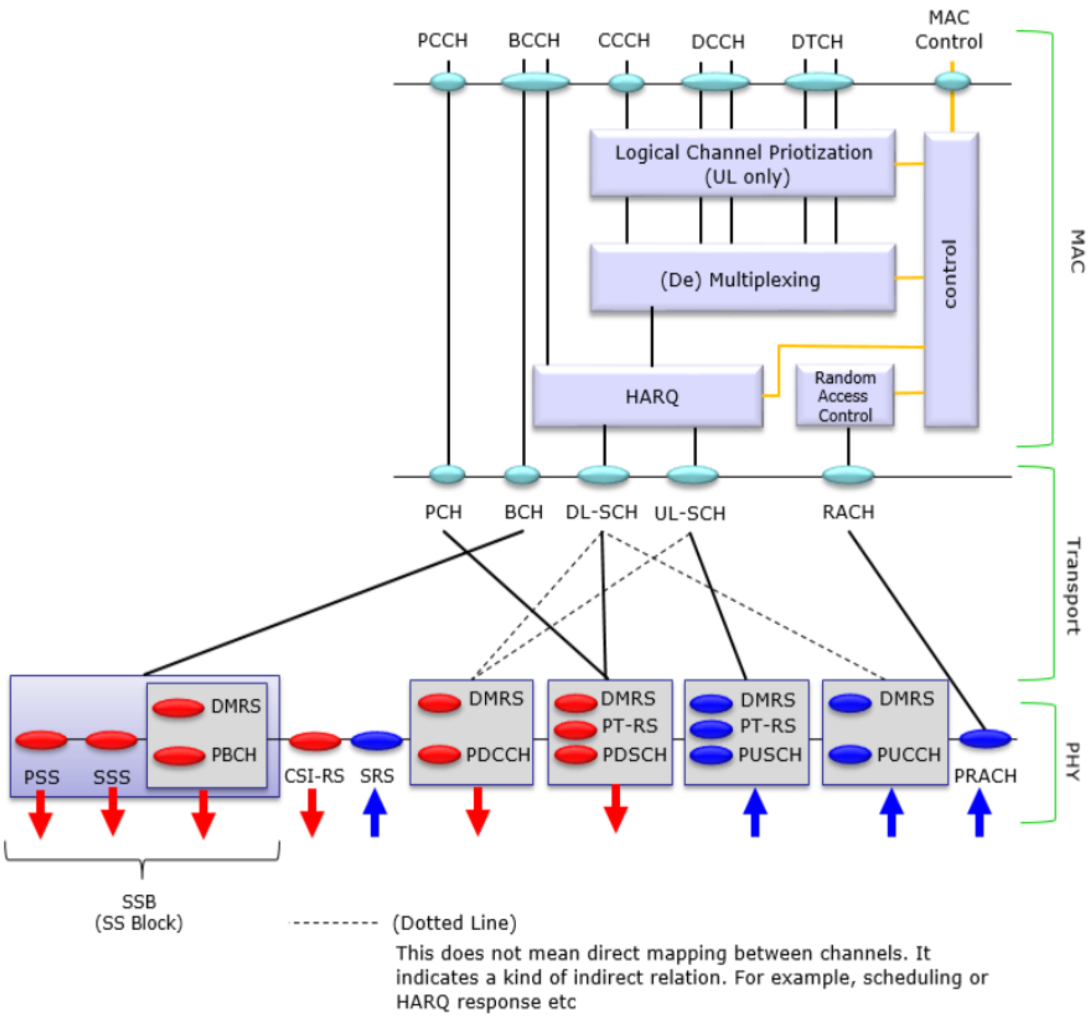


Figure 2.8: MAC/PHY channel mapping

- PSS, SSS, PBCH: Bundled into SS Block (SSB) in the downlink resource grid.
- DL-SCH and PDSCH/DMRS: PDSCH/DMRS needed for PHY/MAC scheduling of DL-SCH.
- UL-SCH and PUSCH/DMRS: PUSCH/DMRS required for PHY/MAC scheduling of UL-SCH.
- DL-SCH and PUCCH/DMRS: PUCCH/DMRS needed for HARQ responses (ACK/NACK) for DL-SCH involving PDSCH/DMRS.

2.6 CORESET

The NR Downlink resource grid's control resource set (CORESET) is a group of physical resources that comprises a set of parameters used to carry PDCCH/DCI [32–37]. As is well known, the DCI (Downlink control information) depicted in figure 2.9 is carried over PDCCH. As illustrated in figure 2.10, the NR CORESET zone is restricted to a particular area in the frequency domain, in contrast to LTE, where the PDCCH region spans the full channel bandwidth.

Types of formats used in DCI are given in table 2.1. Among these, the most commonly used types are 1_0 and 1_1 for Downlink Scheduling, while 0_0 and 0_1 are frequently used for Uplink Scheduling. UE determines which DCI to decode by examining the Radio Network Temporary Identifier (RNTI) masking the DCI.

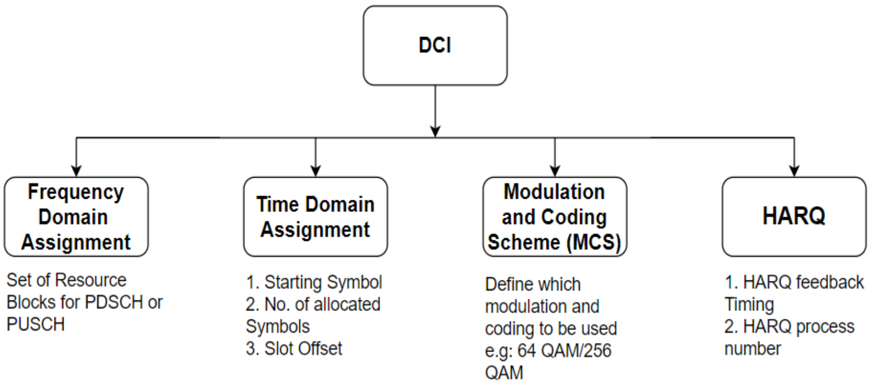


Figure 2.9: Downlink control information

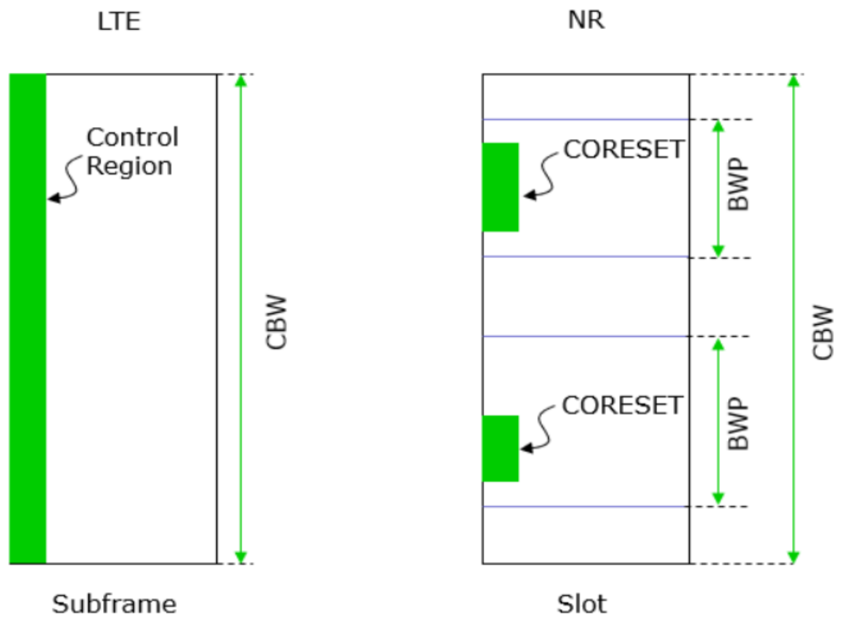


Figure 2.10: CORESET

Table 2.1: DCI format

DCI Format	Usage
Format 0_0	Scheduling of PUSCH in one cell
Format 0_1	Scheduling of PUSCH in one cell DCI format 0_1 with CRC scrambled by C-RNTI DCI format 0_1 with CRC scrambled by CS-RNTI
Format 1_0	Scheduling of PDSCH in one cell DCI format 1_0 with CRC scrambled by C-RNTI DCI format 1_0 with CRC scrambled by C-RNTI for PDCCH Order DCI format 1_0 with CRC scrambled by RA-RNTI DCI format 1_0 with CRC scrambled by TC-RNTI DCI format 1_0 with CRC scrambled by SI-RNTI DCI format 1_0 with CRC scrambled by P-RNTI
Format 1_1	Scheduling of PDSCH in one cell
Format 2_0	Notifying a group of UEs of the slot format
Format 2_1	Notifying a group of UEs of the PRB(s) and OFDM symbol(s) where UE may assume no transmission is intended for the UE
Format 2_2	Transmission of TPC commands for PUCCH and PUSCH
Format 2_3	Transmission of a group of TPC commands for SRS transmissions by one or more UEs
Format 2_4	Notifying the PRB(s) and OFDM symbol(s) where UE cancels the corresponding UL transmission from the UE
Format 2_5	Notifying the availability of soft resources
Format 2_6	Notifying the power saving information outside DRX Active Time for one or more UEs
Format 3_0	Scheduling of NR sidelink in one cell
Format 3_1	Scheduling of LTE sidelink in one cell

2.6.1 NR CORESET and LTE control region comparison

While CORESET in NR and the Control Region in LTE are identical, there are a few key distinctions:

(a) Frequency domain localization: The Control Region spans the entire channel bandwidth in LTE. In NR, CORESET is localized within each BWP, allowing for flexible frequency domain width defined in multiples of 6 RBs.

(b) Frequency domain parameter: Since the frequency domain area uses the entire LTE spectrum, no parameter is required to specify it. Due to its confined nature to specify the frequency domain width for CORESET, NR needs a frequency domain parameter.

(c) Time domain parameter: In LTE, The Physical control format indicator defines the time domain duration of the control region. The RRC option ControlResourceSet.duration defines the time domain length of CORESET.

2.6.2 CORESET structure parameters

The terms listed below in figure 2.11 are fundamental to comprehending the CORESET resource allocation and monitoring procedure.

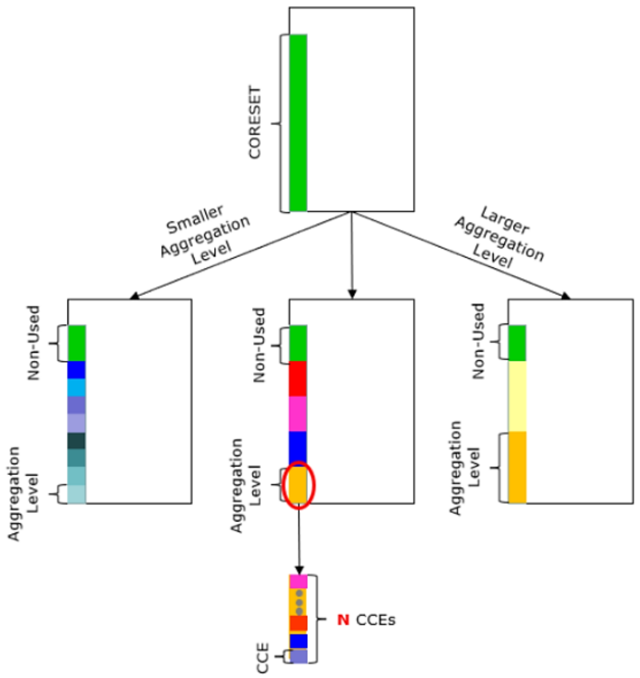


Figure 2.11: CORESET structure

(a) Resource element (RE): The smallest unit in the resource grid, the RE is comparable to LTE and is made up of one OFDM symbol in the time domain and one subcarrier in the frequency domain.

(b) Resource element Group (REG): Consists of one OFDM signal in the time domain and one resource block that is 12 resource components in frequency domain. Six REGs make up a control-channel element; each REG represents a resource block for a single OFDM symbol.

(c) REG bundles: Composed of several REGs, with the RRC parameter reg-bundle-size dictating the bundle size.

(d) Control channel element (CCE): Composed of multiple REGs, the number of which varies within a CCE.

(e) Search space (SS): A CORESET's "Search Space" is a region that UE should keep an eye on in order to identify a particular PDCCH/DCI. CSS (Common search space) and USS (UE specific search space) are the two main categories of SS. The type of RNTI or the RRC configuration specified in [35] determines which search space UE is required to monitor. The number of bits carried by a SS is determined by its size, which is based on the aggregation level. Similar to LTE, different types of aggregation levels exist in NR, and their sizes measured in CCE units, are defined by 3GPP as illustrated below in figure 2.12.

(f) Aggregation level: Aggregation level is defined as the number of resource elements (RE's) of a CORESET that must convey a PDCCH DCI message. It is stated in terms of CCEs (control channel elements).

- 1 REG = 12 SC's X 1symbol = 12 RE's
- 1 CCE = 6 REG's = 72 RE's

1 CCE = 6 REG & 1 REG = 1Resource block

Aggregation Level	CCE	Resource Element Groups(REG)	Resource Elements
1	1	6	72
2	2	12	144
4	4	24	288
8	8	48	576
16	16	96	1152

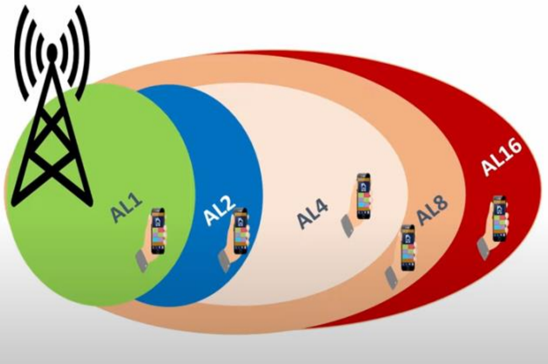


Figure 2.12: CCE and aggregation level

- Impact on coverage

Higher aggregation level: uses more CCEs, which increases the robustness of the control channel message against errors. This is typically necessary in poor signal conditions (e.g., at the cell edge) to ensure the message can be correctly received and decoded by the UE.

Lower Aggregation Level: Uses fewer CCEs, suitable for good signal conditions (e.g., near the cell centre), which conserves resources and allows for more efficient use of the available spectrum.

