DEVELOPING NOVEL RADIO RESOURCE MANAGEMENT TECHNIQUES FOR 5G AND BEYOND

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We certify that we have read this dissertation and that in our opinion it is fully adequate, in scope and in quality, as a dissertation for the degree of Doctor of Philosophy.

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ABSTRACT

DEVELOPING NOVEL RADIO RESOURCE MANAGEMENT TECHNIQUES FOR 5G AND BEYOND

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Application richness and the level of technological development have increased extraordinarily in the last ten years in the field of modern wireless communications. There is a need for a flexible communications infrastructure that can meet different requirements in the current and future wireless systems. Radio resource management (RRM) is one of the important parts for the flexibility. RRM units play crucial roles to provide a flexible infrastructure.

This dissertation is mainly focussed on the waveform parameter assignment and optimization subjects. Also, scheduling and user association topics are studied with the waveform parameter assignment. Moreover, waveform design subjects are studied in detail and a new generalized definition is made for the waveform design. Fifth-Generation (5G) New Radio (NR) is analyzed from these perspectives and several novel RRM techniques are proposed.

5G NR comes with more waveform parameters than the previous generations. Moreover, there are new problem sources like inter-numerology interference (INI). The importance of controlling mechanisms in MAC layer increase. Through multi-numerology based 5G systems, waveform studies become directly related with parameter optimization, scheduling, resource allocation and radio access network (RAN) slicing.

Waveform design fundamentals and waveform parametrization topics are studied in a tutorial format during two chapters. After that, a novel waveform parameter assignment framework, a machine learning (ML) based approach, and various resource management techniques are proposed. All of these frameworks and methods are developed considering the compatibility with 5G NR standards.

Keywords: 5G, interference, machine learning, numerology, resource management, waveform.

ÖZET

5G VE SONRASI İÇİN ÖZGÜN RADYO KAYNAK YÖNETİMİ TEKNİKLERİNİN GELİŞTİRİLMESİ

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Modern kablosuz haberleşme alanında uygulama zenginliği ve teknolojik gelişmişlik düzeyi son on yılda olağanüstü derecede artmıştır. Mevcut ve gelecekteki kablosuz sistemlerde farklı gereksinimleri karşılayabilecek esnek bir iletişim altyapısına ihtiyaç bulunmaktadır. Radyo kaynak yönetimi (RRM) bu esnekliğin önemli parçalarından biridir. RRM üniteleri esnek bir altyapı sağlamak için önemli roller oynamaktadır.

Bu tez çalışması temel olarak dalga şekli parametre atama ve optimizasyonu konularına odaklanmıştır. Ayrıca, zamanlama ve kullanıcı ilişkilendirme konuları dalga şekli parametre ataması ile beraber incelenmiştir. Ayrıca, dalga şekli tasarım konuları detaylı olarak incelenerek dalga şekli tasarımına genel bir tanımlama yapılmıştır. Beşinci Nesil (5G) Yeni Radyo (NR) bu perspektiflerden analiz edilmiş ve yenilikçi RRM teknikleri önerilmiştir.

5G NR, önceki nesillere göre daha fazla dalga şekli parametresi ile birlikte gelmektedir. Ayrıca, numerolojiler arası girişim (INI) gibi yeni problem kaynakları da oluşmaktadır. MAC katmanındaki kontrol mekanizmalarının önemi artmıştır. Çoklu numeroloji tabanlı 5G sistemleri aracılığıyla, dalga şekli çalışmaları, parametre optimizasyonu, zamanlama, kaynak tahsisi ve radyo erişim ağı (RAN) dilimleme ile doğrudan ilişkili bir hale gelmiştir.

Dalga şekli tasarım temelleri ve dalga şekli parametrelendirme konuları iki bölüm boyunca öğretici bir formatta incelenmektedir. Sonraki kısımlarda, yenilikçi bir dalga şekli parametre atama çerçevesi, makine öğrenimi (ML) tabanlı bir yaklaşım ve çeşitli yenilikçi kaynak yönetimi teknikleri önerilmektedir. Bu çerçevelerin ve yöntemlerin tümü 5G NR standartlarıyla uyumlu olmaları gözetilerek geliştirilmiştir.

Anahtar sözcükler: 5G, girişim, makine öğrenmesi, numeroloji, kaynak yönetimi, dalga şekli.

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Chapter 1

Introduction

1.1 Motivation

In the old wireless communication standards, we have only a limited number of applications and services due to technological limits and old trends during those years. Nevertheless, the current and new generation of communication systems are being developed by considering diverse applications and use-cases [1]. Application richness and the level of technological development have increased extraordinarily in the last ten years in the field of modern wireless communications. As shown in Figure 1.1, we are witnessing a wide variety of appplications nowadays including broadband and media everywhere, smart vehicles and transport, critical services and infrastructure control, critical control of remote devices, human machine interaction, and sensors networks. There is a need for a flexible communications infrastructure that can meet different application requirements in the current and future wireless systems [2–4].

The meaning of flexible term includes adaptive, dynamical, configurable, scalable, cognitive, intelligent, adjustable, tunable, programmable, and so on. In the previous generation communications, flexibility terms used in a limited framework. However, they are included in all of the current communications studies

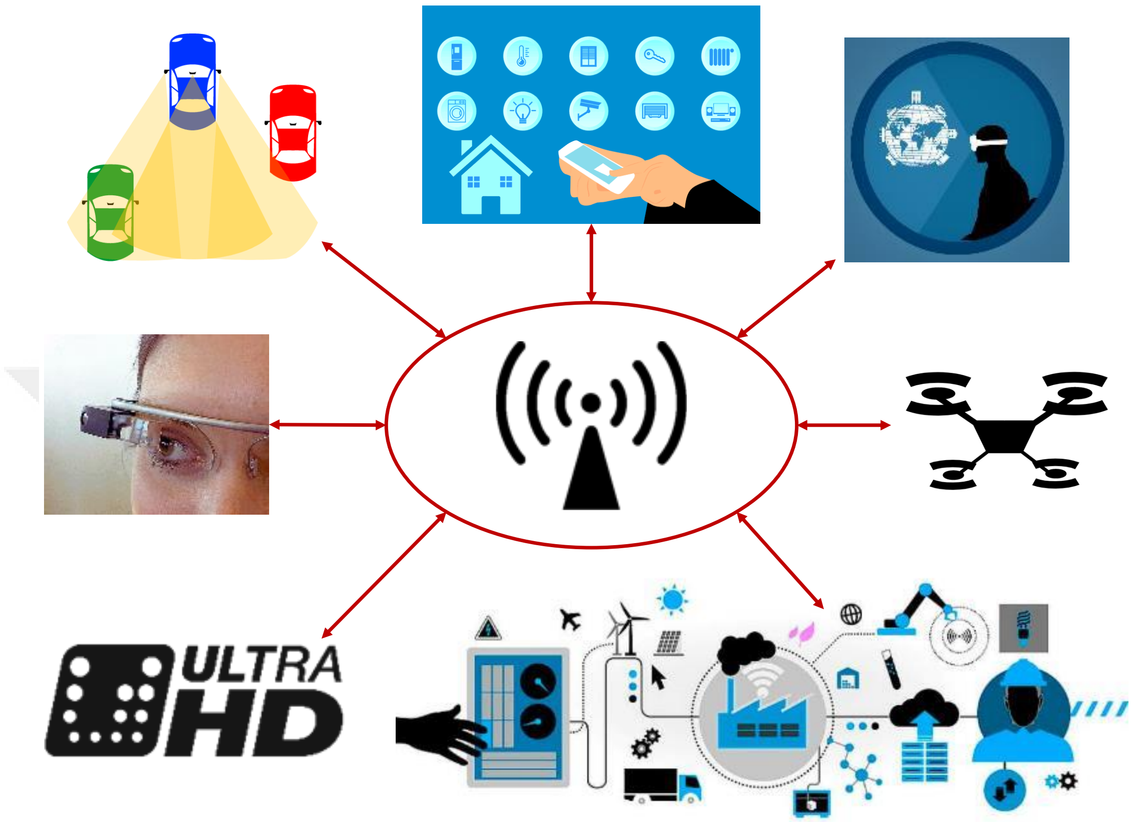


Figure 1.1: Application richness and diversity for new generation communications systems.

nowadays. New generation communications standards are constituted based on a wide variety of wireless communications applications, user conditions and new use cases that are emerged in the last years thanks to the flexible infrastructure of 5G systems [5–7].

Radio resource management (RRM) is one of the important parts for the flexibility in wireless communications systems. As shown in Fig. 1.2, there can be several RRM units in the communications systems. Scheduling and user association, resource allocation and network virtualization are also the part of Long-Term Evolution (LTE) communications systems. However, waveform parameter assignment and radio access network (RAN) slicing are new concepts that come with 5G New Radio (NR). All of the RRM units play crucial roles to provide a flexible infrastructure. Cellular communications standards give an implementation flexibility for the RRM units with some rules. Several inputs such as application

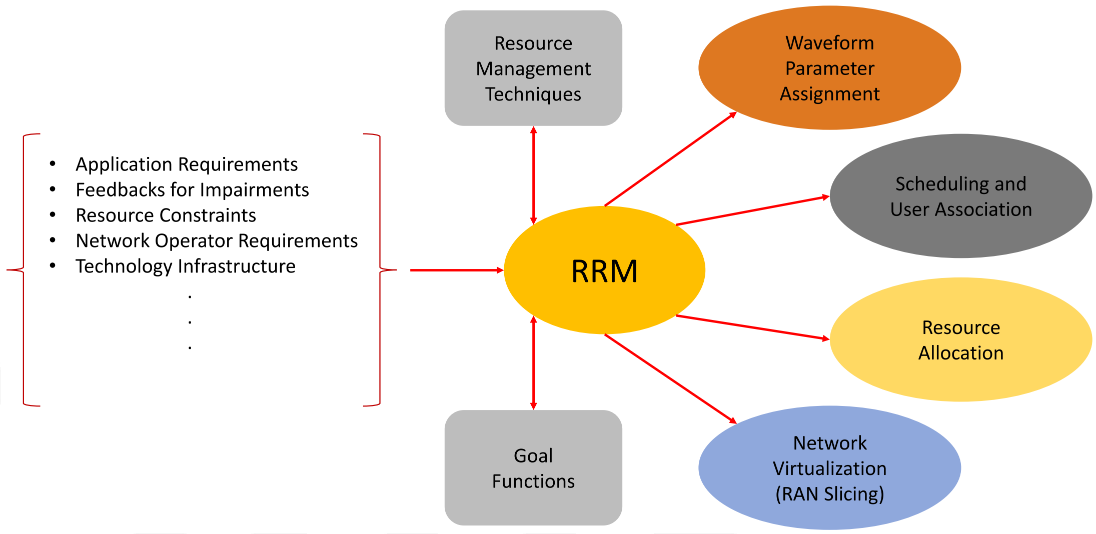


Figure 1.2: Relationships for the Radio Resource Management.

requirements, feedbacks for the impairments, resource constraints, network operator requirements, available technologies, etc. can be used by the RRM units. Goal functions may change under different scenarios. Also, different resource management techniques can be applied case to case.