- Trade-off

Higher aggregation levels improves the reliability of control message decoding, they consume more resources, reducing the overall spectral efficiency. This means fewer resources are available for data transmission, potentially leading to lower throughput. For UEs at the cell edge, higher aggregation levels are often required due to weaker signals and higher error rates. However, this also means that more resources are dedicated to control information rather than data, impacting the overall network efficiency. While higher aggregation levels improve control message reliability in challenging signal conditions, they also consume more resources, impacting spectral efficiency and throughput. This trade-off is a critical consideration in scheduling and resource allocation strategies in 5G networks.

2.6.3 Reference signals

In NR, the absence of CRS (Cell specific reference signal) marks a significant departure from LTE. NR introduces novel reference signals such as phase tracking reference signal, PBCH reference signal, and time/frequency tracking reference signal as shown in figure 2.13.

Reference Signal	Functionality
CSI-RS	CSI aquisition, Beam Management
PDSCH DMRS	Required for PDSCH Demodulation
PUSCH DMRS	Required for PUCCH Demodulation
PDCCH DMRS	Required for PDCCH Demodulation
PUCCH DMRS	Required for PUCCH Demodulation
SRS	Sounding Reference Signal
PBCH DMRS	Required for PBCH Demodulation
PTRS	Used for Phase Tracking for PDSCH
TRS	Used for Time Tracking

Figure 2.13: 5G NR reference signals

2.7 PUSCH/ UCI

The physical channel that the UE uses to transport UCI is called PUCCH. Control information sent from the UE to the gNB over the uplink is referred to as UCI (Uplink control information). Its primary function is to send control signals for uplink scheduling requests, channel quality reports, acknowledgments (ACK/NACK) for downlink data, and other control signals [38].

- PUCCH comprises five types: Formats 0, 1, 2, 3, and 4, distinguished by factors like resource allocation and bit capacity.
- UCI bits of two or less are handled by Formats 0 and 1, whereas UCI bits of two or more are handled by Formats 2, 3, and 4.
- Formats 0 and 2 are part of short PUCCH, covering 1-2 OFDM symbols, whereas Formats 1, 3, and 4 are part of long PUCCH, covering 4–14 symbols.

- In LTE, PUCCH typically occupies entire symbol lengths at channel bandwidth edges; in 5G NR, it can be located anywhere in a slot, often using only a few symbols.

Physical resource allocation involves configuring resource sets and resources, with each UE having multiple resource sets, and the selection of resource sets for PUCCH transmissions determined internally based on UCI bit count. Additionally, the specific resource within the selected set is determined by DCI.

2.8 Higher level view of NR MAC

The NR MAC (Medium Access Control) layer is a sublayer of layer 2 in the 5G NR protocol stack. It is essential for controlling and making the best use of the wireless medium, serving as a service provider for higher layers, and guaranteeing effective data transfer. Key features of the NR MAC layer are given in figure 2.14. The MAC scheduler is provides the efficient utilization of radio resources, determining which UEs can transmit or receive data based on various criteria and discussed in [35]. Key principles of MAC scheduling include:

- Dynamic Resource Allocation: Adapts to changing traffic loads and channel conditions.
- QoS Management: Ensures different types of traffic receive appropriate priority and resources.
- Fairness: Balances resource allocation to provide fair access to all UEs.

  The MAC layer dynamically allocates uplink and downlink resources based on current network conditions, traffic demands, and QoS requirements, optimizing the use of available radio resources.

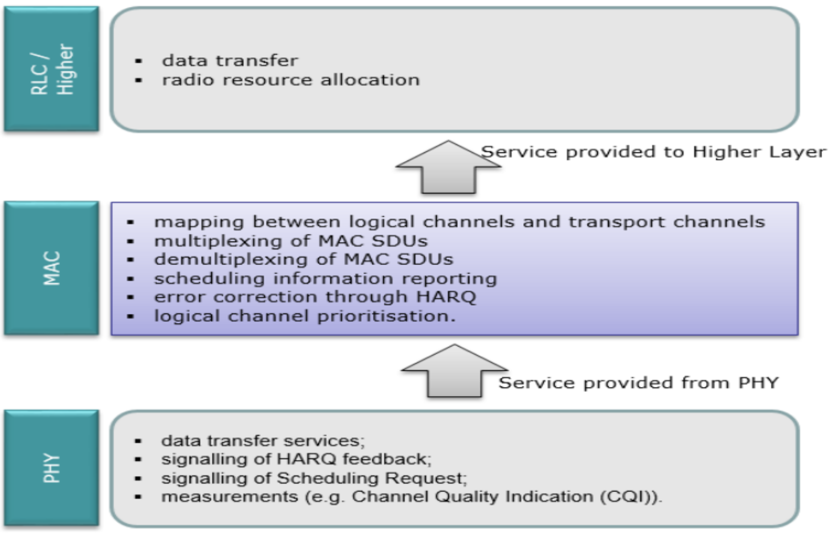


Figure 2.14: MAC for NR

Table 2.2: MAC comparison with LTE vs. NR

	5G/NR	LTE
Services provided to upper layers	• data transfer • radio resource allocation	• data transfer • radio resource allocation
MAC Functions	• mapping between logical channels and transport channels • multiplexing of MAC SDUs • de-multiplexing of MAC SDUs • scheduling information reporting; • error correction through HARQ; • logical channel prioritisation.	• mapping between logical channels and transport channels; • multiplexing of MAC SDUs • de-multiplexing of MAC SDUs • scheduling information reporting • error correction through HARQ • priority handling between UEs • priority handling between logical channels of one MAC entity • Logical Channel prioritisation • transport format selection • radio resource selection for SL
Services expected from physical layer	• data transfer services; • signalling of HARQ feedback; • signalling of Scheduling Request; • measurements (e.g. Channel Quality Indication (CQI)).	• data transfer services; • signalling of HARQ feedback; • signalling of Scheduling Request; • measurements (e.g. Channel Quality Indication (CQI)).

The NR MAC layer's operations and features are mostly comparable to those of the LTE MAC layer. Table 2.2 provides a comparison between NR MAC functions and LTE MAC functions for your reference.

2.8.1 RLC (Radio Link Control)

Error correction, concatenation, in-sequence delivery, segmentation/reassembly, and duplicate detection are all handled by RLC. Three distinct modes are available for NR RLC: AM (Acknowledge mode), UM (Unacknowledged Mode), and TM (Transparent Mode).

- TM: No segmentation/reassembly, buffering at Tx only, no RLC header, and no feedback (i.e., no ACK/NACK).
- UM: RLC Header, Tx and Rx buffering, Partitioning/Compositing, Absence of response (i.e., No ACK/NACK)
- AM: Buffering at both Tx and Rx, RLC Header Partitioning/Compositing, Response (i.e., Ack/Nack)

2.8.2 PDCP (Packet Data Convergence Protocol)

It manages header compression, security encryption and integrity protection (figure 2.15), in-sequence delivery, duplication detection, data transfer, and QoS management. Main functions of PDCP includes:

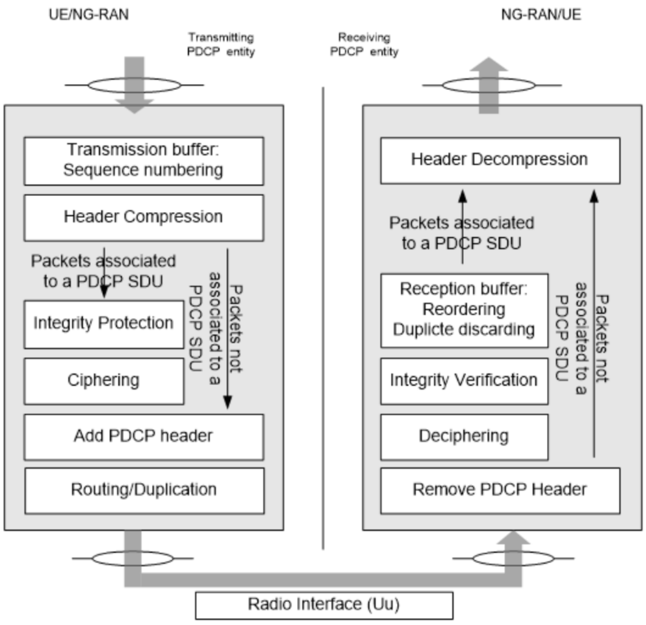


Figure 2.15: PDCP functioning

The tasks include data transfer (either user or control plane), PDCP serial number maintenance, header compression and decompression using the robust header compression algorithm, ciphering and decoding user and control plane data, integrity protection and integrity verification of control plane data and routing or duplication for split bearers.

2.9 High level factors for scheduling

Scheduling in 5G NR involves allocating resources for data transmission, similar to LTE, but with finer granularity, especially in time domain scheduling at the physical layer. This allows for more precise control and efficiency in resource utilization.

The scheduler given in figure 2.16 is the entity or algorithm that performs the scheduling. It decides how to allocate resources to different users or data streams. It can be integrated into the network equipment (such as a base station in a cellular network) via software or hardware.

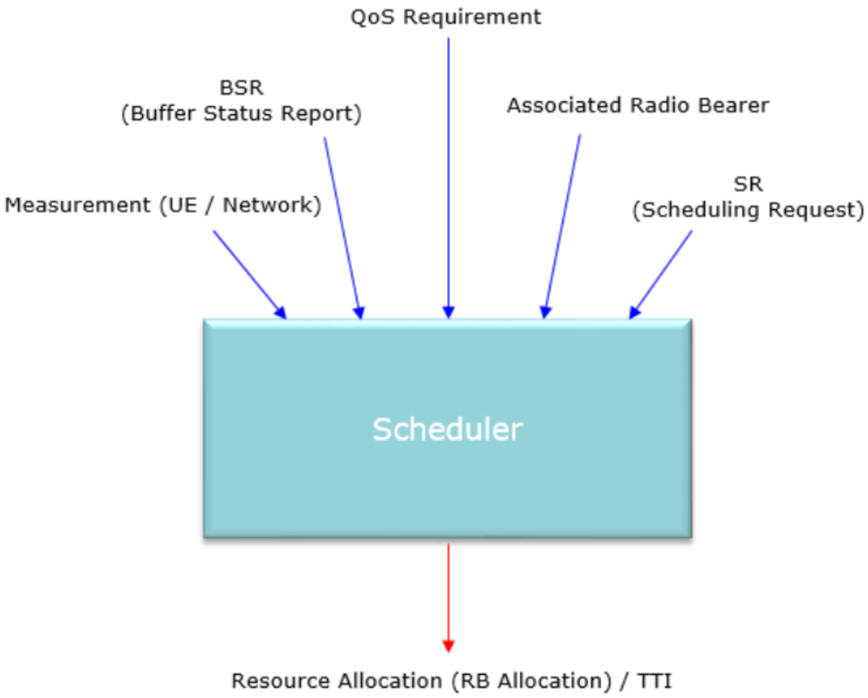


Figure 2.16: NR Scheduler

A scheduler in a network consists of several key components that work together to manage and allocate resources effectively. Here's a brief explanation of each:

(1) Measurement (UE/Network)

The scheduler relies on measurements from both the UE and the network to make informed decisions. For example, if a UE reports poor signal quality, the scheduler might allocate more power or assign it a different frequency band to improve communication.

(2) Buffer status report (BSR)

The BSR assists the scheduler in allocating resources according to the quantity of data that is awaiting transmission from each UE. This ensures that UEs with large amounts of data do not experience excessive delays.

(3) QoS requirements

Different applications have different QoS requirements. For instance, a video call requires low latency, while a file download may tolerate higher latency but needs high throughput. The scheduler uses QoS requirements to prioritize resource allocation.

(4) Associated radio bearer

Each radio bearer can have different priorities and QoS requirements. The scheduler must manage these bearers to ensure that critical services (like emergency calls) receive the necessary resources over less critical services (like regular web browsing).

5) Scheduling request (SR)

When a UE sends an SR, it indicates that it needs uplink resources. The scheduler collects these requests and allocates resources based on the urgency and amount of data to be sent, as well as the overall network conditions.

2.9.1 Essential parameters for time domain resource allocation and Ack/Nack responses

(1) k0 (Slot Offset): Represents the number of time slots that pass between the downlink data (PDSCH) and the downlink control information (DCI) transmission. K0 is 0 if both take place in the same slot.

(2) k1 (HARQ Timing): Indicates how many time slots there are between the transmission of HARQ acknowledgement and negative acknowledgement (ACK/NACK) and the transmission of downlink data (PDSCH).

(3) k2 (UL Timing): It provides the number of time slots between the reception of DCI and the subsequent Uplink Data (PUSCH) transmission.

(4) SLIV (Start and Length Indicator Value): Specifies the beginning symbol and the duration of the symbol that is planned for either PUSCH or PDSCH within a particular time period.

(5) N1 (PDSCH Delay): Defines the minimum time duration required from decoding the DCI to preparing for PDSCH reception, based on the UE's capability.

(6) NU (PUSCH Delay): Represents the minimum time duration required from decoding the DCI to being ready for PUSCH transmission, determined by the UE's capability.

These parameters play a crucial role in optimizing resource allocation, ensuring efficient data transmission, and meeting the performance expectations of user equipment.

2.9.2 HARQ

HARQ, short for Hybrid ARQ [39], combines FEC and ARQ for error detection and correction in data transmission. In NR, it's a physical layer message indicating PDSCH decoding success or failure. Unlike LTE, the timing gap (k1) between PDSCH and Ack/Nack is variable, determined by RRC and DCI configurations. NR allows up to 16 HARQ processes shown in figure 2.17, set via RRC.