It is possible to enhance the quality of service (QoS) for a communications system by just employing effective RRM techniques. The role of RRM increases more for the multi-user resource management under different requirements of the users. Since 5G NR gives a rich requirement flexibility by several service types (use cases), RRM plays the one of leading roles in 5G systems. However, this resource management role should be handled very carefully. And, it is not an easy task to provide a perfect resource management. The main motivation of this dissertation is to make contributions for the RRM units of 5G and beyond communications technologies.

1.2 Scope of the Dissertation

This dissertation is mainly focussed on the waveform parameter assignment subjects. Also, scheduling and user association topics are studied with the waveform parameter assignment. Moreover, waveform design subjects are studied in detail. 5G is analyzed from these perspectives and several RRM techniques are proposed.

There are different requirements associated with the applications, use cases, channel structure, network and user in 5G systems. To meet all of the requirements, several new configurable parameters are defined in 5G NR. It is possible that 6G will have even higher number of configurable parameters based on new potential conditions. In line with this trend, configurable waveform parameters are also varied and this variation will increase in beyond 5G considering the potential future necessities. In this dissertation, association of users and possible configurable waveform parameters in a cell is discussed.

The number of configurable parameters at a transmission point (TP) is increasing with every new generation of cellular communications. There are 500, 1000, and 1500 configurable parameters in 2G, 3G, and 4G TPs, respectively [8]. In line with this trend, it is evident that 5G and 6G nodes will have an even higher number of configurable parameters. The reason for this rise includes more use cases, diverse channel structures, complex and heterogeneous networks, different user-cell association capabilities, and the other possible requirements. A flexible structure is constituted with a rich set of parameter options to simultaneously meet different requirements in 5G NR [3]. Compared to 5G, 6G will need to meet more requirements [7, 9–11] with a large number of configurable parameters.

For the future prediction of the number of configurable parameters, the coexistence of different standards such as Wi-Fi and 6G systems should also be taken into account [6]. Similarly, radar sensing and 6G may complement each other in the future [12]. Different standards constitute a very large set of requirements and configurable parameters together under the leadership of 6G.

Waveform is one of the core components of the physical layer (PHY) design. Generally, the waveform is designed considering the whole communications system. It is like the heart of the communications. The other components are designed considering the chosen waveform in standards. The waveform design is strongly related with application, channel, user conditions, RF front-end, MAC design and the higher layers of the communication stack. This dissertation also aims to describe the role of the waveform design in wireless communications.

Multi-numerology concept is defined in 5G NR standardization to increase flexibility from the waveform perspective. Besides, scheduling and resource allocation become more related with the waveform design thanks to the multi-numerology concept. However, frame flexibility brings more load at a scheduler [4]. There are more waveform parameter options that can be configured by the scheduler in NR compared to Long-Term Evolution (LTE) [8]. Hence, the multi-numerology structures are studied in the dissertation.

1.3 Dissertation Contributions

In this dissertation, the following contributions are done for each chapters.

- Chapter 2
  1. Generalized definition of the waveform is constituted and fundamental concepts are introduced for the waveform design.
  2. Several relationships for the waveform design are investigated.
  3. Analysis of the trade-off situations for different structures of multiple numerologies is provided.
  4. Impact of the waveform design on radio access technologies (RATs) are discussed.
- Chapter 3
  1. New concepts introduced in NR are described regarding to 3GPP Release 15 and possible implementation issues are discussed.
  2. Building blocks of LTE and NR were compared from the flexibility perspective regarding to 3GPP 38-series standardization documents.

3. Research opportunities for multi-numerology systems are presented with a structured manner.
4. Non-orthogonality of multiple numerologies is analyzed.
5. Through computer simulations, INI and SIR results as a function of multi-numerology parameters, guard allocation and user power levels are obtained.

- Chapter 4

1. Waveform parameter assignment concept is introduced by employing the available waveform design more efficient without designing a new waveform.
2. Several subproblems are defined related with the waveform parameter assignment and optimization.
3. Waveform parameter assignment literature is reviewed from the multi-numerology perspective.
4. Case studies for the optimizations in numerology assignment, waveform processing, and joint methods are discussed to reveal the relationships between multi-numerology concept and waveform parameter assignment in 5G NR.
5. Possible waveform parameters are investigated from the 6G perspectives with compared to 5G NR.
6. A general framework is constituted for waveform parameter assignment problems.
7. The role of ML is defined under the proposed framework for waveform parameter assignment and optimization.
8. A case study with ML is provided for the optimal parameter subset decisions.
9. A simulation based dataset generation methodology is proposed together with the given case study.
10. A new flexibility metric is developed as a new performance metric.

11. A novel heuristic method is designed to decide on "the efficient number of mixed numerologies", and control overheads that are caused by multi-numerology structures.

- Chapter 5

    1. Fractional numerology domain (FND) scheduling and power difference based (PDB) scheduling concepts are proposed.
    2. Three ideas are proposed under INI-aware resource allocation based scheduling concepts: 1) Protecting uRLLC users from INI more than the other users. 2) Protecting cell edge users from INI more than the other users. 3) Increasing fairness for the edge subcarriers of multiple numerologies.

1.4 Dissertation Outline

Chapter 1 provides the motivation, scope, contributions and outline of the dissertation. In Chapter 2, fundamentals of the waveform design is presented with a generalized definition, several relationships, and flexible design guidelines for RATs. In Chapter 3, flexible 5G NR waveform frame is introduced as an example design and research opportunities for multi-numerology waveforms are discussed. In Chapter 4, a waveform parameter assignment framework is proposed and then various novel techniques are explained with all details. In Chapter 5, a novel resource management algorithm is introduced to enhance reliability using inter-numerology interference (INI) awareness. Finally, Chapter 6 concludes the dissertation along with investigating future directions on RRM techniques. Relationships between the main chapters are demonstrated in Fig. 1.3.

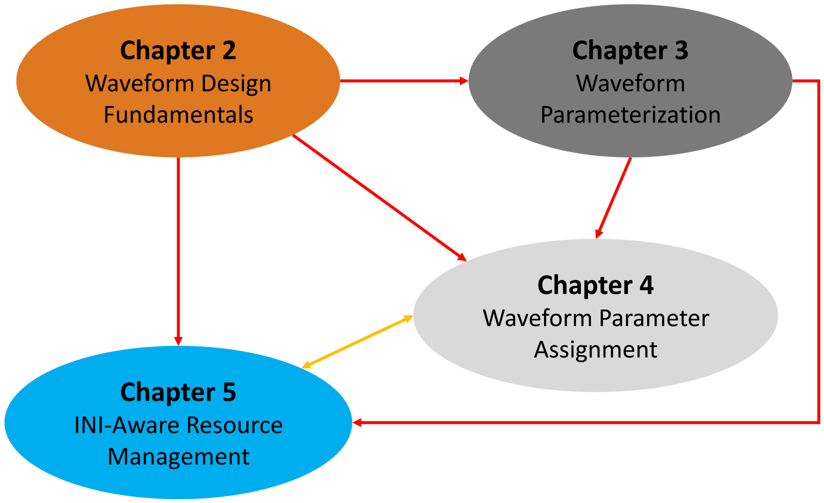


Figure 1.3: The relationships of the chapters under this dissertation.

1.5 Publications

The following publications are used while constituting the content of the chapters in this dissertation.

- Chapter 2 is prepared mostly based on the publication in [13].
- Chapter 3 is prepared mostly based on the publication in [14].
- Chapter 4 is prepared based on the publications in [15], [16], [17], and [4].
- Chapter 5 is prepared based on the publication in [18].

Chapter 2

Waveform Design Fundamentals

In this chapter, fundamental concepts are introduced for the waveform design. Generalized definition of the waveform is given to provide a basis for the discussions in the next chapters. Several relationships for the waveform design are investigated and then application requirements of different wireless communications standards are discussed. Impact of the waveform design on radio access technologies (RAT) are examined.

2.1 Introduction to Waveform Design

2.1.1 The Generalized Definition of the Waveform

The main components of a waveform are defined in this section to understand concept of the waveform design in a better way. Basically, waveform is a physical signal that contains information. Data bits are mapped to the physical signal through a proper waveform. Also, additional symbols (e.g., redundancy, preconditioning like precoding and guard utilization, noise, etc.) are the parts of the physical signal. These signals occupy physical resources (like bandwidth, time, space, code, power, etc.) in multi-dimensional hyperspace. Figure 2.1 shows the

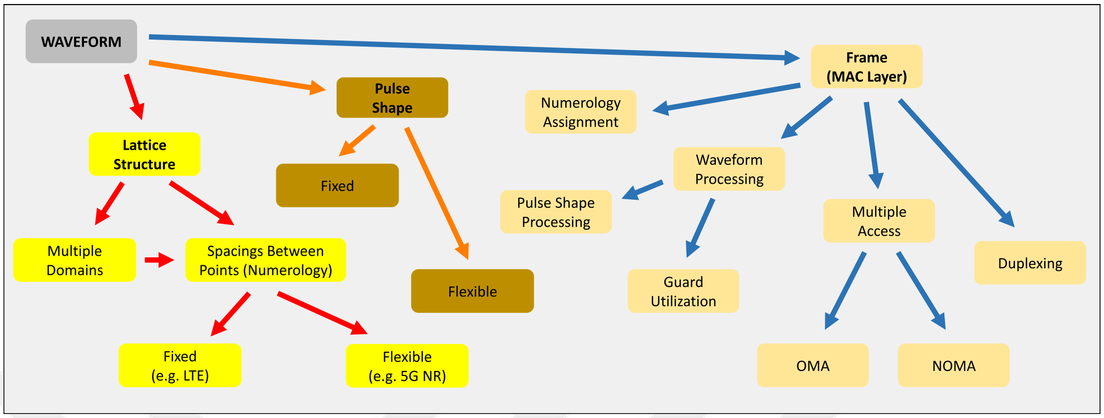


Figure 2.1: The main components of the waveform design.

main components of a waveform design including lattice structure, pulse shape and frame structure.