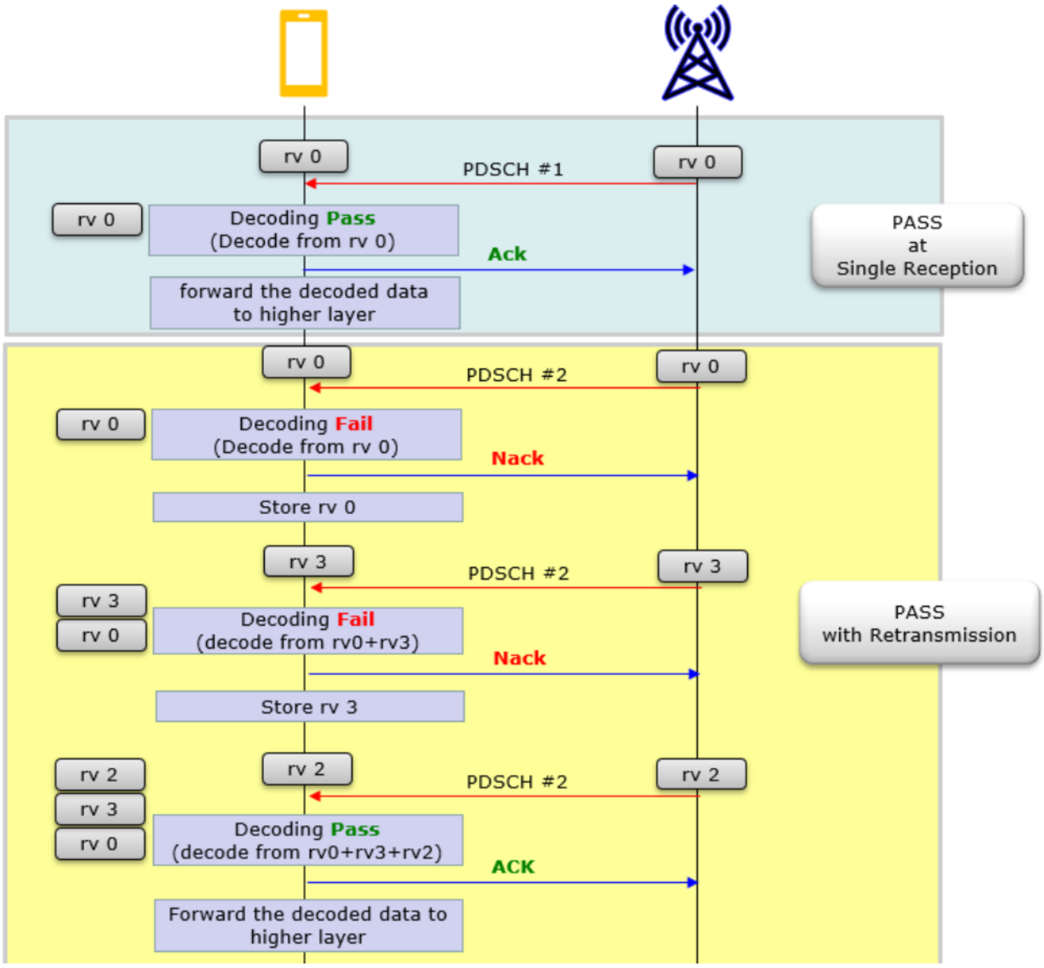


Figure 2.17: HARQ process

In Case 1, the gNB transmits PDSCH, the UE successfully receives it, and sends an ACK, requiring no retransmissions. In Case 2, after failed CRC checks, the gNB retransmits data based on NACKs, with UE combining previous data in buffer, until successful decoding prompts an ACK where *rv* is redundancy version given by 3GPP in [40].

CHAPTER 3

LITERATURE SURVEY

This literature survey chapter explores the existing body of knowledge surrounding scheduling techniques in the realm of 5G networks. The objective of this chapter is to present a thorough overview of the state-of-the-art approaches, methods, and tactics used in 5G network scheduling as we set out on this investigation. By synthesizing and critically analysing the extant literature, this survey seeks to identify trends, challenges, and gaps in the existing research landscape, through an examination of key scholarly contributions, industry developments, and emerging trends, this literature survey chapter aims to offer insights into the various dimensions of scheduling in 5G.

3.1 Literature review

In [41] simulation-based analysis of various cooperative strategies for cell-edge users in downlink was reported. They proposed that a cooperative cell edge user's capacity is not necessarily greater than average transfer. Only the results of the two BSs scenario that were captured in a static environment were shown in the simulation. In the simulation, inter-cell interference (ICI) and BSs load were not taken into account. Additionally, that study did not account for the QoS of each individual user.

Similar to this, [42] recommended base station collaboration for cell edge users in order to increase system capacity and improve full frequency reuse (FFR) network performance. However, the main emphasis of [42] was on a hybrid method that coupled the modelling of cell edge users with FFR. [43] authors findings show that when co-operation is used instead of non-co-operation, a high SNR near the cell edge can be attained, leading to a higher spectral efficiency.

In [44] author made the conclusion that a user with a poorer channel will gain more from cooperation. Therefore, it is unclear why the results reported in [43]-[44] are counterintuitive. The problems with cell edge user sub-carrier allocation from two base stations (BSs) are covered in [45] and [46], which also offer simulation and analytical results for outage probability and reliability. None of them, meanwhile, provided a description of the zone where cell edge users can allocate subcarriers from multiple BSs.

Because of the time complexity, heuristic optimization algorithms given in [47–49] are rarely used in NR resource scheduling [50-51]. Whereas heuristic optimization approaches assume a large amount of processing power and time to find the solution, like in offline applications, RB scheduling and allocation in NR is a real-time operation that must be carried out each TTI (i.e., 1 ms). Very few RBs are used in the works [50-51] to get over the delay brought on by the heuristics. PF is the most widely used scheduling method for LTE systems because of its quick response time and careful consideration of throughput and fairness [52]. Nevertheless, cell edge users are not particularly included in any of the schedulers mentioned above.

Performance of the system and the cell edge user are greatly impacted by interference from the adjacent cell. Consequently, in order to address the issues of low throughput and poor quality of service for cell edge users, inter-cell interference has been researched in the past [53-54]. For LTE systems, the authors take into consideration the inter-cell interference coordination method known as soft frequency reuse (SFR) in [55–56]. In [55], a low-complexity decentralized SFR scheduling algorithm is suggested that takes user classification into account and balances throughput and fairness for all users.

A modified variant of SFR called the gentler frequency reuse, approach was proposed by the authors in [56]. The frequency reuse factor (FRF) of one is shared by the cell edge and the cell centre in this strategy. Cell edge users are assigned high power frequency bands, while cell centre users are assigned low power bands. According to the traffic load, [57] considers an adaptive SFR by varying the transmit power and the number of major subcarriers for specific cells.

Using the nearby cells to share the subcarrier, transmit power, and rate information decentralizes the decision-making process about resource allocation. Other factors, including as the user's location, the weather, and the geographic area, might also cause interference.

In order to prevent interference, fractional frequency reuse, or FFR, is employed in [58], where the frequency band is split into many sub-bands. For cell edge users, the authors take into account the FRF three, and for cell centre users, the FRF one. Using this technique, distinct sub-bands are assigned to various cell edge regions. In [59], a technique for reducing cross-tier co-channel interference is presented that makes use of pilot sensing and frequency reuse. The femtocell detects the pilot signals from the neighbouring cell after deploying the FRF of three to the macrocell. The femtocell, which hasn't been assigned to another cell, receives the remaining frequency from the scheduler.

In [60], an exhaustive examination of the distinctive novel features and applications within 5G NR systems are conducted. Noteworthy features such as scalable numerology and flexible spectrum contribute to broad coverage and network flexibility. The forward compatibility and ultra-lean design of 5G NR ensure compatibility with future technologies and enhance energy efficiency by mitigating interference from 'always-on' signals. Additionally, the paper proposes the architecture for the next-generation wireless network, establishing a connection between the existing 5G network and the upcoming beyond 5G/6G network.

Despite the imminent commercialization of 5G technology, deployment encounters challenges in effectively utilizing services. The heterogeneous deployment of three distinct use cases prompts issues addressed through network slicing based on service demand. The paper effectively tackles challenges arising from high modulation schemes and inter-RAT connectivity, crucial for the seamless migration from 5G to 6G. A virtualized network slicing-based 6G architecture is introduced, featuring three sliced layers: intelligent cloud layer slicing, RAN slicing, and application slicing. This proposed architecture is poised to facilitate diverse technologies and applications within the 6G network.

Furthermore, the paper underscores the incorporation of tactile internet as a fundamental service offered by 6G, recognized as the catalyst for haptic communication. Conclusively, various challenges linked to 6G network technologies are deliberated upon, presenting this paper as a potential foundation for future research in the evolution of wireless systems into the next generation.

In [61], a comprehensive survey of recent advancements and future prospects of packet scheduling algorithms, spanning from 5G to beyond systems. The survey explains in several key sections. Initially, an overview of scheduling algorithms is presented, highlighting crucial characteristics such as throughput, link utilization, delay-bound considerations, fairness, and algorithmic complexity. Subsequently, the paper delves into metric-based scheduling algorithms, presenting a detailed table encompassing all pertinent metrics associated with these algorithms. Further, the state-of-the-art centralised and joint scheduling algorithms are elucidated. Finally, the paper outlines research directions and future challenges in the realm of packet scheduling algorithms within the ambit of 6G systems.

The insights provided in this survey provide a deep understanding of scheduling algorithms. It becomes evident from the discussion that substantial research endeavours are imperative to formulate a fully operational URLLC scheduling system tailored for the evolving landscape of 6G systems. The elucidated overviews and future directions aim to guide and inspire future research initiatives in the dynamic field of packet scheduling for emerging 6G networks.

In [62], a thorough examination of pivotal subjects within the realm of 5G channel measurements and modelling, shedding light on essential requirements for effective channel modelling in the 5G context. The paper carefully examines and talks about current channel measurements and models, with an emphasis on the most difficult communication scenarios in 5G networks. Massively MIMO, V2V, HST, and mm wave communication are some examples of these scenarios. Furthermore, the paper introduces general channel models that span a broader spectrum of 5G scenarios, accompanied by a comparative analysis of these models. The synthesis of this information provides a comprehensive understanding of the current landscape of 5G channel modelling. Looking ahead, the paper outlines future research directions for both 5G and B5G channel measurements and models.

The recognition that 5G channel models need to accurately represent wireless propagation channels across a wide frequency range, support various network topologies, and be flexible enough to accommodate a variety of scenarios is noteworthy. The evolving nature of 5G systems may necessitate the adoption of multiple channel modelling approaches or hybrid models. This shift could address the multifaceted challenges presented by 5G systems while striking a balance between model accuracy and complexity. In essence, the paper contributes not only to the present understanding of 5G channel modelling but also provides a roadmap for future research endeavours in this dynamic and crucial field.

In [63], an in-depth evaluation of IIoT, delving into its architecture and the objectives encapsulated in the concept of B5G-IIoT. While much of the earlier literature has concentrated on the architectural aspects of IIoT, this paper takes a distinctive focus on the URLLC and eMBB techniques specifically tailored for 5G/B5G-IIoT applications.

The paper scrutinizes the trade-offs between URLLC and eMBB within the context of 5G-IIoT, offering insights that are particularly pertinent to various applications. As we look forward, the anticipation is that future wireless communication will play a pivotal role in enhancing the reliability and throughput of IIoT systems. This underscores the critical importance of optimizing communication technologies to meet the unique requirements of industrial applications, setting the stage for a more resilient and efficient industrial internet of things in the beyond 5G era.

In [64] the focus revolves around the examination of centralized multi-cell scheduling for URLLC in 5G NR. The paper introduces dynamic algorithms that consider scenarios with and without segmentation of URLLC payloads, aiming to enhance both latency and reliability. The proposed solutions exhibit low computational complexity, rendering them attractive for practical Cloud radio access network (C-RAN) implementations.

To assess the performance of the planned solutions, the study employs an advanced 5G NR compliant system-level simulator. The results validate that the centralized multi-cell scheduling solutions put forward yield substantial latency performance gains, showing improvements to 60% compared with traditional distributed solutions. Furthermore, the study emphasizes the effectiveness of segmentation in reducing queued data, resulting in notable URLLC latency enhancements for centralized and distributed scheduling approaches. The paper concludes by highlighting the importance of channel-delay aware scheduling for URLLC.

The article in [65] discusses how to optimize 5G mobile communication resources and flow efficiencies by using the buffer status parameter. In order to increase UE efficiency, the author focuses on presenting a novel downlink scheduling method created specifically for eMBB. In comparison to traditional schedulers and recently developed algorithms reported in the literature, the suggested scheduler presents a more accurate and efficient method since it uses channel condition information and buffer state to allocate radio resources. This new scheme achieves a favourable trade-off between efficiency, fairness, and buffer status. It ensures a minimum acceptable goodput for all users in the cell, fostering fairness and facilitating the smooth transmission of buffered data.

In [66], a new scheduling algorithm is proposed that modifies the average throughput computational equation within the PF algorithm. Additionally, the proposed algorithm combines PF and B-CQI metrics. Through simulation evaluations, the modified PF algorithm, when compared to three other averaging methods demonstrates superior fairness. Furthermore, the proposed scheduling algorithm, when contrasted with the original PF and B- CQI Schedulers, exhibits a worthy balance between fairness and throughput.

The results of the simulation highlight the effectiveness of the proposed algorithm, particularly when employing the geometric mean average method. This method outperformed the other two proposed averaging methods, showcasing its efficacy, especially in congested network environments. The findings underscore the potential of the proposed algorithm to address fairness

concerns and enhance throughput in wireless communication scenarios, making it a promising candidate for practical implementations in diverse network settings.

In [67], the achieved throughput surpasses that of existing algorithms primarily due to the incorporation of user packet delay considerations in the new Proportional Fairness (PF) algorithm. Upon configuring the gNB with a specified delay threshold, the PF algorithm assigns a higher scheduling priority when the packet transmission delay exceeds this threshold. Consequently, time-frequency resources are allocated preferentially, resulting in enhanced throughput. The throughput improvement demonstrated by the suggested scheduling strategies is validated by the simulation results.

The key factor contributing to this improvement lies in the PF algorithm's consideration of the transmitted data packet delay. In comparison to the other three scheduling algorithms, the PF algorithm presented in the paper accounts for packet delay in its decision-making process. For a predetermined and reasonable packet delay threshold, a direct correlation exists between packet delay and the proportional fairness factor. Consequently, as packet delay increases, the scheduling priority rises, leading to the prioritized allocation of time-frequency resources for corresponding packet transmissions.

3.2 Challenges in deploying 5G NR

(1) Signal distortion from advanced modulation: As wireless technology advances, modulation schemes become more complex. Using higher-order modulations packs constellation points closer together, making them susceptible to signal distortions.

(2) Inter-RAT handover synchronization for high mobility: For users with high mobility, handovers between different radio access technologies can increase processing time, leading to poor beam synchronization and potential call drops.

(3) High frequency propagation losses: Higher frequencies, such as mmWave and terahertz, suffer from greater propagation losses. These losses comprise partitioning, absorption, and atmospheric attenuation, all of which degrade signal quality and lower SNR.

(4) Coexistence of eMBB, uRLLC, and mMTC services: The simultaneous presence of all three 5G NR use cases within the same RAN can negatively impact each other's functionality. For example, massive user connectivity can increase queuing delays, violating the strict requirements of uRLLC.

(5) Coexistence of 5G NR and other wireless networks: The numerous frequencies used by 5G NR, spanning both FR1 and FR2 bands, overlap with existing frequency allocations can made difficulties in deploying 5G NR network. Therefore, spacings of frequency bands is crucial for smooth coexistence and efficient spectrum utilization.

CHAPTER 4

METHODOLOGY OF PROPOSED WORK

In this chapter, we will discuss the methodology used to provide a detailed code flow from the main program in the MATLab 5G toolbox to the MAC scheduler, with a focus on TDD symbol-based scheduling simulations. This chapter outlines the steps involved in designing a novel scheduling algorithm, motivated by the need to optimize resource allocation and enhance data transmission efficiency in a network. We will cover the development process, the simulation environment, and the specific techniques employed to achieve these goals.

4.1 MAC scheduler's role

The role of a scheduler is to determine the ideal number of resource blocks for each UE in a slot based on variables such as coding scheme, modulation, and channel quality. As stated in the main program, the scheduler is unable to allocate more resource blocks in the downlink or uplink direction than RBAllocationlimit. The main program can be configured to set either RBAllocationlimitUL or RBallocationlimitDL, which is fewer than or equal to the total amount of Resource blocks.

4.1.1 TDD UL/DL pattern

NR offers both DL and UL resource configurations that are adjustable. The following are the essential variables for defining a customized TDD configuration:

- DL-UL period: The millisecond interval that the DL and UL pattern repeats over.
- Reference SCS: Used to determine the DL-UL pattern's slot count, which usually corresponds to the transmission's real subcarrier spacing.
- Full DL Slots: Full DL slots, that are available in a row at the commencement of each DL-UL pattern.
- DL symbols: The number of consecutive DL symbols at the commencement of the slot that follows the last full downlink slot.
- Full UL slots: The number of complete UL slots at the end of each DL-UL pattern.
- UL symbols: The number of UL symbols in a row at the end of a slot before the first complete UL slot.

For example: reference_scs = 15 kHz (i.e. 1 ms slot), DLULPeriodicity = 5 ms, numDLSlots = 3, numDLSyms = 7, numULSlots = 1, numULSyms = 5

Number of slots in DL-UL periodicity with respect to reference SCS of 15 kHz, NumSlotsDLULPeriodicity = 5

NumberOfGuardSymbols = TotalSymbolsInPattern - TotalSymbolsWithTypeSpecified

(14 * NumSlotsDLULPeriodicity) - (numDLSlots*14 + numDLSyms + numULSyms + numULSlots*14) = 2 symbols (see figure 4.1).

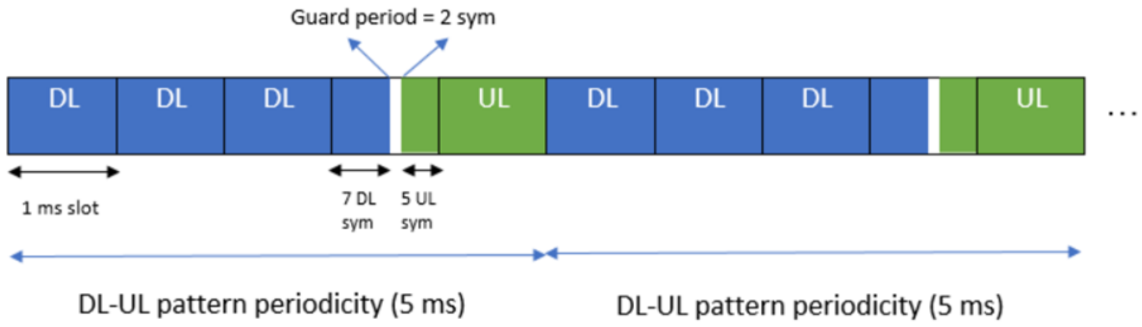


Figure 4.1: TDD DL/ UL Pattern

TDD mode has been chosen for following reasons:

(1) Flexibility in resource allocation: TDD allows dynamic allocation of uplink and downlink resources, making it well-suited for adapting to varying traffic demands and user requirements.

(2) Efficient spectrum utilization: By using time division for uplink and downlink transmissions, TDD can make more efficient use of the available spectrum, especially in scenarios with asymmetric traffic loads.

(3) Synchronization benefits: TDD systems can be synchronized across cells, reducing interference and improving overall network performance.

(4) Adaptability to channel conditions: TDD symbol-based scheduling can respond more effectively to changing channel conditions, allowing for real-time adjustments that enhance data transmission efficiency.

(5) Future proofing: As 5G networks evolve, the ability to flexibly allocate resources and adapt to new use cases and traffic patterns is increasingly important. TDD provides a robust framework for meeting these future demands.

4.1.2 Symbol based scheduling

With the help of NR, the Transmission Time Interval (TTI) can start at any symbol location throughout a slot and have symbol-level granularity. The uplink (UL) scheduler uses a TTI granularity of two symbols to allocate UL symbols within a slot. This is shown in Figure 4.2. Six UL symbols are present in the slot that is shown. Three iterations, each handling two symbols, are used by the scheduler to allocate the frequency resources. For DL scheduling, the downlink (DL) scheduler employs a similar technique.

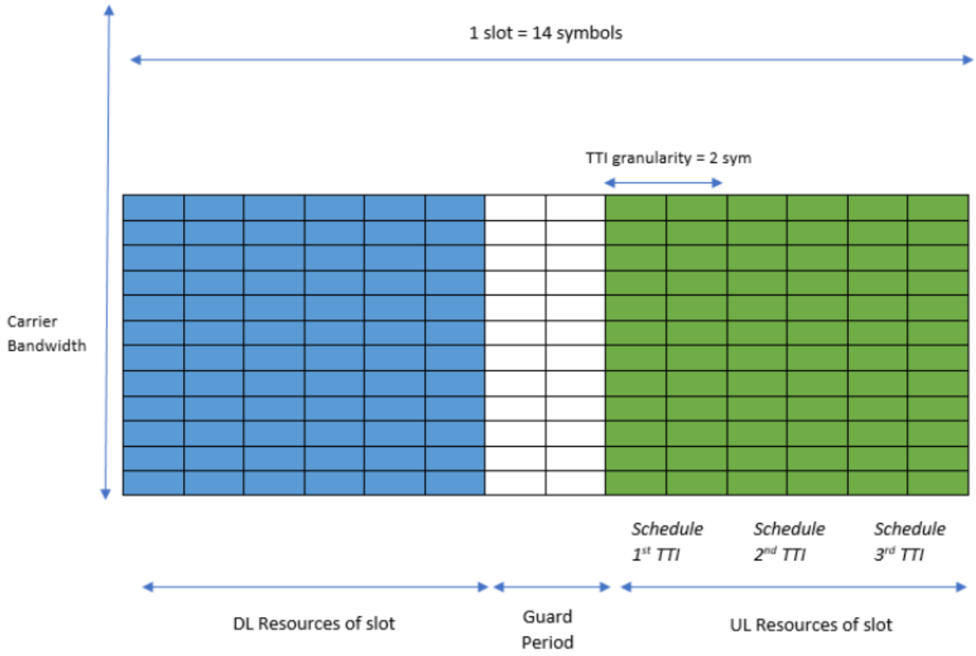


Figure 4.2: Symbol based scheduling

4.1.3 5G toolbox – MATLab

MATLab 5G toolbox is used for all scheduling method simulations. It offers examples and functions that meet with standards for the modelling, simulation, and validation of 5G NR communications systems. The toolkit facilitates the production of test waveforms, compliance testing and link-level simulation. End-to-end 5G NR communications networks can be configured, simulated, measured, and analysed with the toolkit. The toolbox functionalities are flexible and can serve as implementation models for 5G systems and devices. The toolbox provides functions and reference cases to help you characterize uplink and downlink baseband specifications and simulate the effects of RF designs and interference sources on system performance. You may programmatically or interactively build waveforms and modify test benches using the wireless waveform generator. These waveforms may be used to verify that your designs, prototypes, and implementations comply with the 3GPP 5G NR requirements.

4.2 Algorithm of proposed scheduler

As outlined in Chapter 1, we have developed a novel 5G NR scheduler specifically to guarantee reliable data access for cell edge users. The proposed scheduling algorithm prioritizes modulation schemes for UEs with higher CQI values and pending data transfer, dynamically selecting UEs for communication depending on channel quality. UEs' distances from the gNB are used to generate CQI values, which are vital for this procedure.

The UE and gNB's communication channel quality is measured using a metric called the CQI. Better channel conditions, which often permit higher-order modulation schemes and coding rates, result into greater CQI values and faster data throughput.

According to our approach, the UEs' distance from the gNB affects the CQI; UEs that are closer to the gNB often have better channel conditions and higher CQI values. The scheduler optimizes the overall efficiency and performance of the network by guaranteeing that UEs with better channel conditions are given priority through the use of CQI as a metric. High data speeds and dependable connections are maintained with the help of this adaptive strategy, which is particularly important for edge customers who could otherwise suffer from decreased service quality.

Notations used in algorithm given in table 4.1.

Table 4.1: Algorithm notations

V_{cqi}	Channel Quality Indicator (CQI) value.
S_i	Scheduler input
N_E	Number of eligible user
U_s	Selected user
M_i	Modulation and coding scheme Index (MCS)
U_d	Scheduled User
E_i	Eligible index
B_s	Buffer Status

The next subsection contains a full description of this scheduler's algorithm.

4.2.1 Flowchart

Figure 4.3 provides the flowchart for proposed algorithm.

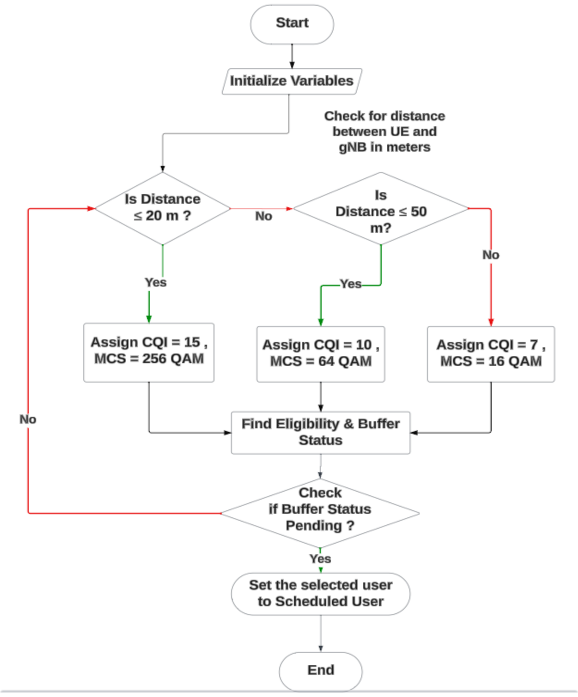


Figure 4.3: Flowchart for adaptive channel scheduler

4.2.2 Algorithm

The proposed scheduler is given below.

Step1: Initialize Variables
N_E = size (V_{cqi},1);
U_s = -1; initialize no user selection
M_i= -1; initialize unknown MCS index
U_d = U_s; initialize with no scheduled user
Step 2: Scheduling
***for** $i = 1:N_E$*
$U_s = mod(U_d, N_E) + 1$;
$U_s = U_d+1$;(update scheduler for next iteration)
$cqi(U_s) = V_{cqi}(U_d)$; (find the CQI value of selected user from its position, where V_{cqi} matrix gives user distance versus cqi mapping)

***if** $cqi(U_s) == 15$*
M_i = 28;(cqi=15 indicates the highest possible CQIas per3GPP standard. For highest CQI, 256-QAM modulation is assigned with MCS=28)
else if
M_i = 10; (MCS=10 is chosen which uses 64-QAM for transmission)
else
M_i = 7; (MCS=7 which uses 16-QAM for transmission)

end

E_i= find(U_d==1: N_E);
$B_s = S_i(U_d)$;
***if** $B_s > 0$ (Check Buffer Status for pending data and start transmission of U_s data over transmission frame with selected M_i value)*
break;
end
end

4.2.3 Algorithm description

The adaptive channel scheduler algorithm given in figure 4.3, is a dynamic resource allocation mechanism designed to enhance the performance of wireless networks. The algorithm starts by initializing several important variables in Step 1. N_E represents the number of users in the system, and U_S and U_d are variables used to keep track of the selected user for scheduling. They are initially set to -1, indicating no user has been selected yet. M_i is initialized to -1 as well, indicating an unknown MCS index.

Step 2 involves the actual scheduling process. A loop is used to iterate through all the users in the system, from 1 to N_E. U_s is updated by taking the modulus of U_d and N_E, which helps in selecting the next user in a circular manner. U_s is also updated as '$U_s = U_d + 1$' for the next iteration, ensuring that the scheduler moves to the next user.

cqi(U_s) is set to the CQI value of the user U_d. This information is obtained from the V_{cqi} matrix, which likely stores CQI values for each user based on their position or distance. The algorithm checks if distance of UE from gNB is less than or equal to 20 meters, cqi(U_s) is equal to 15. If it is, it indicates the highest possible CQI, and in accordance with the 3GPP standards, M_i is set to 28. This value of M_i corresponds to the use of 256-QAM modulation, which is a high-order modulation scheme suitable for excellent channel conditions. If UE is between 20 to 50 meters from gNB then CQI is set to 10 and M_i is set to 20. In this case, a lower-order modulation scheme, 64-QAM, is used, which corresponds to a lower MCS value of 20. Similarly if UE distance is greater than 50 meters from gNB than Mi is set to 7, 16-QAM is used in this scenario.