Lattice structure is a multi-dimensional resource mapping and each point show a location of one resource element [19]. The resource element is the smallest discrete part that contains physical signal on a lattice structure. For example, the resource element is one symbol and one subcarrier for fifth generation (5G) New Radio (NR) in time-frequency planes, respectively. The possible spacings between lattice points give numerology structures for a waveform. Lattice structure can be uniform or non-uniform. If the lattice structure is uniform, it means that lattice spacings are fixed and there is a single-numerology waveform. For example, the spacings between Long Term Evolution (LTE) lattice points are fixed and LTE employs a single-numerology waveform. However, 5G NR uses a flexible non-uniform lattice structure that indicates multiple numerologies. Additionally, both of LTE and 5G NR use a multi-dimensional lattice on time-frequency planes. More dimensions can be possible in the future communications systems.

Pulse shape (also known as filter) gives the main characteristic to a waveform by deciding how to transmit the symbols on lattice points [19]. As a result, waveform defines the physical shapes that contains energy in the hyperspace. The variances of energy in the hyperspace give the localization of a pulse shape. Moreover, correlation between the lattice points is determined by the pulse shapes [19]. This correlation and the localization show the orthogonality of a waveform design. In the literature, the following filters are utilized while designing waveforms [19]: Rectangular, hanning (raised-cosine), exact hamming, exact blackman, tapered-cosine-in-time, tapered-cosine-in-frequency, root-raised-cosine, Mirabbasi-Martin, prolate, optimal finite duration pulses, Kaiser, modified Kaiser, Gaussian, IOTA, Hermite, and extended Gaussian. These pulse shapes have different localization characteristics.

Frame structure can be defined as a packaging (formation) of multiple user information because waveform is the process of generating the collective pysical signal corresponding to multiple users (and/or multiple information data) that occupies the hyperspace. Waveform characterizes the multiple-access scheme using the frame structure. The multiple-access scheme controls the sharing of resources by multiple users and multiple shapes in the hyperspace. Individual pulse shapes are combined under a frame structure to form a waveform. The frame controls the interaction between the pulse shapes by utilizing waveform processing. For example, lattice points can be used as guard intervals if it is beneficial for the overall performance of a waveform design. The lattice points do not need to carry data and they are controlled by the frame structure. The waveform frame is constituted by the scheduling units in a communications systems. Within this context, numerology assignment, waveform processing (pulse shape processing and guard utilization), orthogonal multiple access (OMA), non-orthogonal multiple access (NOMA) and duplexing decisions are applied via frame structure of a waveform design.

2.1.2 Waveform Relationships of Channel and RF Impairments

Example interactions between several requirements, communications layers, channel structure and core technologies are shown in Figure 2.2. They are all connected to each other strongly with important relationships. If the waveform can be related with the other parts of communications, then the overall system can be

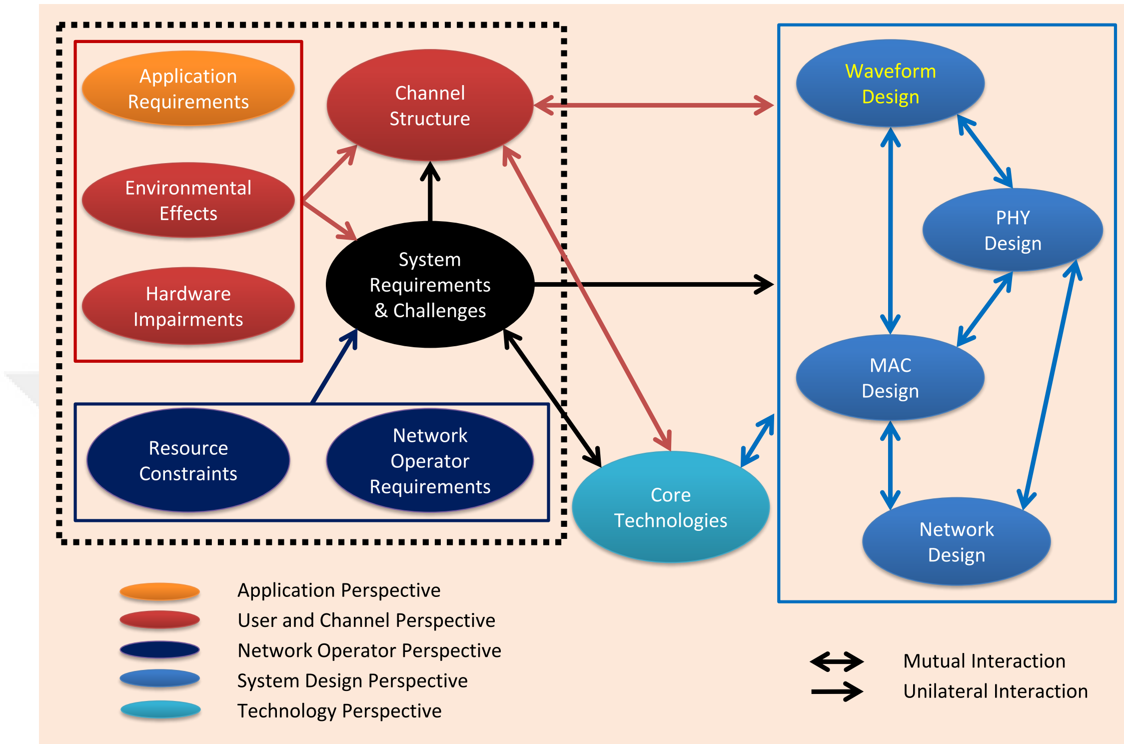


Figure 2.2: Relationships between the requirements and several communications layers.

designed properly. For the relationships, effects of wireless channel and RF hardware impairments are discussed in this section. Application requirements and impacts of the waveform design on RATs are investigated in the next sections.

There are several relationships of MAC and network layers with the waveform design as shown in Figure 2.2. MAC layer decides distribution of resources among the users. It controls the resource allocation and scheduling mechanisms together with the waveform frames [18]. As an example relation for the network layer, if there are overlapping in any lattice domain of a waveform design, synchronization can be difficult in this domain. Overlapping can cause an interference if there is a misalignment in anyway. Therefore, synchronous networks have problems with the waveform designs that have overlapping in any lattice domain.

User requirements are other important aspects for the system designs in 5G and beyond. The user requirements include various constraints which can be described as wireless channel conditions and RF-hardware impairments. Some of these effects can be given as 1) Doppler spread, 2) multipath effects, 3) path loss, 4) phase noise, 5) frequency offset, 6) power amplifier (PA) non-linearity. This list may be improved to include other impairments in the future. We assumed that all these impairments are provided as feedbacks via channel quality information and other similar systems.

The waveform design has strong relations with the **wireless channel**. First of all, single-carrier and multi-carrier waveform designs have different impacts on the channel. Single-carrier waveforms use whole bandwidth (BW) for one carrier. If transmission BW is larger than coherence BW, the channel becomes frequency-selective. In multi-carrier waveforms, transmission BW are divided into subcarriers. If narrow bands are less than coherence BW, a flat response is received from each portion of the BW. Additionally, the lower limit of subcarrier spacing is generally determined with the coherence time to handle inter-carrier interferene (ICI) [20]. Single-carrier waveforms are better with respect to Doppler spread. Hence, it is better to prefer single-carrier waveforms for a time-selective channel (dispersive in frequency domain). On the other hand, multi-carrier waveforms can be used for frequency-selective channels (dispersive in time domain).

For example, if there is a selectivity in frequency, localized pulses in frequency domain need to be used for the waveform design. If there is a selectivity in time, then localized pulses in time domain need to be used. As a last example, if there is a selectivity in space, the waveform design needs localized beams in angular domain. Depending on the channel requirements, a proper trade-off has to be done to design a suitable waveform.

If the channel impairments are to be addressed, then a larger subcarrier spacing is needed to be used for the high Doppler spread which is a result of mobility, multipath, and angular spread. Furthermore, a longer CP duration is a need for the scenarios with long delay spreads. Additionally, the low number of subcarriers is needed for high path loss scenarios because the high number of subcarriers results in high PAPR values which is not a good condition for PA usage. Basically, the key necessities of the channel impairments can be achieved in this way.

Understanding the relation between **RF impairments** and waveform is critical for the design of proper waveforms. Within this context, single-carrier and multi-carrier waveform designs have different significant effects on the RF impairments. For multi-carrier waveforms, the increasing number of subcarriers results with more power amplifier (PA) non-linearities. PAs are not linear in nature, they show non-linearities after specific thresholds for the input powers. PA non-linearities cause in-band interference (IBI) and interference with neighboring band that constitutes out-of-band emission (OOBE). For single-carrier waveforms, PA non-linearities increase as roll-off factor decreases or modulation order increases.

As another RF impairment, phase noise affect the single-carrier waveforms with time varying and correlated noise. Besides, phase noise causes ICI for the multi-carrier waveforms. It is an important problem especially in high frequencies. Moreover, the effect of sample timing offset (STO) is different on single-carrier waveforms and multi-carrier waveforms. Loss of the optimal sampling phase is the problem caused by STO in single-carrier waveforms. For multi-carrier waveforms, STO causes ICI. In [21], different waveforms are compared from the carrier frequency offset (CFO) together with the in-phase and quadrature (IQ) imbalance perspectives. Non-identical amplitudes and not fixed 90 degree phase difference between I-branch and Q-branch lead to IQ imbalance. Ideally, I and Q should be orthogonal. Single-carrier waveforms are generally more robust against the IQ imbalance problems because of the ability of better spectrum controlling.