Further, E_i represents the index of the selected user U_d in the range from 1 to N_E and B_s represents the buffer status of the user U_d. The algorithm checks if there is pending data to transmit for this user. If B_s is greater than 0, indicating that there is data in the buffer to transmit, the algorithm breaks out of the loop, and the selected user's data is scheduled for transmission using the chosen M_i value. The proposed adaptive channel scheduler incorporates the channel quality and adapts the allocation of resources and modulation and coding schemes accordingly.

This adaptability makes it more efficient in utilizing the available bandwidth and accommodating users with varying channel conditions.

4.3 Considerations taken for developing a novel scheduling algorithm

Below are the few considerations that are taken into considerations while developing the algorithm:
(1) Dynamic user scheduling: The algorithm dynamically selects users based on their positions and updates the scheduler for each iteration. This adaptability allows the system to respond to changing channel conditions and user positions, ensuring efficient use of available resources.

(2) Channel quality consideration: By considering the CQI of each selected user, the algorithm aims to optimize the transmission by assigning MCS based on the observed channel conditions. Higher CQI values result in the assignment of more advanced modulation schemes for increased data rates.

(3) Adaptive modulation and coding: The algorithm adapts the MCS based on the CQI values, choosing between 256-QAM for the highest CQI and 64-QAM for lower CQI. This adaptive modulation and coding approach helps in maximizing data rates while maintaining reliable communication in varying channel conditions.

(4) Efficient resource utilization: The algorithm incorporates a check for buffer status to determine if there is pending data for transmission. This ensures that resources are allocated to users with actual data to transmit, preventing unnecessary resource wastage and improving overall system efficiency.

(5) Compliance with 3GPP standards: The algorithm aligns with 3GPP standards by assigning MCS values based on CQI, which reflects industry best practices. This alignment ensures compatibility with existing communication standards and facilitates interoperability within the broader wireless communication ecosystem.

(6) Quick decision making: The algorithm is designed for quick decision-making during each iteration, breaking the loop when there is pending data to transmit. This rapid response to channel conditions and buffer status contributes to low-latency communication, crucial for real-time applications and improving overall user experience.

4.4 Comparison of proposed scheduler with existing scheduling algorithm

Performance of adaptive channel algorithm is compared with following scheduling algorithms.

(1) Round Robin (RR): Round Robin [68] a simple scheduling algorithm which allocates resources to active users in a cyclic manner, giving each user an equal share of the resources. Resources are distributed in a round-robin fashion, with each user taking turns to use the available resources. Once all users have had their turn, the algorithm repeats the cycle. It ensures fairness by providing each user with an equal opportunity to use the resources. However, it may not be efficient in maximizing overall system throughput.

(2) Best CQI: The Best CQI algorithm prioritizes users based on their channel quality indicator (CQI) [69]. It distributes resources to the user with the highest CQI, aiming to maximize spectral efficiency. The system continuously monitors the CQI of all active users and assigns resources to

the user holding the highest CQI at any given time. This means that users with better channel conditions are given priority. Drawback of Best CQI is that edge user is assigned zero resources leading to zero throughput.

(3) Proportional Fair (PF): The PF scheduling algorithm aims to strike a balance between fairness and spectral efficiency [70]. It allocates resources to users in such a way that users with better channel conditions get more resources, but it also ensures that all users receive some resources to maintain fairness.

4.5 Scenario configuration

Three UE's are taken within a pico cell in our simulation. Figure 4.4 illustrates the distance between the UE and the gNB. TDD mode has been employed because it can improve spectral efficiency by adjusting the time slots allotted for uplink and downlink traffic. Moreover, TDD can optimize the use of the available spectrum for scheduling based on symbols.

We assessed how well the scheduling technique performed in terms of guaranteeing spectral efficiency in resource sharing and reaching medium access control throughput. Table 4.2 describes the input parameters for scenario set up to show the outcomes of the suggested scheduler in section. We have taken into account the fundamentals of a scheduling system that serves three UE's in a single cell, however, the suggested method offers scalability when taking into account multiuser networks.

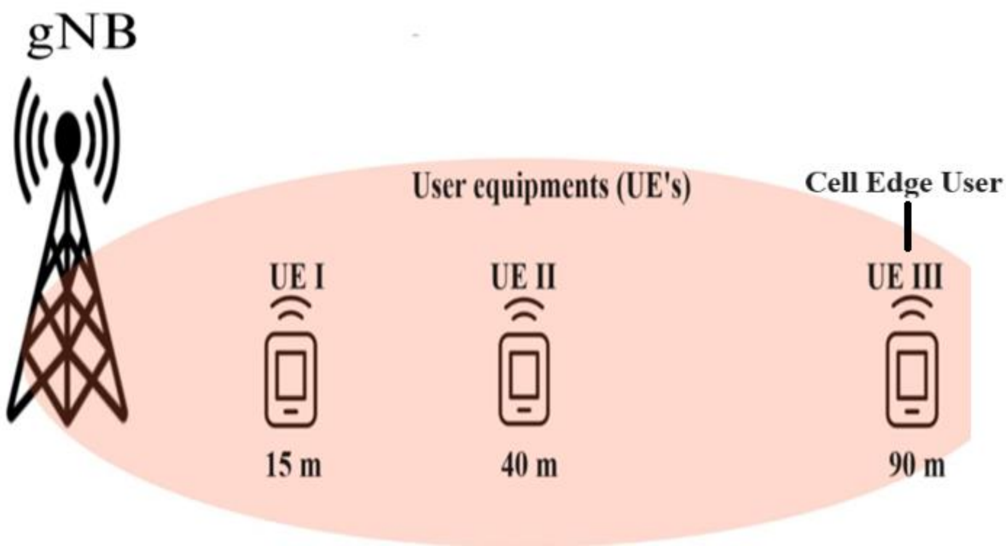


Figure 4.4: Distance of UE's from gNB in meters.

Table 4.2: Input parameters

Parameter	Value
Scheduling Type	Symbol
Carrier Frequency	3.5 GHz
Bandwidth	5 MHz
Sub Carrier Spacing(Δf)	15 KHz
No. of Users	3
No. of Resource Blocks	25
Duplex Mode	TDD
Modulation Order	64/256 - QAM
Cyclic Prefix	Normal
No. of Cell	1
No. of Frames	10
Frame Duration	10ms
Simulation Time	100ms

4.6 Code flow for simulation

The code flow for this scheduling algorithm is depicted in Figure 4.5. Additionally appendix A and B provides the code for parameters configuration to simulation respectively

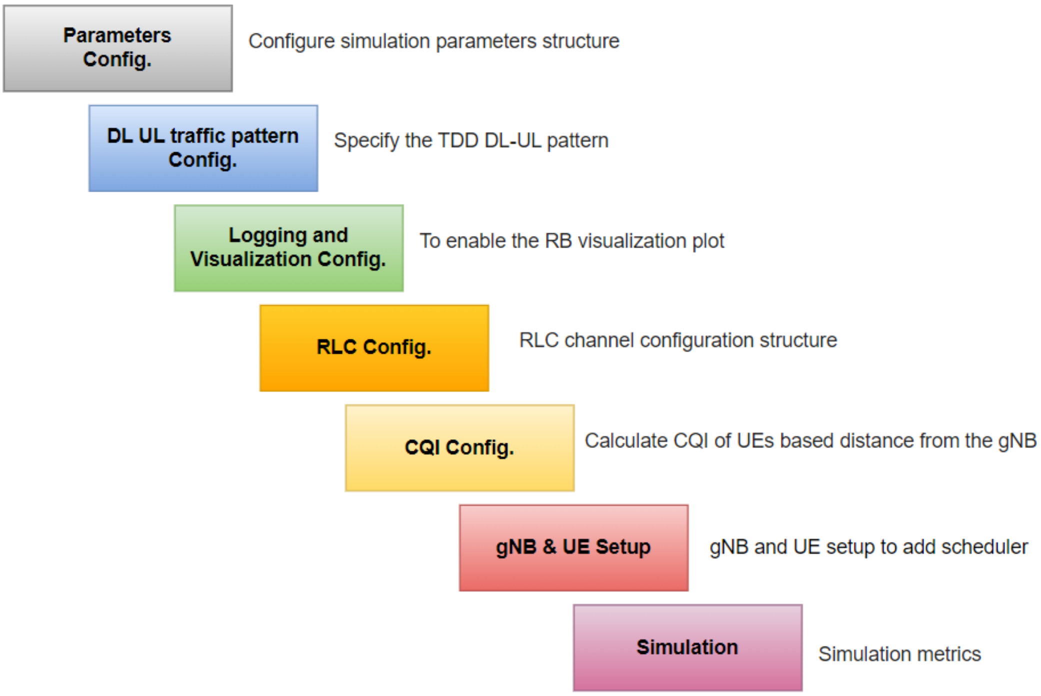


Figure 4.5: Code flow for simulation

CHAPTER 5

RESULTS

The results of the simulations and analysis carried out with the new 5G NR scheduler are presented in this chapter. The results highlight the performance improvements in resource allocation and data transmission efficiency. We have presented a thorough data analysis that contrasts the novel scheduling algorithm with existing methodologies. Key performance indicators such as throughput, goodput, and spectral efficiency among users are discussed.

We have also discussed how the suggested scheduler affects the overall network performance, particularly for cell edge users and explore the consequences of the results. The discussions will also cover potential limitations and areas for future research, providing a holistic view of the scheduler's efficacy and applicability in real-world scenarios.

5.1 Evaluation metrics

In this section, we outlined the metrics used to evaluate the performance of the proposed 5G NR scheduler. These metrics are essential for assessing the efficacy of the scheduler in optimizing resource allocation, enhancing data transmission efficiency, and ensuring fair distribution of resources among users. The primary evaluation metrics considered are explained in subsections.

5.1.1 Maximum throughput calculation

The equation (5.1) given by [71], is used for 5G NR to determine the max data rate that a cell can achieve for a given number of aggregated carriers in a band or band combination.

$$\text{Throughput (in Mbps)} = 10^{-6} \cdot \sum_{j=1}^{J} \left(v_{Layers}^{(j)} \cdot Q_m^{(j)} \cdot f^{(j)} \cdot R_{\max} \cdot \frac{N_{PRB}^{BW(j),\mu} \cdot 12}{T_s^{\mu}} \cdot \left(1 - OH^{(j)}\right) \right) \tag{5.1}$$

In 5G NR, carriers can have different bandwidths depending on the deployment scenario and spectrum availability. Aggregating carriers allows for higher data rates by effectively increasing the available bandwidth for transmission. By adjusting the parameters such as bandwidth per carrier, modulation scheme, and number of carriers, one can optimize the data rate according to the specific requirements and constraints of the network deployment scenario. The equation provides an estimate of the achievable data rate based on the specified parameters. Terms used in equation (5.1) is given in figure 5.1.

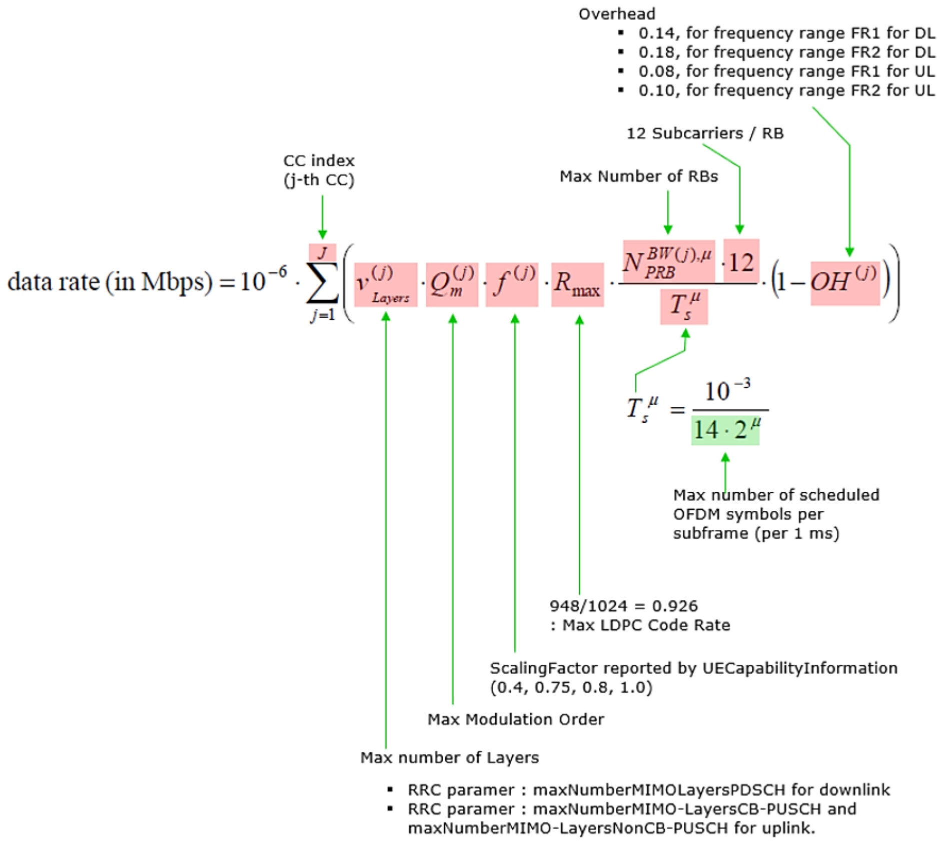


Figure 5.1: Throughput calculation

5.1.2 Achieved throughput

It is calculated by the amount of bytes a UE transmits (including retransmissions) in specific time. It is given by equation (5.2).

$$\text{Throughput (in Mbps)} = \frac{\text{Total amount of Data Transmitted}}{\text{Transmission Time}} \tag{5.2}$$

5.1.3 Goodput

For evaluating the real data rate that the user is experiencing, goodput is an essential parameter to consider. The goodput is computed by dividing the total number of useful data bits that are successfully transmitted over a communication channel by the transmission time [72]. As per [73], the goodput can be obtained from equation (5.3).

$$\text{Goodput (in Mbps)} = \frac{\text{Useful Data}}{\text{Transmission Time}} \tag{5.3}$$

5.1.4 Spectral efficiency

An essential measure for evaluating the capability and performance of 5G networks is spectral efficiency. Bits per second per hertz (bps/Hz), is the unit of measurement for spectral efficiency, which shows how well a wireless system uses the available frequency spectrum to transmit data. It is given in equation (5.4).

$$\text{Spectral Efficiency} = \frac{\text{Throughput (bps)}}{\text{Channel bandwidth(Hz)}} \tag{5.4}$$

5.1.5 Resource share percentage

The percentage of each UE's available uplink capacity that is shared among them out of the total uplink resources is known as the resource share percentage. This metric is critical for assessing and ensuring fairness in scheduling and given by equation (5.5).

$$\text{Resource share percentage for UEs} = \frac{\text{Resource allocated to UE}}{\text{Total resources}} \text{ x } 100 \tag{5.5}$$

5.2 Results

This section compares the proposed adaptive channel scheduler's simulation results to existing scheduling algorithms discussed in chapter 4.

5.2.1 Time step records

Figure 5.2 displays an example of a time step entry. Based on the selected symbol-based scheduling type, each row in the table represents a symbol. If the type of symbol is DL, the information in a row pertains to DL same for the UL also. The following details are included in each row:

Timestamp	Frame	Slot	Symbol	Type	RBG Allocation Bitmap	MCS	HARQ Process	NDI	Tx Type	CQI for UEs	HARQ NDI Status	Throughput Bytes	Goodput Bytes	Buffer Status of UEs
5	5	0	0	....	....	.....	.....	....	.....	....	......	.....	.....	....
51.2857	5	1	4	'UL'	[0 0 1 1 0 1 0 1 0 1 0 0 0] [1 1 0 0 0 0 0 0 0 0 1 0 0] [0 0 0 0 1 0 1 0 1 0 0 1 1]	[10 12 8]	[0 3 6]	[0 0 1 -1]	['newTx', 'newTx', 'reTx', 'noTx']	[5 8 9 8 7 8 9 8 9 11 12 .....] [5 7 3 4 9 5 9 7 9 10 15 .....] [3 9 9 6 9 4 9 8 9 9 13 ......]	[1 0 0 1 0 1 0 ..] [1 1 0 1 0 1 0 ..] [1 0 0 1 0 1 1 ..]	[46 54 38]	[46 54 0]	[299480 135671 77567
52	5	2	0	....	....	.....	.....	....	.....	....	......	.....	.....	....

Figure 5.2: Time step records

- Time Stamp: Time in (milliseconds)
- Frame: The number of frames.
- Slot: The frame's slot number.
- Symbol: The slot's symbol number
- Type: 'DL', 'UL', or 'Guard' are the symbols (or slots). Only DL/UL is allowed for type in slot-based scheduling. Given that the guard symbols are believed to be at the end of the slot, the slot is believed to be a DL slot.

- Distribution of RBG : It is an N by Q matrix where N is the number of UEs and Q is the number of RBGs in the bandwidth. When a UE is allocated an RBG, the bit that corresponds to that assignment is set to 1.
- MCS: It is a N length row vector, where N represents all of the UEs. For PUSCH or PDSCH transmissions, each number relates to the MCS index.
- Row vector of length N: This row vector is used by the HARQ process where N is the number of UEs. The HARQ process ID, which is utilized by gNB for PDSCH transmission or by the UE for PUSCH transmission. For instance, [0 2 5] shows that UE I, UE II, and UE III are given UL resources for the HARQ process IDs 0, 2, and 5.
- HARQ NDI status: NDI is new data indication. The value selected for PUSCH or PDSCH transmission is the NDI flag value. For instance, [0 0 1] implies that UL resources are allotted to UEI, UE II, and UE III. Based on the NDI flag values of 0, 0, and 1, respectively, they decide whether to send a fresh transmission or a retransmission.
- Tx kind: Tx Type specifies the new transmission or retransmission. The row vector has a length of N, and the number of UEs is N.
- CQI of UEs: An N by Q matrix, where N is the number of UEs and Q is the number of RBs in the bandwidth, is used to represent the CQI for UEs. For UE with RNTI i at RB j, a matrix element at location (i, j) corresponds to the CQI value.
- Throughput bytes: The row corresponding to the transmission's initial symbol displays the total throughput bytes for the whole PUSCH or PDSCH transmission.
- Goodput bytes: Similar to throughput, goodput bytes for a full PUSCH or PDSCH are all of the bytes that a UE has communicated in a certain period of time. There are N UEs, and the row vector has a length of N. The values in this symbol reflect new UL or DL transmission MAC bytes sent by or on behalf of the UEs.
- UE buffer status: The numbers show how many UL direction pending buffers there are at UEs (or how many DL direction pending buffers there are for UEs at gNB).

5.2.2 Resource grid assignment

The resource grid assignment to UEs is illustrated in the figure 5.3. This 2-D time-frequency grid demonstrates how resources are allocated to the UEs. With symbol-based scheduling, the RB symbol allocation from the previous slot is displayed on the grid, which is updated for each slot. Note that we have chosen a 15 kHz subcarrier spacing, resulting in 25 RBs. While the current view shows only 19 blocks, the range can be adjusted to display the full 25 RBs.

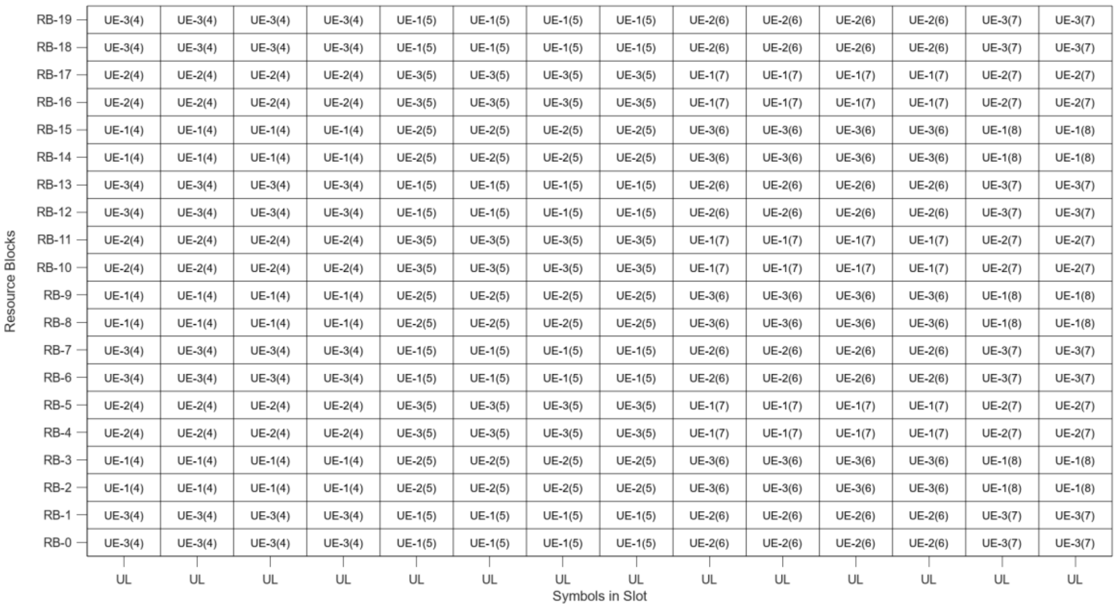


Figure 5.3: Resource allocation grid

5.2.3 Understanding the RBG allocation

The RBG allocation is a matrix used to represent which Resource block groups (RBGs) in the bandwidth are assigned to which UEs. For example matrix dimensions are N×P, where:

$$\begin{matrix} 0 & 0 & 1 & 1 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 1 & 1 \end{matrix}$$

P is the number of RBGs in the bandwidth, and N is the number of UEs. In the matrix, every element is a bit (0 or 1). When a bit is set to 1, it means that the specific UE is assigned the corresponding RBG. The RBG is not assigned to the UE when a bit is set to 0.UE I (first row): [0, 0, 1, 1, 0, 1, 0, 1, 0, 1, 0, 0, 0]

RBG indices assigned to UE I are where the bits are 1.

Assigned RBGs: 2, 3, 5, 7, 9

UE II (second row): [1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0]

Assigned RBGs: 0, 1, 10

UE III (third row): [0, 0, 0, 0, 1, 0, 1, 0, 1, 0, 0, 1, 1]

Assigned RBGs: 4, 6, 8, 11, 12

The assignment of 1s and 0s in the RBG allocation bitmap is not random it is determined by the scheduling algorithm used in the 5G network. The scheduling process involves several steps and considerations like channel quality, buffer status, scheduling request, and Qos requirements such as latency, throughput, and reliability to allocate resources efficiently and meet various network performance criteria.

5.2.4 CQI calculation

The distance between UEs and gNB is used to calculate CQI. Better channel quality and CQI 15 are assigned to the closer UE. Parallel to this, UE gets CQI 10 and 7, respectively, farther. As a result, MCS will be selected using an algorithm based on CQI. The CQI values for UEs are sown in figure 5.4.

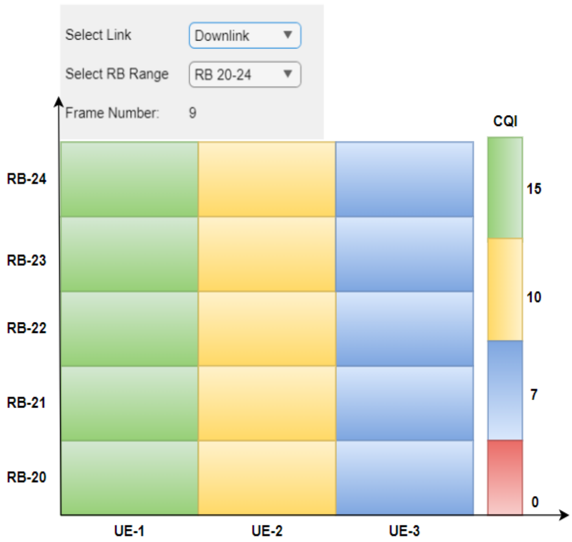


Figure 5.4: CQI visualisation

5.2.5 Throughput evaluation

Our proposed scheduling strategy has been compared with RR, Best CQI, and PF schedulers. Both downlink and uplink implementations of each algorithm were made and shown in figure 5.5 and 5.6 respectively. Maximum throughput, as determined by equation (5.1), is given in Table 5.1.

Table 5.1 Maximum cell throughput attained

Operation	Maximum cell throughput (Mbps)
Uplink (UL)	16.00
Downlink (DL)	14.22

Figure 5.5, 5.6 displays the scheduling performance for both uplink and downlink operation as we first examine the throughput attained in the cell using four distinct scheduling algorithms. Figure 5.7 shows that, in comparison to previous algorithms, our proposed adaptive channel scheduler

offers greater cell throughput, **6.87 Mbps** for UL and **6.75** Mbps for DL. The total average throughput of all users within the cell is the achieved cell throughput calculated by equation (5.2).