For the RF-hardware impairments, a larger subcarrier spacing is a necessity for the high phase noise and frequency offset. Moreover, the low number of subcarriers is a solution for high PA non-linearity to restrain high PAPR values like in the high path loss scenario. For the necessity of the low number of subcarriers, larger subcarrier spacings can be preferred.

There are various wireless communications scenarios, and service requirements according to ETSI 3GPP documents [22]. These scenarios include 1) indoor hotspot, 2) dense urban, 3) rural, 4)urban macro, 5) high speed, 6) extreme long distance coverage in low density areas, 7) urban coverage for massive connection, 8) highway, 9) urban grid for connected car, 10) commercial air to ground, 11) light aircraft, 12) satellite extension to terrestrial. In [22], the given scenarios are discussed and some detailed scenario parameters are provided for 5G systems. These parameters are also used in the remaining part of this thesis when needed. Different scenarios change the weights of different requirement parameters related to the services and users in the coverage area of a system.

2.1.3 Waveform Relationships of Application Requirements

A detailed analysis is presented for the requirements of use cases and standards for wireless communications in this section. Cellular and Wi-Fi, namely IEEE 802.11 family of standards, communications are discussed. Applications are mapped to the requirements for the standards of cellular and Wi-Fi communications.

In LTE, i.e., fourth generation (4G), and other previous generations, different requirements were not grouped and there was only a single service type in a single standard for cellular communications. However, different application requirements are grouped under various service types in one standard starting from 5G NR. Thus, the requirements of cellular communications are investigated considering three main service types of 5G NR: eMBB, URLLC and mMTC.

For Wi-Fi communications, different application requirements are grouped under several standards rather than the service types in one standard. Requirements are analyzed under several Wi-Fi standards that include IEEE 802.11ay, 802.11ad, 802.11be, 802.11ax, 802.11ac, and 802.11ah. In light of these standards, one can state that a set of new requirements generally brings a new Wi-Fi standard.

It can be expected to see more sophisticated service types for beyond 5G and a higher number of standards for Wi-Fi because diversity requirement continues to increase. Additionally, different standards might have similar set of system requirements. As an example, mMTC service type in 5G has almost the same set of requirements with IEEE 802.11ah standard.

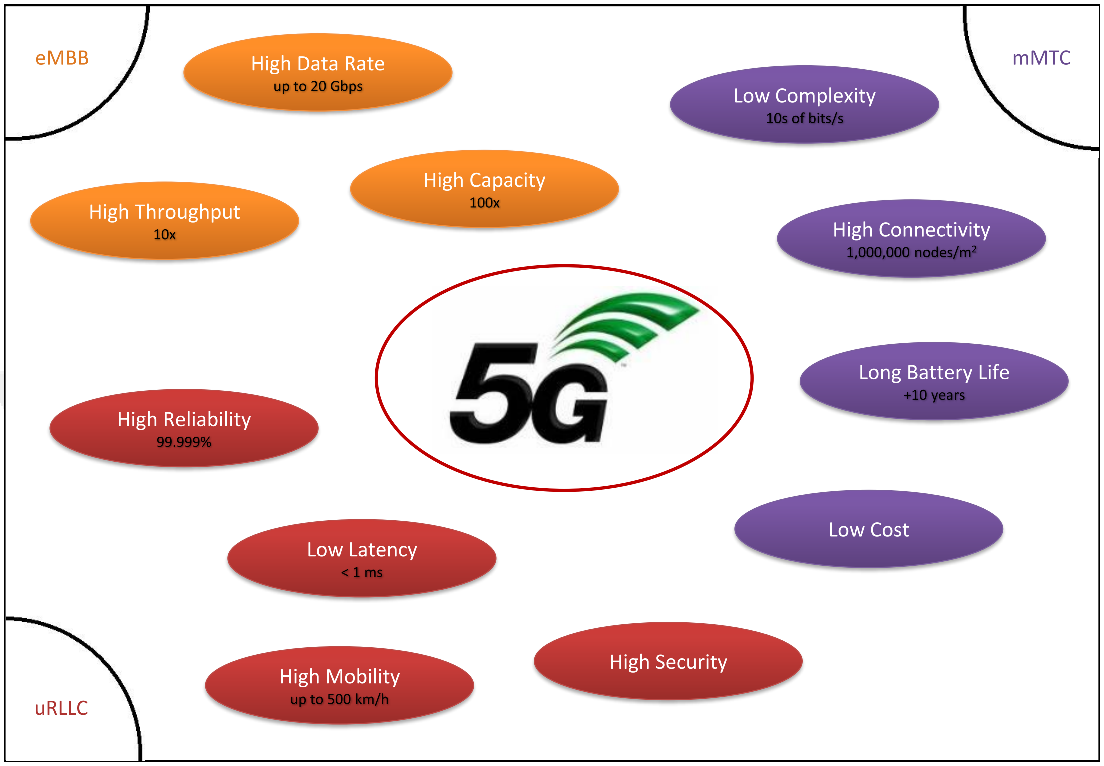


Figure 2.3: Application requirements in 5G NR.

2.1.3.1 Cellular Communications Use Cases

Figure 2.3 shows the main requirements in 5G NR for three different service types (use cases or application groups). The requirements also can be listed as follows:

- Peak data rates of 5G NR need to be 20 Gbps under eMBB.
- Reliability requirement is generally shown with five nines as 99.999% for URLLC services. Throughput and capacity need to be very high in consideration of the given data rates and reliability. User-plane latency requirement of 5G NR is lower than 1 ms, and end-to-end system delay needs to be less than 5 ms. Mobility requirement is taken as 500 km/h in 5G NR.
- There can be 1000000 nodes/km^2 for the connectivity requirement of 5G NR for mMTC applications. Battery life of the ultra-low energy communications systems in 5G NR needs to be at least 10 years.

The class of eMBB services generally requires high throughput and high data rate to provide the best opportunities for very high wireless data transfer. Because of that, the key necessities of eMBB services are mainly related to the spectrum usage. High spectral efficiency is a very critical necessity for the spectrum below 6 GHz. Employing mm-wave frequencies is also another solution for eMBB services.

A massive number of sensor devices form mMTC service class that include the service types related with smart homes, smart cities, wearable sensors, environment monitoring, ultra-low energy sensors, and all other similar usages. The key requirements of mMTC services are high energy efficiency and support for small data bursts because these requirements are essential for the sensor communications. In this context, short data bursts result with large subcarrier spacing, and the low number of subcarriers is a need. Discrete Fourier Transform spread (DFT-s) OFDM waveform is a solution in uplink transmission of 5G for the low-power sensor devices because DFT-s OFDM provides the necessity of the low number of subcarriers. However, mMTC services need large subcarrier spacings for short data bursts in downlink and uplink transmissions.

URLLC services, as the name implies, require high reliability, and low latency to be preferred by services related with autonomous vehicles, aviation, robotics, and medical applications. TTI durations are needed to be kept short to provide low latency. As another key requirement, high reliability can be provided by using larger subcarrier spacings; and longer CP durations will help to decrease interferences. In this way, packet loss rate can be reduced to increase reliability.

For beyond 5G, a higher number of service types might be expected, however this would increase the overall system complexity. Therefore, service types should be inclusive as much as possible while providing a flexibility in diverse applications and use-cases. It is an optimization problem to find the most suitable service types considering the application requirements. NR-Light and industrial internet of things (IoT) are some possible new service types for 5G NR Release 16 and 17 [1]. Moreover, the possible future application groups are listed in Table 2.1 regarding [1, 7, 9–11]. Some other studies are also currently available that focuses on the requirements for sixth generation (6G) cellular communications [23–26].

Table 2.1: Possible new use cases for beyond 5G.

Reference	Possible Service Types
[7]	**(1)** eMBB Plus; **(2)** big communications (BigCom); **(3)** secure uRLLC (SuRLLC); **(4)** three-dimensional integrated communications (3D-InteCom); **(5)** unconventional data communications (UCDC).
[9]	**(1)** Reliable eMBB; **(2)** mobile broadband reliable low latency communication (MBRLLC); **(3)** massive URLLC (mURLLC); **(4)** human-centric services (HCS); **(5)** multi-purpose services (MPS).
[10]	**(1)** Further-enhanced mobile broadband (FeMBB); **(2)** extremely reliable and low-latency communications (ERLLC); **(3)** ultra-massive machine-type communications (umMTC); **(4)** long-distance and high-mobility communications (LDHMC); **(5)** extremely low-power communications (ELPC).
[11]	**(1)** Ubiquitous mobile ultrabroadband (uMUB); **(2)** ultrahigh-speed-with-low-latency communications (uHSLLC); **(3)** ultrahigh data density (uHDD).

2.1.3.2 Wi-Fi Communications Standards

A summary of the requirements for Wi-Fi communications standards is presented in Figure 2.4 and Table 2.2. Data rate requirements of different Wi-Fi standards generally change regarding the target coverage area. If the focus is on only one room in an indoor environment, 802.11ay (new) or 802.11ad (old) standards can be preferred. 802.11ay and 802.11ad use millimeter-wave bands, so data rates are very high due to huge available BWs. However, millimeter-wave bands are not suitable for large areas with multiple rooms because of the blockage effects. To cover more than one room in an indoor setup, 802.11be (under development), 802.11ax (new) or 802.11ac standards are employed with 2.4 GHz and 5 GHz frequency bands. In this case, data rates can go up to 1 Gbps. For the coverage of large areas like a campus, 802.11ah standard is developed with low data rates (up to 100 Mbps). Besides, long battery life is one of the main requirements.

There are also some other Wi-Fi standards such as 802.11bd (new) or 802.11p (old). 802.11bd is developed for next generation V2X communications and it has

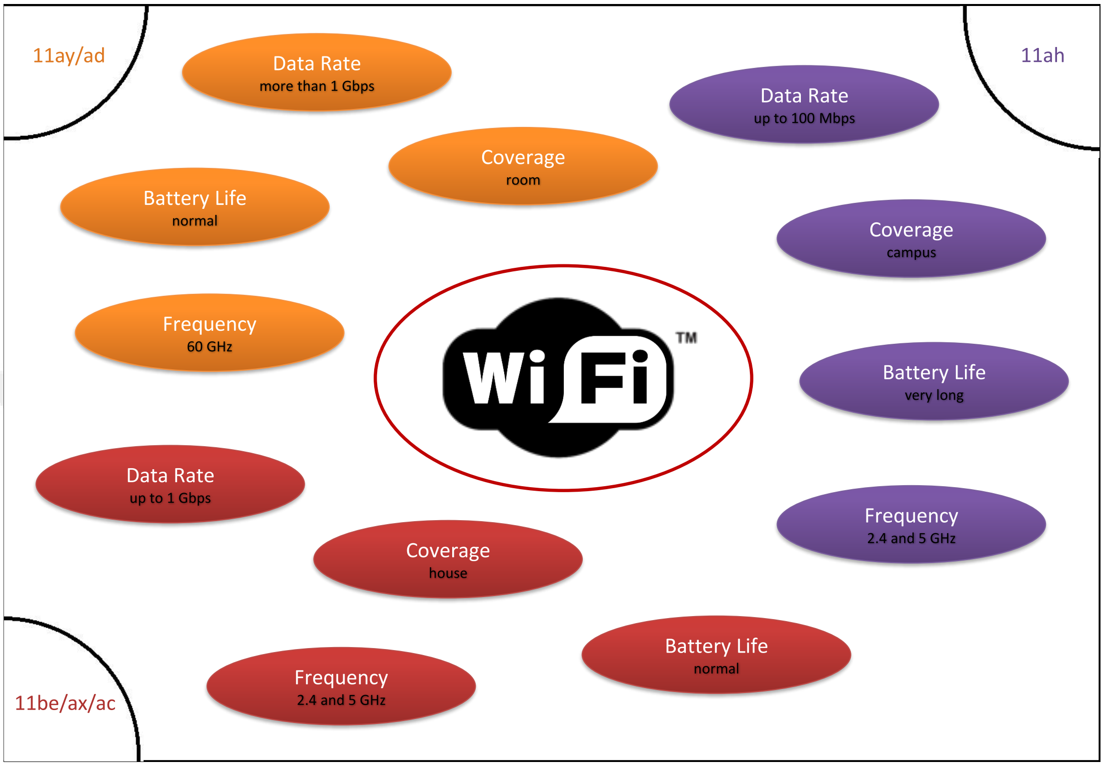


Figure 2.4: Application requirements in several Wi-Fi standards.

similar requirements with URLLC service type in 5G NR. High reliability and low latency are two main requirements. Coverage range is 1 km for 802.11bd [27].

Table 2.2: Comparison for the requirements of Wi-Fi standards.

Requirements	**802.11ay/ad**	**802.11be/ax/ac**	**802.11ah**
Data Rate	More than 1 Gbps	Up to 1 Gbps	Up to 100 Mbps
Coverage	Room	House	Campus
Battery Life	Normal	Normal	Very long
Frequency	60 GHz	2.4 and 5 GHz	2.4 and 5 GHz

2.2 Impact of the Waveform Design on RATs

This section provides relationships between the requirements and waveform design considering the RATs. Firstly, possible limitations and challenges for RATs are explained. Then, key performance indicators (KPI) are given to measure the success of a waveform design with respect to the requirements. At the end, the waveform design priorities for several RATs are investigated. In the literature, [4] and [28] discuss the similar concept.

2.2.1 Limitations and Challenges for RATs

Wireless communications standards are developed based on a wide range of RATs including, but not limited to, millimeter-wave, small cell, multi-input multi-output (MIMO), beamforming, non-terrestrial transmission points, cognitive radio, coordinated multipoint (CoMP), centralized radio access network (RAN) and heterogeneous network (HetNet). 802.11be standard will have multi-access point coordination technology similar to CoMP [6]. For beyond 5G, THz communications [23], visible light communication (VLC) [29,30], joint radar communications (JRC) [31, 32] and reconfigurable intelligent surface (RIS) [24] may be taken as other candidate RATs. All of these core technologies can be considered as functional tools to meet the some of given requirements for different service types. Concepts, techniques and the related algorithms in the literature are developed considering the target requirements and available RATs. Although RATs are used to meet the requirements, they may have several limitations and challenges. These limitations and challenges are the inevitable situations while using one available technology. The ideal algorithm designs for a RAT should meet the application requirements while dealing with these limitations and challenges.

The use of millimeter-wave frequencies [33] greatly increases data rates and capacity. However, blockage effects and path loss are higher compared to lower frequency spectrum because of the channel characteristics of millimeter-wave bands [34]. Additionally, phase noise is another important problem. MIMO and beamforming technologies [35] increase spectral efficiency by using space-domain to multiplex users. However, they can be called as complex systems in general. Non-terrestrial transmission points [36, 37] will be used in the future cellular networks to increase capacity and they need several requirement priorities like low complexity, long battery life and high security. For example, it is not a useful option to install a MIMO system into a non-terrestrial transmission point. Cognitive radio technologies [38] generally require high reliability to protect primary users from the secondary users. For CoMP and centralized RAN infrastructures [39], reliability and capacity can be enhanced but complexity is a challenge. Multi-access point coordination in Wi-Fi standards has a similar drawback. As it is seen from the example RATs, they have different limitations and challenges while employing them to meet application requirements.

2.2.2 Performance Indicators for the Waveform Design

Sometimes, it can be difficult to separate the requirements and performance indicators from each other. A performance indicator is used to evaluate a design considering a requirement. There can be several performance indicators for one specific requirement and it is possible to use different techniques for a performance indicator. Moreover, one performance indicator can be employed for different requirements jointly. Figure 2.5 shows an example demonstration for the relationships of waveform design, key performance indicators (KPIs) and the requirements. Additionally, it is possible to use **metric** instead of the **indicator**. In the remaining part of the thesis, two of them are preferred in different times.

Performance indicators can be utilized while revealing the relationships of wireless channel, RF impairments, applications and use cases with the waveform design. For a waveform design, generally the following performance indicators are used in the literature. Designs are compared with each other using these performance metrics. All of the performance metrics approach a design from different perspectives. They are important references for the waveform design.

- Spectral efficiency
- Inter-symbol interference (ISI)
- Inter-carrier interference (ICI)
- Adjacent channel interference (ACI)
- Inter-numerology interference (INI)
- Signal-to-interference-plus-noise ratio (SINR)
- Out-of-band emission (OOBE)
- Orthogonality in different domains
- Localization in different domains
- Robustness to dispersions in different domains
- Coexistence with unlicensed spectrum
- Latency
- Security gap
- Computational complexity
- MIMO compatibility
- Hybrid traffic operation capability
- Asynchronous access capability
- Connected terminal density
- Peak-to-average power ratio (PAPR)
- Energy efficiency
- Flexibility and adaptivity
- Backward compatibility

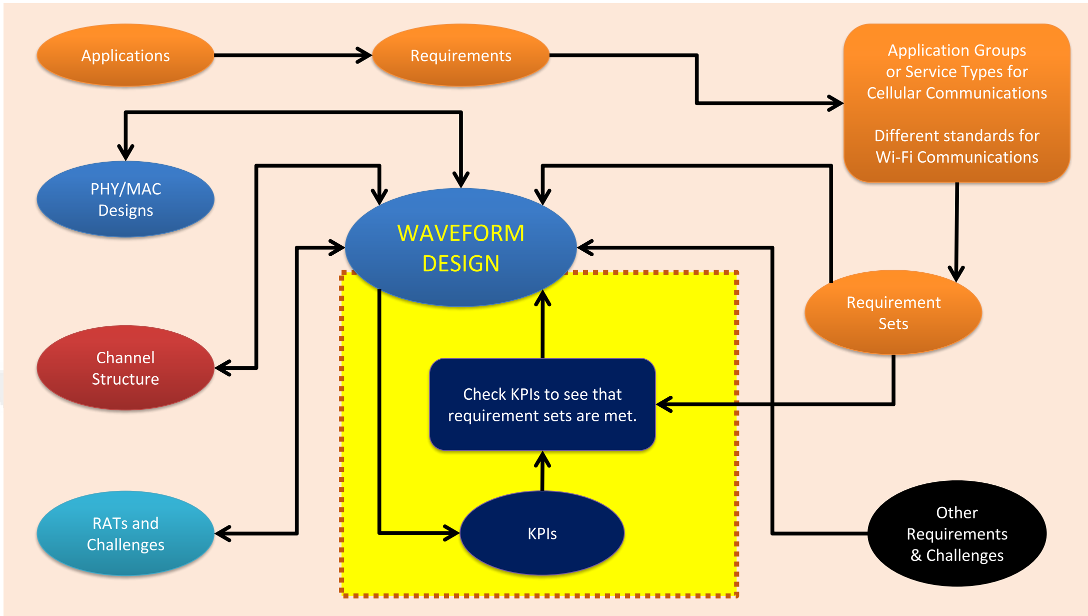


Figure 2.5: The role of KPIs in waveform design.

Spectral efficiency is an important KPI for the requirements of data rate, throughput and capacity. Measurement of various interference types, SINR, OOBE, orthogonality, localization and robustness to dispersions can be used to estimate the reliability of a waveform design. Moreover, hybrid traffic operation capability, asynchronous access capability and connected terminal density are performance metrics for the connectivity requirement in mMTC applications.

2.2.3 Waveform Design Guidelines for RATs

Technology-specific optimizations are discussed here like [28] from the waveform perspective. The related cellular and Wi-Fi technologies are analyzed together.