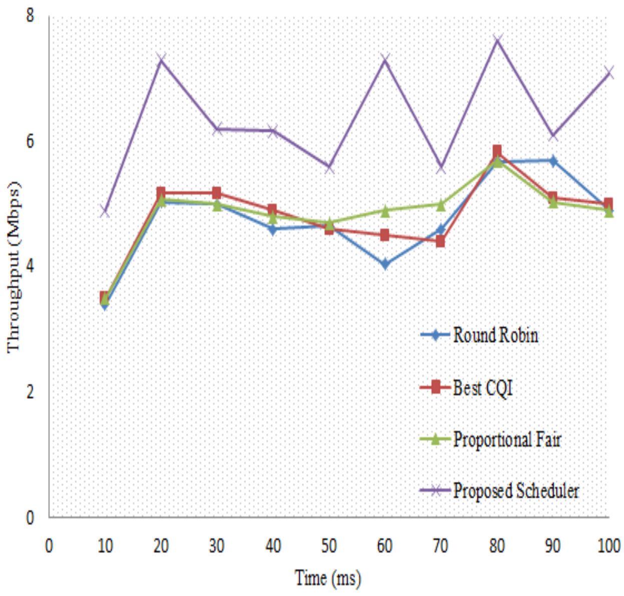


Figure 5.5: UL scheduling performance

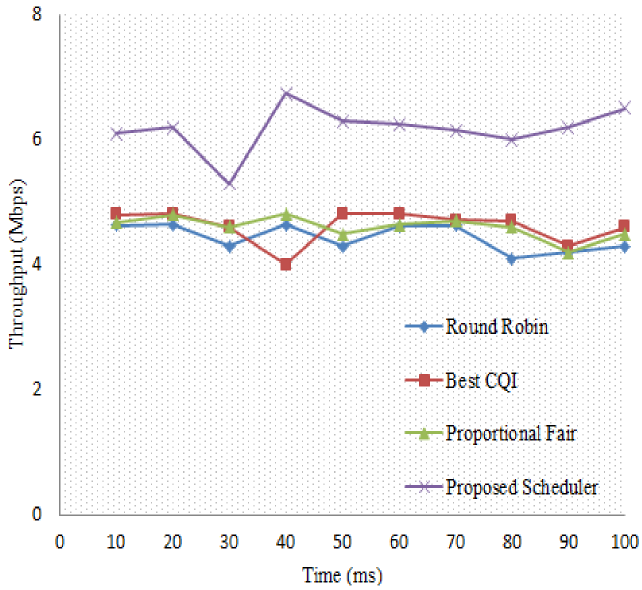


Figure 5.6: DL scheduling performance

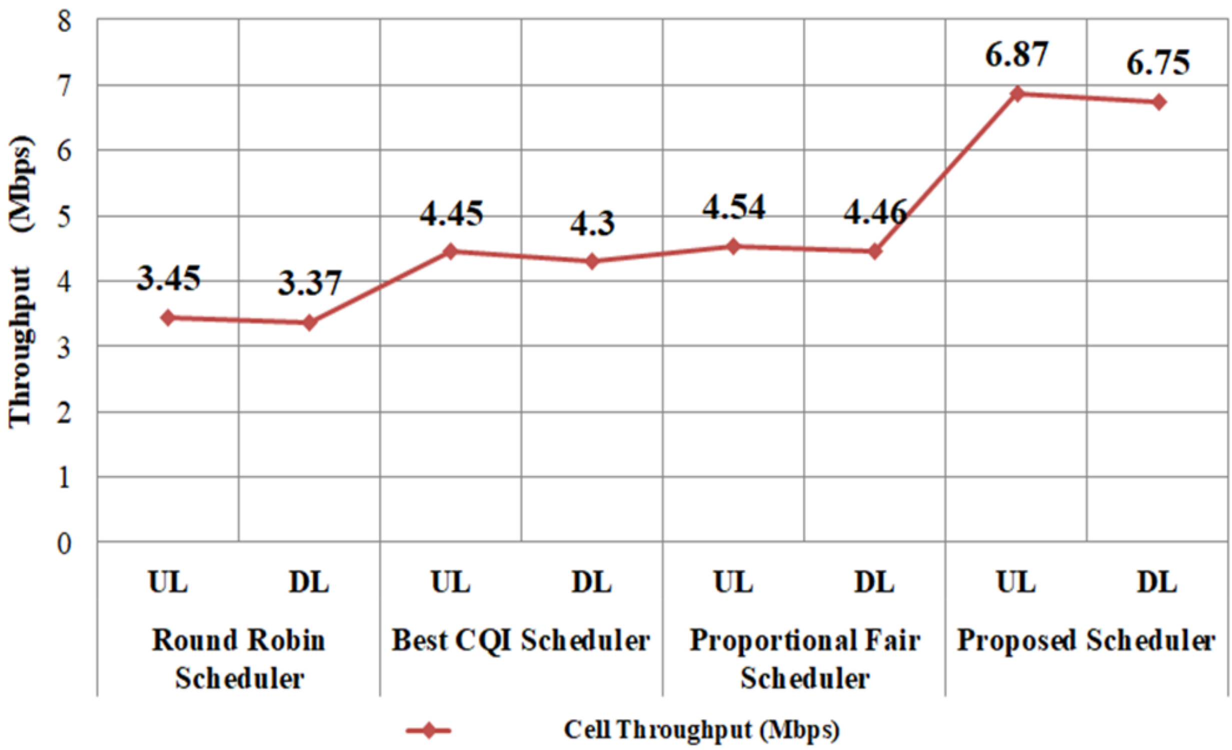


Figure 5.7: Cell throughput achieved by schedulers

5.2.6 Edge cell user connectivity

We examined throughput for the cell edge user (UE III), which is shown in figure 5.8, and is the furthest away from gNB depicted in Fig. 4.4 in chapter 4. We found that the suggested scheduler offers a greater throughput than alternative algorithms. This results from the modulation and coding method being adjusted based on the channel conditions. Therefore, the proposed scheduler offers cell edge users (UE III) guaranteed connectivity and improved data rates.

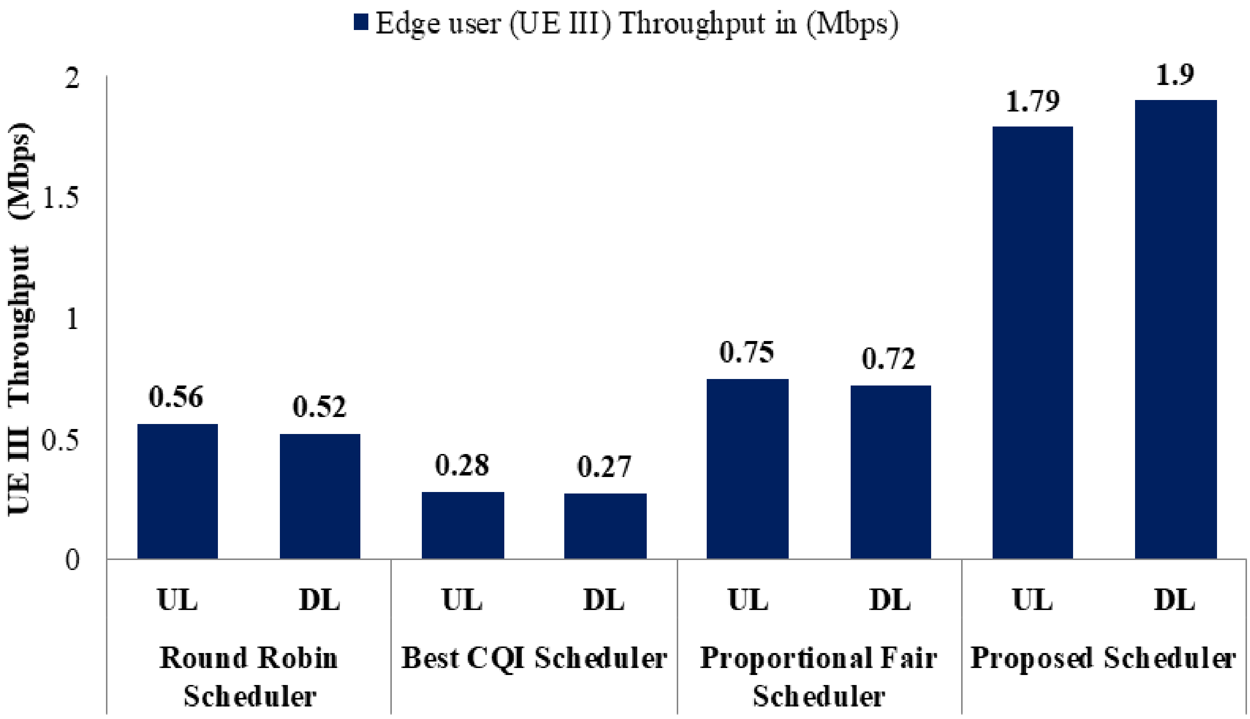


Figure 5.8: Edge user (UE III) throughput comparison with existing schedulers

As seen in table 5.2 , the achieved throughput by UE III is negligible when compared to existing methods, indicating a significant improvement in resource allocation and scheduling efficiency for cell edge user guaranteed connectivity.

Table 5.2 Throughput attained by cell edge user (UE III) for UL & DL

Scheduler	UL/DL	Edge user (UE III) Throughput in (Mbps)
Round Robin Scheduler	UL	0.56
	DL	0.52
Best CQI Scheduler	UL	0.28
	DL	0.27
PF Scheduler	UL	0.75
	DL	0.72
Proposed Scheduler	**UL**	**1.79**
	DL	**1.9**

5.2.7 Goodput evaluation

Goodput is calculated from equation (5.3) in earlier section of this chapter. Proposed scheduler achieves greater cell goodput for UL and DL at **6.1 Mbps** and **6.25 Mbps**, respectively, as illustrated in figure 5.9. In comparison to current schedulers, our suggested scheduler delivers greater throughput and accurately received bits, these results verify its accuracy (table 5.3).

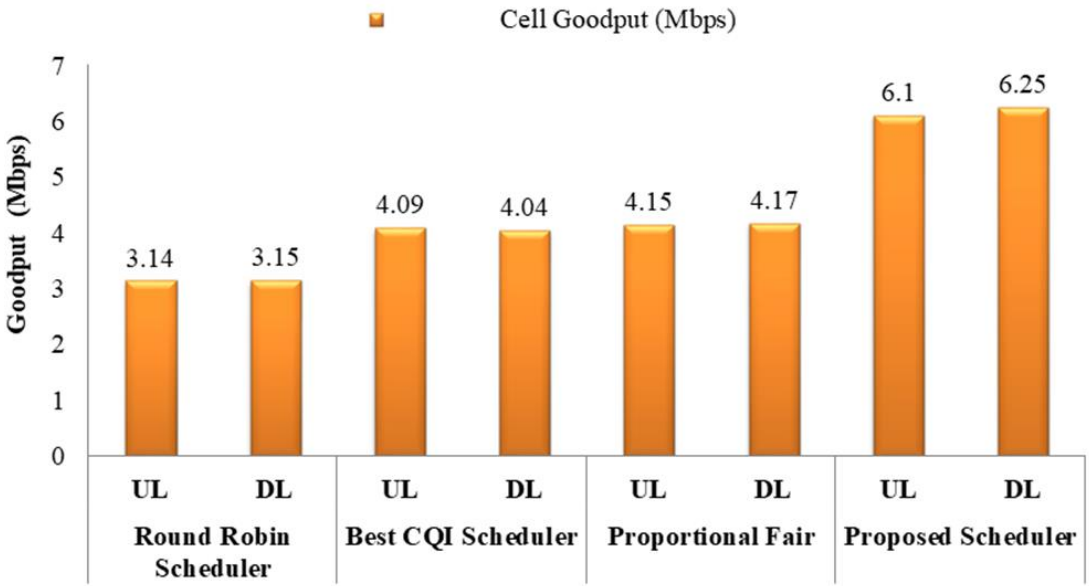


Figure 5.9: Goodput evaluation of different schedulers

Table 5.3 Goodput attained by UE III for UL & DL

Scheduler	UL/DL	Cell Goodput (Mbps)
Round Robin Scheduler	UL	3.14
	DL	3.15
Best CQI Scheduler	UL	4.09
	DL	4.04
Proportional Fair	UL	4.15
	DL	4.17
Proposed Scheduler	**UL**	**6.1**
	DL	**6.25**

5.2.8 Spectral efficiency

As per equation (5.4), Peak cell UL spectral efficiency is **2.84 bps/Hz** and DL spectral efficiency is **3.20 bps/Hz.** Our proposed adaptive channel scheduler provides highest achieved cell spectral efficiency among other schedulers in the order of **1.22 bps/Hz** and **1.25 bps/Hz** shown in figure 5.10 for UL and DL respectively. While rest of the schedulers, spectral efficiency is compared in Table 5.4. While overall performance metrics comparison of proposed scheduler with existing scheduling methods is given in table 5.5.

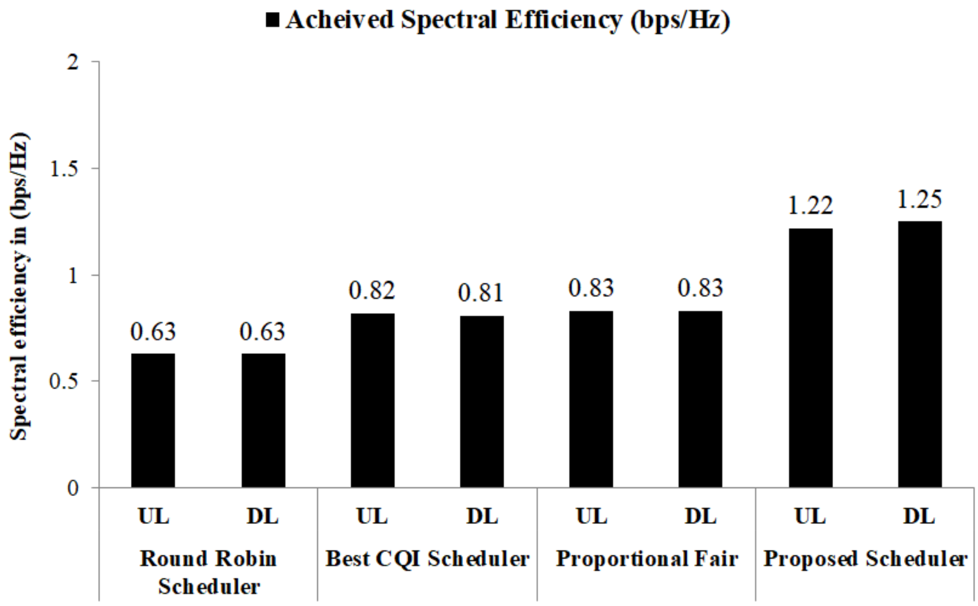


Figure 5.10: Achieved spectral efficiency

Table 5.4 Achieved spectral efficiency for UL & DL

Scheduler	**(UL)/ (DL)**	**Achieved Spectral Efficiency (bps/Hz)**
Round Robin Scheduler	UL	0.63
	DL	0.63
Best CQI Scheduler	UL	0.82
	DL	0.81
Proportional Fair	UL	0.83
	DL	0.83
Proposed Scheduler	**UL**	**1.22**
	DL	**1.25**

Table 5.5 Performance metrics comparison of proposed scheduler with existing scheduling methods

Scheduler	UL/ DL	Cell throughput in (Mbps)	Cell goodput in (Mbps)	Throughput for each user in (Mbps)			Goodput for each user in (Mbps)			Achieved spectral efficiency in (b/s/Hz)
				UE I	UE II	UE III	UE I	UE II	UE III	
RR	UL	3.45	3.14	1.99	0.9	0.56	1.85	0.80	0.49	0.63
	DL	3.37	3.15	1.94	0.9	0.52	1.82	0.84	0.49	0.63
Best CQI	UL	4.45	4.09	3.03	1.14	0.28	2.83	1.01	0.25	0.82
	DL	4.30	4.04	2.93	1.10	0.27	2.76	1.03	0.25	0.81
PF	UL	4.54	4.15	2.61	1.18	0.75	2.41	1.06	0.67	0.83
	DL	4.46	4.17	2.57	1.17	0.72	2.42	1.09	0.67	0.83
Proposed Scheduler	**UL**	**6.87**	**6.1**	**2.66**	**2.42**	**1.79**	**2.36**	**2.11**	**1.63**	**1.22**
	DL	**6.75**	**6.25**	**2.61**	**2.24**	**1.9**	**2.44**	**2.03**	**1.78**	**1.25**

5.2.9 Resource share percentage

Resource share percentage is calculated by equation (5.5) discussed earlier in chapter. Resource share percentage occupied by UE's for UL and DL using proposed scheduler is shown in figure 5.11. Similarly comparison with existing scheduling algorithm is given in table 5.6 for UL and DL respectively.