Millimeter-wave frequencies became crucial in cellular communications with 5G NR and Wi-Fi communications in 802.11ay/ad standards. Frequency spectrum is a scarce source and the usage of millimeter-wave frequencies is the only way to exploit the larger frequency spectrum. On the other hand, disadvantages of millimeter-wave communications is mainly related with its channel characteristics. Increased path loss and prevalent blockage effects make millimeter-wave communications unreliable especially for beyond 52.6 GHz. Sensitivity to hardware impairments such as phase noise, non-linear power implication, I/Q imbalance and limited analog-to-digital converter resolution also effect the design of millimeter-wave communications systems. **Small cell** transmission points are preferable at that point. Millimeter-wave and small cell concepts are complementary pairs for each other. Spectral efficiency is not a requirement for millimeter-wave communications since there is a huge availability in the higher frequencies. Therefore, OOBE is also not a big problem because there is an opportunity to employ large guards. In order to compensate the high path loss, narrower beams are utilized in millimeter-wave frequencies to allow similar coverage as compared to the microwave frequencies. As a result of narrow beams and poor reflections, channel delay spread decreases and thus a long cyclic prefix (CP) is not required to avoid ISI. For millimeter-wave waveform designs, PAPR should be low because path loss is high and there is a necessity of efficient power amplifiers. Larger subcarrier spacing and less number of subcarriers should be used to limit PAPR and phase noise in millimeter-wave frequencies. As a conclusion, millimeter-wave technology can be useful for most of the eMBB applications, but it can have drawbacks for URLLC and mMTC applications since there is an unreliability and high path loss. The first phase of standardization of 5G cellular systems covers bands up to 52.6 GHz, however, the next phase of 3GPP Release 17 will discuss frequency bands beyond 52.6 GHz. For Wi-Fi communications, 802.11ay and 802.11ad standards use 60 GHz band in a coverage of a single room.

MIMO is one of the core technologies in LTE, 5G NR and Wi-Fi standards to increase spectral efficiency by exploiting the space domain. Moreover, massive MIMO concept is introduced with 5G. Complexity of massive MIMO structures is high. This played an important role while deciding the 5G waveform [40], as discussed in Chapter 2. MIMO compatibility was one of the main criterion to compare the candidate waveforms for 5G NR. Especially, massive MIMO technology provides a good enhancement in spectral efficiency for eMBB applications. **Beamforming** can be considered as a complementary technology of MIMO.

Inter-beam interference and complexity of beam management are two main drawbacks while designing suitable waveforms for the beamforming.

Non-terrestrial transmission points include communications with low-altitude platforms (LAP), high-altitude platforms (HAP), and satellite systems. There can be air-to-ground (A2G) or air-to-air (A2A) communications links under the non-terrestrial transmission points concept. Non-terrestrial platforms are integrated into the terrestrial networks in some of the standardization studies for cellular communications. A2A communications channels have less multipath effects compared to the A2G channels. Delay spread and the amount of paths are very limited in non-terrestrial communications links. Hence, Doppler shifting is effective rather than Doppler spread. Additionally, the number of subcarriers to be selected can be kept low to limit PAPR and decrease latency with short frames. Also, short CP durations can be used to increase spectral efficiency because of the single-tap wireless channel. Long battery life is another important requirement for non-terrestrial transmission points. Therefore, computational complexity of the waveform design should be kept low to provide an energy efficiency.

Cognitive radio (CR) targets the spectral efficiency enhancement by dynamic spectrum access techniques. Coexistence with unlicensed spectrum is an important concept for CR. Good spectral containment, flexible BW usage and granularity are main requirements for this coexistence. A large number of subcarriers is beneficial due to high spectrum flexibility. However, spectral localization of the subcarriers is crucial in CR applications because the subcarriers of secondary user(s) should not interfere the subcarriers of primary user(s). Therefore, OOBE is one of the main KPIs for the waveform design of CR networks [41].

CoMP and centralized RAN technologies are used to improve system capacity and cell edge user throughput in a fairness perspective. However, system complexity increases as a drawback. Chapter 14 gives all basic details for them. eMBB and URLLC can be considered as suitable application groups for CoMP and centralized RAN. 5G NR waveform does not exploit these technologies but coordinated waveform designs can be developed for beyond 5G as utilizied in IEEE 802.11be Wi-Fi standardization [6].

Chapter 3

Waveform Parameterization

There is a trend that shows a linear increment in the number of configurable parameter options with each cellular generations [8]. There are two key points from the flexibility perspective. The first one is the number of configurable parameters in the system. Availability of more configurable parameters generally means high flexibility. The second key point is to have a capability of to provide different parameterization options in a same frame for the users in one coverage area. 5G NR has availability of different configurable parameters and it also provides a capability of assigning different parameters to users at a time [42]. In the future, there may be all different parameters for each users in a frame but it is not the case for 5G NR. There are drawbacks while employing multiple parameters in one frame and they limit the number of parameter options that are available for the assignment [4]. Therefore, the current cellular systems have limited parameter sets that are defined in the standards.

The number of configurable parameters for a waveform design is also increased with 5G to achieve better flexibility in an effort to support diverse services and user requirements. Orthogonal frequency division multiplexing (OFDM) waveform parameters are enriched with flexible multi-numerology structures in 5G NR. This chapter gives a short summary for the 3GPP NR standard and then describes the differences of building blocks for LTE systems and NR from the flexibility perspective. Inter-numerology interference (INI) and signal-to-interference (SIR) results as a function of multi-numerology parameters, guard allocation and user power levels are obtained through computer simulations. Finally, research opportunities for multi-numerology systems are presented in a structured manner.

3.1 An Example Waveform Frame: 5G NR Standardization

This section summarizes the 5G frame through the 3GPP NR specifications as a case study of the waveform design. Fundamentals of the 5G NR frame are discussed. Numerology options, bandwidth part (BWP) issues and slot structures are presented for the waveform design of 5G NR. All of these subjects are reviewed from the implementation perspective. In the last subsection, 5G NR is compared with LTE to find out the frame-based differences.

The physical layer of 5G communications systems is designed to achieve better flexibility in an effort to support diverse requirements as discussed in the previous chapters [4]. OFDM and its alternatives were discussed in 3GPP meetings (similar to Chapter 2) for three years before 3GPP Release 15 is announced in 2018. In the end, a multi-numerology OFDM structure was decided upon [43].

In the downlink, 5G NR uses CP-OFDM waveform with multiple numerologies on a time-frequency plane flexible lattice. In the uplink, there is an option to use either the CP-OFDM and DFT-s OFDM waveforms with multiple numerologies for NR [44]. OFDM waveform parameters are enriched with multiple numerologies in 5G NR despite the various drawbacks of OFDM. Flexibility is provided by the coexistence of different numerologies, where each numerology consists of a set of parameters defining the distances between the lattice points for a waveform [14]. The frame is also designed as flexible in 5G NR, e.g. flexible guard utilization in time and frequency domains, mini-slot concept.

Table 3.1: Document descriptions of 3GPP 38.200 series.

Document Number	Description
TS 38.201	NR; Physical layer; General description
TS 38.202	NR; Services provided by the physical layer
TS 38.211	NR; Physical channels and modulation
TS 38.212	NR; Multiplexing and channel coding
TS 38.213	NR; Physical layer procedures for control
TS 38.214	NR; Physical layer procedures for data
TS 38.215	NR; Physical layer measurements

Different numerologies are multiplexed orthogonally in time domain in [20]. It is one of the first studies that incorporated multi-numerology or mixed-numerology systems and designed a framework that provides numerous services simultaneously in a unified frame. However, multiple numerologies are multiplexed in both time and frequency domains with 5G NR [45].

3.1.1 Reference Documents for 3GPP

Firstly, the reference documents for the related 3GPP specifications that define 5G NR frame are introduced. 3GPP RAN Working Group-1 (WG1) is also called "Radio layer 1" and RAN WG1 is responsible for the specification of the physical layer for the cellular communications.

The radio interface described in 38.201 specification covers the interface between the user equipment (UE) and the network [42]. The radio interface includes three layers that are Layer 1, 2 and 3. This thesis takes the Technical Specification (TS) 38.200 series documents as a reference since they introduce the Layer 1 (Physical Layer) specifications. Short descriptions of the 38.200 series documents are presented in Table 3.1. Also, UE and base station (BS) radio transmission and reception specifications are listed in Table 3.2 as 38.100 series. The other related documents of Technical Report (TR) 38.800 series and 38.900 series are presented in Table 3.3 for ongoing studies considering the future 3GPP releases.

Table 3.2: Document descriptions of 3GPP 38.100 series.

Document Number	Description
TS 38.101-1	NR; User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone
TS 38.101-2	NR; User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone
TS 38.101-3	NR; User Equipment (UE) radio transmission and reception; Part 3: Range 1 and Range 2 Interworking operation with other radios
TS 38.101-4	NR; User Equipment (UE) radio transmission and reception; Part 4: Performance requirements
TS 38.104	NR; Base Station (BS) radio transmission and reception

Table 3.3: Document descriptions of 3GPP 38.800 series and 38.900 series.

Document Number	Description
TR 38.802	Study on new radio access technology Physical layer aspects
TR 38.808	Study on supporting NR from 52.6 GHz to 71 GHz
TR 38.812	Study on Non-Orthogonal Multiple Access (NOMA) for NR
TS 38.824	Study on physical layer enhancements for NR ultra-reliable and low latency case (URLLC)
TR 38.829	Study on Narrow-Band Internet of Things (NB-IoT) / enhanced Machine Type Communication (eMTC) support for Non-Terrestrial Networks (NTN)
TR 38.830	Study on NR coverage enhancements
TR 38.838	Study on XR (Extended Reality) evaluations for NR
TR 38.840	Study on User Equipment (UE) power saving in NR
TR 38.855	Study on NR positioning support
TR 38.857	Study on NR positioning enhancements
TR 38.866	Study on remote interference management for NR
TR 38.875	Study on support of reduced capability NR devices
TR 38.885	Study on NR Vehicle-to-Everything (V2X)
TR 38.889	Study on NR-based access to unlicensed spectrum
TR 38.900	Study on channel model for frequency spectrum above 6 GHz
TR 38.901	Study on channel model for frequencies from 0.5 to 100 GHz

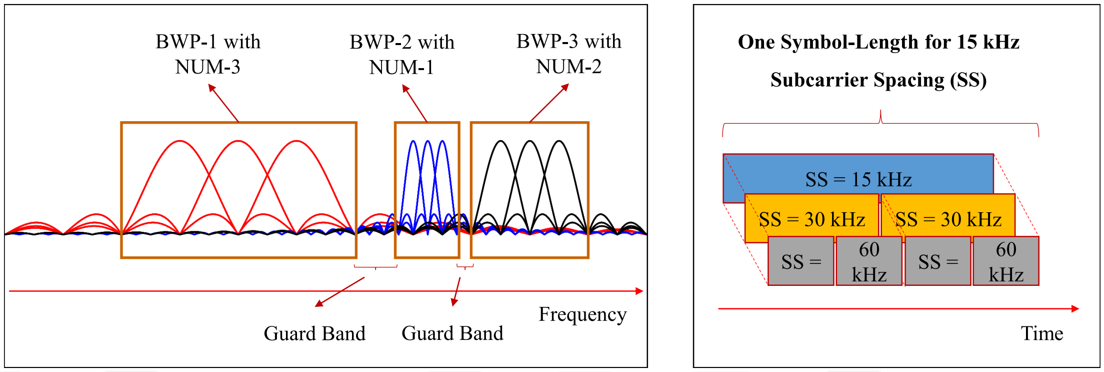


Figure 3.1: Example demonstrations for multiple numerologies in frequency and time domains.

3.1.2 Numerology Structures

In this section, building blocks of the waveform-related new concepts [1,5,46,47] in 5G NR are explained and possible implementation issues are discussed. Pulse shape processing and guard utilization concepts are also included.

The same single mother waveform OFDM is employed for both LTE and NR. However, in contrast to the single-numerology utilization in LTE, NR allows simultaneous multi-numerology utilization [44]. Multiple numerologies are multiplexed in frequency domain with 5G NR [45]. In [20], different numerologies are multiplexed orthogonally in time domain. It is one of the first studies that incorporated multi-numerology or mixed-numerology systems and designed a framework that provides numerous services simultaneously in a unified frame. However, the concept of time domain multi-numerology multiplexing is not applied in 5G.

Table 3.4: Numerology structures and the corresponding maximum BW allocations for data channels in 5G NR.

Frequency Range (FR)	Δf (kHz)	T_{CP} (μs)	Slot Duration (ms)	# of Symbols in One Slot	Max. BW (MHz)
FR-1	15	4.76	1	14	50
	30	2.38	0.5	14	100
	60	1.19 | 4.17	0.25	12 | 14	100
FR-2	60	1.19 | 4.17	0.25	12 | 14	200
	120	0.60	0.125	14	400

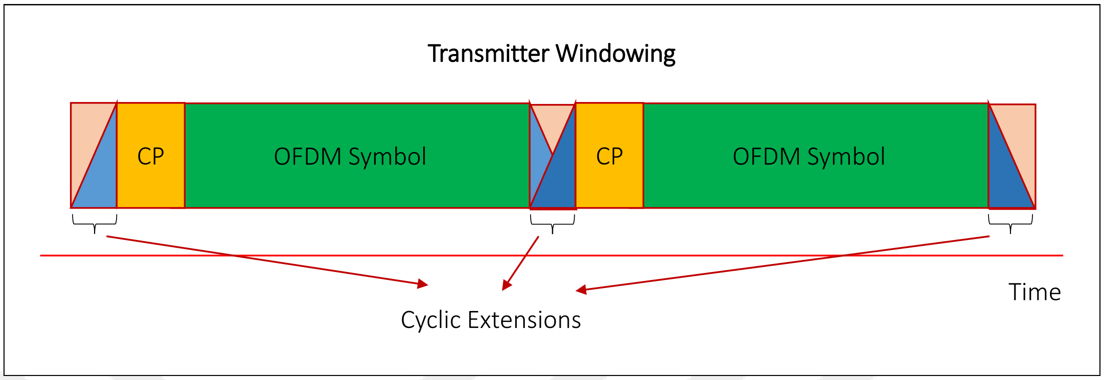


Figure 3.2: Example demonstration for a transmitter windowing.

Lattice domains are same in 5G NR compared to LTE. Time-frequency plane is taken as a reference for the 5G NR lattice structure. As a difference with LTE, NR defines flexible time-frequency lattice enabling multi-numerology structure. For the case of OFDM with time-frequency lattice, numerology set consists of subcarrier spacing and CP duration [4]. The subcarrier spacing and CP duration options for 5G numerologies are presented under a NR frame in Table 3.4 [44,48]. Individual CP usage for each OFDM symbol is preferred for 5G NR [44]. In addition, extended CP option is available only when Δf is 60 kHz.

For signalization purposes, it is also possible to use 240 kHz of Δf. 480 kHz subcarrier spacing was considered in the previous version of 3GPP standardization but it is not included in Release 15. The upcoming releases may have larger subcarrier spacings especially for 52.6 GHz and beyond frequencies. The minimum 60 kHz subcarrier spacing is used for mm-wave frequencies or frequency range-2 (FR-2) that is above 6 GHz. It may be also possible to use a single-carrier waveform in downlink for higher frequencies in Release 17 and beyond.

For 5G NR, different numerologies can be used simultaneously in a cell. However, all of the NR numerologies do not need to be used all the time [4]. Figure 3.1 shows an example demonstration for multiple numerologies that are multiplexed in frequency domain. BWP issues are explained in the next subsection.

In [19], different pulse shapes are compared to each other. 5G NR allows different options for pulse shape processing. As an example, there is a flexibility to apply windowing with different or same roll-off factors on the subframes for each numerologies or composite signal of multiple numerologies at the transmitter. Representative demonstration for a transmitter windowing is shown in Figure 3.2. Receiver windowing is the another option for 5G NR. Filtering is also possible in addition to windowing. Applying proper methods such as filtering and windowing are left for the implementation as long as it is transparent to the counterpart of the 5G NR communications regarding the 3GPP specifications [17].

Inter-numerology guard band utilization aims to decrease the INI effects rather than changing the pulse shape like in windowing and filtering. All of them can be called as waveform processing techniques but inter-numerology guard bands are utilized while designing the frame structure. As discussed in the previous chapters, multiple numerologies are related with the lattice structure, applying window and filter are related with the pulse shape, and inter-numerology guard band is related with the frame structure. Guard band utilization can be in fixed or adaptive manners. For example, some of the subcarriers that are not affected by INI in the guard bands are used for data communications in [49]. It is possible to develop different types of adaptive guard band utilization method. Additionally, the amount of inter-numerology guard bands are left flexible in 3GPP standards and there is not any limitations. In 3GPP standards, it is revealed that there are minimum guard band requirements, a maximum or an optimum value is not enforced, making guard bands choices flexible with high granularity [50]. Adaptive guard utilization methods can be applied optionally in 5G NR rather than fixed solutions [49, 51]. This provides an extra flexibility.

3.1.3 Bandwidth Part Issues

A BWP is a new term that defines a fixed band over which the communication taking place uses the same numerology [52]. BWPs are controlled at the BS and BWP is a bridge between the numerology and scheduling mechanisms. BWP is a practical tool for multi-numerology systems as BWP defines a specific numerology. BS can modify the user numerologies by changing BWPs. Moreover,

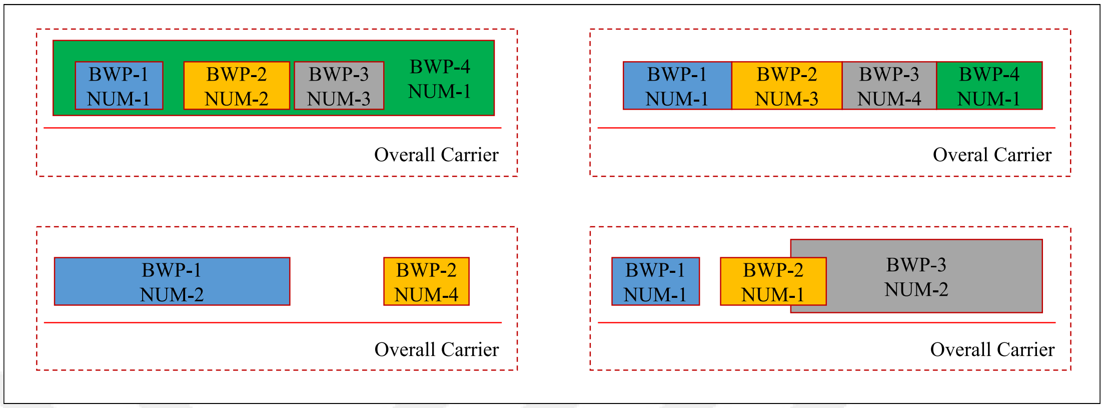


Figure 3.3: Example BWP implementations and configurations.

NR allows overlapping of BWPs using different numerologies in time-frequency lattice [46]. Example BWP implementations and configurations are shown in Figure 3.3. Although not imposed by the standard [44], it is generally preferred that BWPs are configured to use the same numerologies consecutively in an effort to reduce guards.

BWPs allow user to process only part of the band that contain their symbols, reducing power consumption and enabling longer battery lives. This is very useful for the low-power communications systems, particularly mMTC services [46].

Parameter configuration process for the BWPs is employed by bandwidth adaptation (BA) tool on BS [53]. There can be up to four defined BWPs for each user but there is one active BWP at a time for each user in Release 15. However, future NR releases are planned to allow multiple active BWP configurations. For example, self-driving cars can have eMMB and URLLC requirements together while communicating with the base station. One BWP can be employed to serve for eMBB applications in the car, and the other BWP can be configured to provide an ultra reliable link with a low latency.

BS channel BW is another new term that refers to the contiguous BW currently in use by the node B (gNB) for either transmission or reception [50]. In other words, it refers to the total BW that is processed by the gNB.

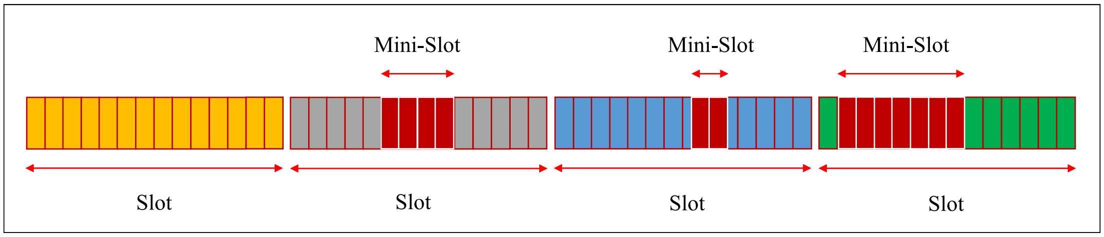


Figure 3.4: Example mini-slot implementations with 2, 4 and 7 OFDM symbols for a same numerology.