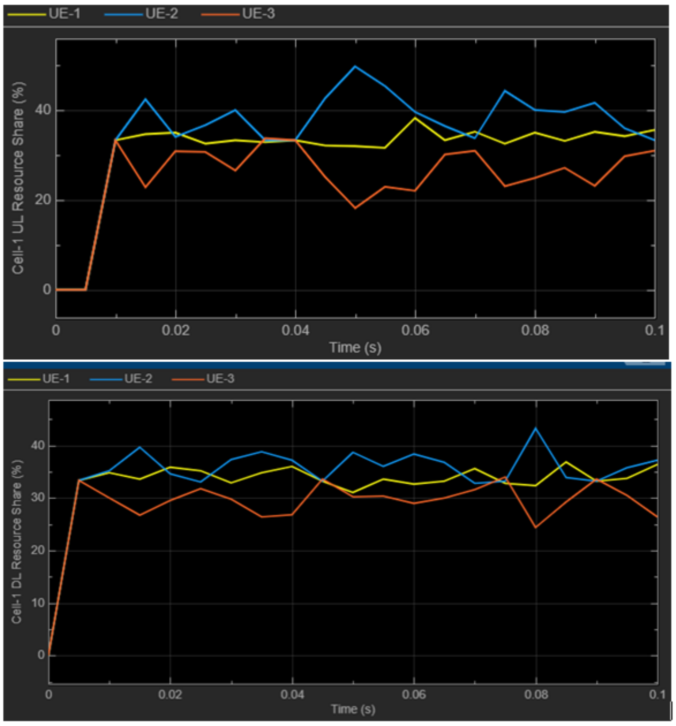


Figure 5.11: Resource share percentage of UEs

Table 5.6 Resources share occupied by UEs with different scheduling approaches

Scheduler	UL/DL	UE I	UE II	UE III
RR	UL	58.90%	25.48%	15.61%
	DL	57.78%	26.67%	15.56%
Best CQI	UL	69.20%	24.69%	6.11%
	DL	68.32%	25.50%	6.19%
PF	UL	58.21%	25.60%	16.18%
	DL	57.89%	26.8%	16.03%
Proposed Scheduler	UL	38.18 %	35.52%	**26.30%**
	DL	38.62%	33.19%	**28.15%**

The proposed scheduler provides fairness by allocating a higher percentage of resources to UE III compared to other scheduling approaches.

CHAPTER 6

CONCLUSION & FUTURE SCOPE

In this chapter, we will explore the concluding insights drawn from our study and outline potential avenues for future research.

6.1 Conclusion

Based on the comprehensive evaluation and analysis of the results obtained from our study, it is evident that the proposed scheduler represents a significant advancement in resource allocation for 5G networks. Through a careful design process and evaluation, we have demonstrated the superiority of our scheduler over conventional methods in terms of throughput, goodput, and spectral efficiency. The core objective of our proposed scheduler was to address the dynamic and heterogeneous nature of 5G networks by intelligently managing the allocation of radio resources to users. By incorporating both channel condition information and buffer status into the scheduling decision process, proposed algorithm achieves a fine balance between maximizing network throughput and ensuring fairness among users.

One of the key findings of our study is the clear distinction observed in throughput variations between conventional schedulers and our proposed approach. The proposed scheduler consistently outperforms traditional methods, delivering higher data rates and spectral efficiency while maintaining fairness and quality of service for all users. Furthermore, analysis reveals that the proposed scheduler provides significant improvements in data rates, particularly for cell edge users. By dynamically adapting resource allocation based on channel conditions, algorithm can mitigates the impact of fading and interference due to poor coverage, resulting in enhanced connectivity and user experience across the network. In comparison to existing scheduling methods found in the literature, as well as newly developed algorithms, our approach stands out as a more efficient and effective solution for 5G networks. Its ability to optimize resource allocation in real-time based on dynamic network conditions makes it well-suited for future deployments in diverse environments and use cases.

Future work could explore additional optimization techniques, integration with emerging technologies such as artificial intelligence and machine learning, and validation through field trials and real-world deployments.

In conclusion, our study underscores the importance of innovative scheduling algorithms in maximizing the performance and efficiency of 5G networks. The adaptive channel scheduler represents a significant step forward in this regard, offering a scalable, adaptive, and efficient solution for next-generation wireless communication systems.

6.2 Future work

(1) Enhanced scheduling algorithm: Our future research will concentrate on the development of an advanced scheduling algorithm aimed at further enhancing the achieved data rates and overall network performance. This algorithm will be designed to cater to the demanding requirements of eMBB and URLLC simultaneously, addressing the diverse needs of 5G networks in densely populated urban environments.

(2) Integration of emerging technologies: In our quest for improved scheduling efficiency, we will explore the integration of emerging technologies such as AI and ML. By leveraging AI/ML techniques, we aim to create a dynamic and adaptive scheduling framework capable of autonomously optimizing resource allocation based on real-time network conditions and user requirements.

(3) Multi-objective optimization: Recognizing the multi-faceted nature of 5G networks, our future work will focus on multi-objective optimization approaches for scheduling. We will seek to balance competing objectives such as maximizing throughput, minimizing latency, and ensuring fairness among users, thereby achieving a harmonious trade-off across diverse network metrics.

(4) Edge computing and network slicing: As edge computing and network slicing emerge as pivotal technologies in 5G and beyond, we will explore their integration into our scheduling framework. By harnessing the capabilities of edge computing and network slicing, we aim to create tailored scheduling solutions that cater to specific service requirements and application scenarios, ensuring optimal resource utilization and quality of service.

(5) Validation through field trials: In addition to theoretical development, our future research will involve validation through extensive field trials and real-world deployments. Collaborating with industry partners and network operators, we will conduct comprehensive field tests to evaluate the performance and scalability of our scheduling algorithm in diverse deployment scenarios, including urban, suburban, and rural environments.

(6) 6G scheduling algorithm design: Looking further ahead, we envision extending our research efforts to the design and development of scheduling algorithms for future 6G networks. By anticipating the evolving requirements and challenges of next-generation wireless communication systems, we will strive to innovate and create cutting-edge scheduling solutions capable of meeting the demands of future wireless networks.

In summary, our future endeavours will focus on pushing the boundaries of scheduling algorithm design in 5G networks, with the ultimate goal of achieving unprecedented levels of efficiency, reliability, and performance. Through a combination of theoretical research, practical experimentation, and industry collaboration, we aim to set the way for the evolution of wireless communication towards a more connected, intelligent, and responsive future.

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APPENDIX A

A1. Parameters configuration

```
rng('default'); % Reset the random number generator
simParameters = []; % Clear simParameters variable
simParameters.NumFramesSim = 10; % Simulation time in terms of number of 10 ms frames
simParameters.SchedulingType = 1; % Set the value to 0 (slot-based scheduling) or 1 (symbol-based scheduling)
simParameters.NumUEs = 3;
% Assign position to the UEs assuming that the gNB is at (0, 0, 0). N-by-3
% matrix where 'N' is the number of UEs. Each row has (x, y, z) position of a
% UE (in meters)
simParameters.UEPosition = [15 0 0;
                            40 0 0;
                            90 0 0;];
```

```
simParameters.NumRBs = 25;
simParameters.SCS = 15; % kHz
simParameters.DLBandwidth = 5e6; % Hz
simParameters.ULBandwidth = 5e6; % Hz
simParameters.DLCarrierFreq = 3.5e9; % Hz
simParameters.ULCarrierFreq = 3.5e9; % Hz
simParameters.DLULPeriodicity = 5; % Duration of the DL-UL pattern in ms
simParameters.NumDLSlots = 2; % Number of consecutive full DL slots at the beginning of each DL-UL pattern
simParameters.NumDLSyms = 8; % Number of consecutive DL symbols in the beginning of the slot following the last full DL slot
simParameters.NumULSyms = 4; % Number of consecutive UL symbols in the end of the slot preceding the first full UL slot
simParameters.NumULSlots = 2; % Number of consecutive full UL slots at the end of each DL-UL pattern
simParameters.SchedulerStrategy = 'AdaptiveChannelScheduler'; % custom scheduling
simParameters.TTIGranularity = 4;
simParameters.RBAllocationLimitUL = 15; % For PUSCH
simParameters.RBAllocationLimitDL = 15; % For PDSCH
simParameters.BSRPeriodicity = 1; % Buffer status report transmission periodicity (in ms)
simParameters.PUSCHPrepTime = 200; % In microseconds
simParameters.ChannelUpdatePeriodicity = 0.2; % In sec
simParameters.CQIDelta = 1;
```

A2. DL/ UL Pattern and RB visualisation

```
simParameters.DMRSTypeAPosition = 2; % Type-A DM-RS position as 2 or 3
% PUSCH DM-RS configuration
simParameters.PUSCHDMRSAdditionalPosTypeB = 0;
simParameters.PUSCHDMRSAdditionalPosTypeA = 0;
simParameters.PUSCHDMRSConfigurationType = 1;
% PDSCH DM-RS configuration
simParameters.PDSCHDMRSAdditionalPosTypeB = 0;
simParameters.PDSCHDMRSAdditionalPosTypeA = 0;
simParameters.PDSCHDMRSConfigurationType = 1;
% Set the periodic DL and UL application traffic pattern for UEs
dlAppDataRate = 16e4*ones(simParameters.NumUEs,1); % DL application data rate in kilo bits per second (kbps)
ulAppDataRate = 16e4*ones(simParameters.NumUEs,1); % UL application data rate in kbps
% Validate the DL application data rate
validateattributes(dlAppDataRate, {'numeric'},{'nonempty','vector','numel',simParameters.NumUEs,'finite','>',0}, ...
    'dlAppDataRate','dlAppDataRate');
% Validate the UL application data rate
validateattributes(ulAppDataRate,{'numeric'},{'nonempty','vector','numel',simParameters.NumUEs,'finite','>',0}, ...
    'ulAppDataRate', 'ulAppDataRate');
simParameters.CQIVisualization = true;
simParameters.RBVisualization = true;
enableTraces = true;
simParameters.NumMetricsSteps = 20;
parametersLogFile = 'simParameters'; % For logging the simulation parameters
simulationLogFile = 'simulationLogs'; % For logging the simulation traces
```

APPENDIX B

B1. RLC channel and CQI configuration

```
numLogicalChannels = 1;
simParameters.LCHConfig.LCID = 4;
simParameters.RLCConfig.EntityType = 2;
lchInfo = repmat(struct('RNTI',[],'LCID',[],'EntityDir',[]), [simParameters.NumUEs 1]);
for idx = 1:simParameters.NumUEs
    lchInfo(idx).RNTI = idx;
    lchInfo(idx).LCID = simParameters.LCHConfig.LCID;
    lchInfo(idx).EntityDir = simParameters.RLCConfig.EntityType;
end
rlcChannelConfigStruct.LCGID = 1; % Mapping between logical channel and logical channel group ID
rlcChannelConfigStruct.Priority = 1; % Priority of each logical channel
rlcChannelConfigStruct.PBR = 8; % Prioritized bitrate (PBR), in kilobytes per second, of each logical channel
rlcChannelConfigStruct.BSD = 10; % Bucket size duration (BSD), in ms, of each logical channel
rlcChannelConfigStruct.EntityType = simParameters.RLCConfig.EntityType;
rlcChannelConfigStruct.LogicalChannelID = simParameters.LCHConfig.LCID;
simParameters.maxRLCSDULength = 9000;
maxUECQIs = zeros(simParameters.NumUEs, 1); % To store the maximum achievable CQI value for UEs
```

B2. gNB setup

```
gNB = hNRGNB(simParameters);

        scheduler = hNRSchedulerAdaptiveChannelscheduler(simParameters);

addScheduler(gNB, scheduler); % Add scheduler to gNB

gNB.PhyEntity = hNRGNBPassThroughPhy(simParameters); % Add passthrough PHY
configurePhy(gNB, simParameters);
setPhyInterface(gNB); % Set the interface to PHY layer
UEs = cell(simParameters.NumUEs, 1);
for ueIdx = 1:simParameters.NumUEs
    simParameters.Position = simParameters.UEPosition(ueIdx, :); % Position of the UE
    UEs{ueIdx} = hNRUE(simParameters, ueIdx);
    UEs{ueIdx}.PhyEntity = hNRUEPassThroughPhy(simParameters, ueIdx); % Add passthrough PHY
    configurePhy(UEs{ueIdx}, simParameters);
    setPhyInterface(UEs{ueIdx}); % Set the interface to PHY layer

    % Initialize the UL CQI values at gNB scheduler
    channelQualityInfoUL = struct('RNTI', ueIdx, 'CQI', simParameters.InitialChannelQualityUL(ueIdx, :));
    updateChannelQualityUL(gNB.MACEntity.Scheduler, channelQualityInfoUL);


    % Initialize the DL CQI values at gNB scheduler
    channelQualityInfoDL = struct('RNTI', ueIdx, 'CQI', simParameters.InitialChannelQualityDL(ueIdx, :));
    updateChannelQualityDL(gNB.MACEntity.Scheduler, channelQualityInfoDL);

    % Initialize the DL CQI values at UE for packet error probability estimation
    updateChannelQualityDL(UEs{ueIdx}.MACEntity, channelQualityInfoDL);

    % Setup logical channel at gNB for the UE
    configureLogicalChannel(gNB, ueIdx, rlcChannelConfigStruct);
    % Setup logical channel at UE
    configureLogicalChannel(UEs{ueIdx}, ueIdx, rlcChannelConfigStruct);

    % Create an object for On-Off network traffic pattern and add it to the
    % specified UE. This object generates the uplink (UL) data traffic on the UE
    ulApp = networkTrafficOnOff('GeneratePacket', true, ...
        'OnTime', simParameters.NumFramesSim/100, 'OffTime', 0, 'DataRate', ulAppDataRate(ueIdx));
    UEs{ueIdx}.addApplication(ueIdx, simParameters.LCHConfig.LCID, ulApp);

    % Create an object for On-Off network traffic pattern for the specified
    % UE and add it to the gNB. This object generates the downlink (DL) data
    % traffic on the gNB for the UE
    dlApp = networkTrafficOnOff('GeneratePacket', true, ...
        'OnTime', simParameters.NumFramesSim/100, 'OffTime', 0, 'DataRate', dlAppDataRate(ueIdx));
    gNB.addApplication(ueIdx, simParameters.LCHConfig.LCID, dlApp);
end
```

B.3 Simulation

```
% Calculate the simulation duration (in seconds) from 'NumFramesSim'
simulationTime = simParameters.NumFramesSim * 1e-2;
% Run the simulation
run(networkSimulator, simulationTime);
displayPerformanceIndicators(metricsVisualizer);
metrics = getMetrics(metricsVisualizer);
```

PUBLICATIONS

1. Shubham, S. Pandit, and A. Kumar, "Adaptive Channel Aware Scheduler for 5th Generation Networks," International Conference on Integrated Circuits, Communication, and Computing Systems (ICIC3S-2024). [Accepted]

2. Shubham, S. Pandit, and A. Kumar, " A survey on resource allocation challenges in URLLC and MEC networks". [Communicated]

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RESOURCE ALLOCATION AND ADAPTIVE CHANNEL SCHEDULING FOR 5G NEW RADIO

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