3.1.4 Slot Structures

5G NR slots can consist of 14 symbols for all subcarrier spacings and 12 symbols as an extra option for 60 kHz subcarrier spacing [54]. The number of slots per subframe depends on the subcarrier spacing and is given by the multiplicative inverse of the slot duration [44]. Furthermore, NR resource block (RB) is defined only using the same BW definition with 12 subcarriers; their durations are not fixed [44]. A radio frame includes 10 subframes/slots and total duration of a frame is 10 ms. Subframe is defined as one slot in 5G NR but slot length is variable as shown in Table 3.4.

One of the new concepts in 5G NR is mini-slot. As a difference with a normal slot, mini-slots are not linked to the frame structure. There is no need to wait for scheduling, mini-slots can be used within the existing frame asynchronously regarding the starting point of a normal slot. It is not a conventional slot based scheduling. NR TTI may be a mini-slot especially in the case of URLLC. It can be defined as a slot for regular operation, or multiple slots in the case of large number of eMBB packets [54]. An example demonstration for the mini-slot concept is shown in Figure 3.4. It is possible to implement mini-slot with 2, 4, or 7 OFDM symbols. Hence, mini-slot with 2 OFDM symbols is the minimum scheduling unit in 5G NR.

3.1.5 Comparison for Building Blocks of 5G NR and LTE

LTE physical layer specifications are given under 3GPP 36.200 series listed in Table 3.5. LTE waveform is optimized to serve high data rate applications. There is only limited support for the other applications due to the inflexibility of the waveform and LTE cannot support the rich requirements of the 5G vision. NR aims to provide wide variety of services flexibly by rendering waveform parameters. In this section, firstly, the LTE frame is reviewed with the fundamental properties. Then the differences between NR and LTE are revealed.

RB is defined as 12 subcarriers with 7 OFDM symbols (for short CP) in LTE. The size of resource element is fixed and it consists of one subcarrier with one OFDM symbol. Subcarrier spacing is not flexible and it is 15 kHz. There are normal and extended CP options. However, all users need to use only one option together, so it is not a multi-numerology structure. Distances between the time-frequency lattice points are fixed as exemplified in Figure 3.5. In addition, guard utilization between different users is not necessary in single-numerology OFDM for the same frame.

Frame length of LTE is 10 ms, and there are 10 subframes in the whole frame. Minimum scheduling unit is subframe in LTE. Subframes consist of two slots that have fixed size of 0.5 ms. There are totally 20 fixed-size slots in one frame. The number of symbols per slot is 6 or 7 for extended and normal CP, respectively.

Table 3.5: Document descriptions of 3GPP 36.200 series for Evolved Universal Terrestrial Radio Access (E-UTRA).

Document Number	Description
TS 36.201	E-UTRA; LTE physical layer; General description
TS 36.211	E-UTRA; Physical channels and modulation
TS 36.212	E-UTRA; Multiplexing and channel coding
TS 36.213	E-UTRA; Physical layer procedures
TS 36.214	E-UTRA; Physical layer; Measurements
TS 36.216	E-UTRA; Physical layer for relaying operation

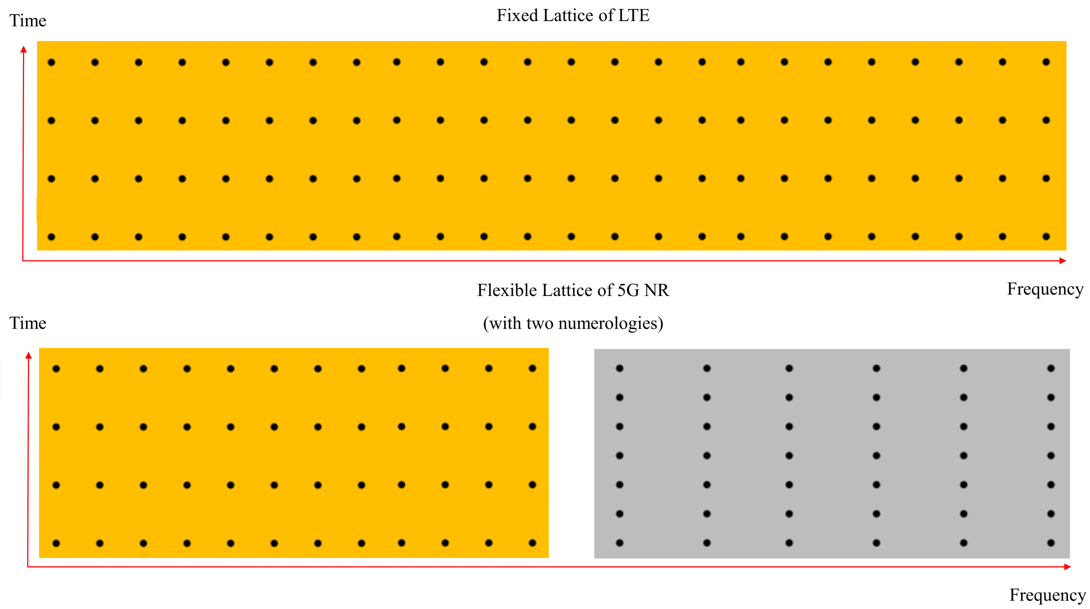


Figure 3.5: Comparison of the example lattice structures of 5G NR and LTE.

It is possible to configure the 5G NR similar to LTE as one option. Hence, it can be said that 5G NR includes LTE but 5G has more options. The flexibility and variety of options make 5G NR different than the LTE systems. Example comparisons are provided in Figure 3.5 and Table 3.6.

LTE and NR use the same mother waveform but there is only one numerology in LTE. In the uplink, the only option in LTE is DFT-s OFDM with a single numerology. However, there is an option to use either of CP-OFDM and DFT-s OFDM with multi numerologies for 5G NR.

LTE uses a fixed lattice in which the frequency (and corresponding time) spacing between each two points is always the same throughout the whole transmission band [14]. LTE is a single-numerology system thus all lattice parameters are fixed at all times for a BS. On the contrary, NR defines flexible time-frequency lattice enabling multi-numerology structure. Furthermore, NR does not define the RB in time domain, however RB definition in LTE includes time-frequency domains together. The size of resource element is variable in 5G NR while it is fixed in LTE. RB and resource element comparison is shown in Figure 3.6.

Table 3.6: 5G NR and LTE comparison from the frame perspective.

Criterion	LTE	5G NR
Lattice domains	Time-frequency	Time-frequency
Downlink waveform	CP-OFDM	CP-OFDM
Uplink waveform	DFT-s OFDM	CP-OFDM and DFT-s OFDM
Numerology Structure	Fixed, single-numerology	Flexible, multi-numerology
RB definition	12 SCs and 0.5 ms	12 SCs
Resource element	Fixed	Variable
SC spacing	15 kHz	15, 30, 60 and 120 kHz
# of SCs per RB	12	12
Max. transmission BW	up to 20 MHz	up to 400 MHz
Max. # of RBs	up to 100	up to 275
FFT size for max. BW	2048	4096
Frame length	10 ms	10 ms
Subframe length	2 slots	1 slot
# of slots per subframe	2	1, 2, 4 and 8
Slot duration	0.5 ms	0.125, 0.25, 0.5 and 1 ms
# of symbols per slot	6 or 7	12 or 14
Min. scheduling unit	Subframe	Mini-slot
Normal CP length	4.69 us (1st one is 5.21 us)	0.60, 1.19, 2.38 and 4.76 us
Extended CP length	16.67 us	4.17 us for 60 kHz SC spacing

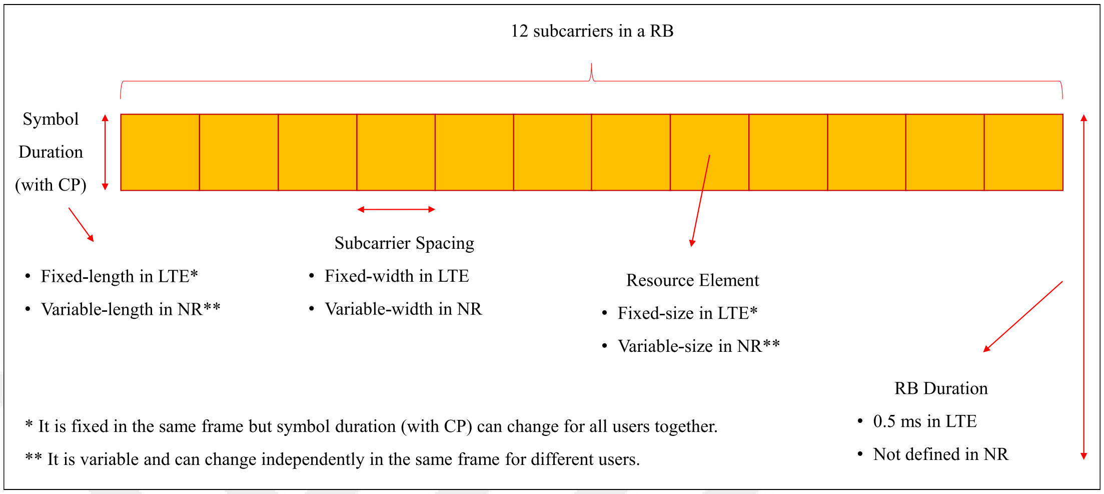


Figure 3.6: RB and resource element comparison for 5G NR and LTE.

In contrast to LTE, 5G UE does not need to monitor the whole transmission BW; they only scan the BWP assigned to themselves. Additionally, maximum transmission BW is increased from 20 MHz to 400 MHz.

Unlike LTE slots that consist of 7 OFDM symbols in case of short CP, NR slots can consist of 14 symbols for subcarrier spacings up to 60 kHz [54]. As opposed to the fixed LTE TTI duration of one slot, NR TTI may be a mini-slot. NR re-uses the LTE frame definition [42], however, the number of slots per subframe is variable for 5G.

Multiplexing waveforms with different parameterization in 5G gives rise to several penalties that include new forms of interferences, such as inter-numerology interference (INI). INI is a leakage between different numerologies, causing many challenges and presents new research opportunities. In LTE, INI is not a problem because there is only one numerology in a waveform frame. One of the main differences between LTE and 5G NR can be accepted as the INI problem.

3.1.6 Simulation Results for Multi-Numerology Systems

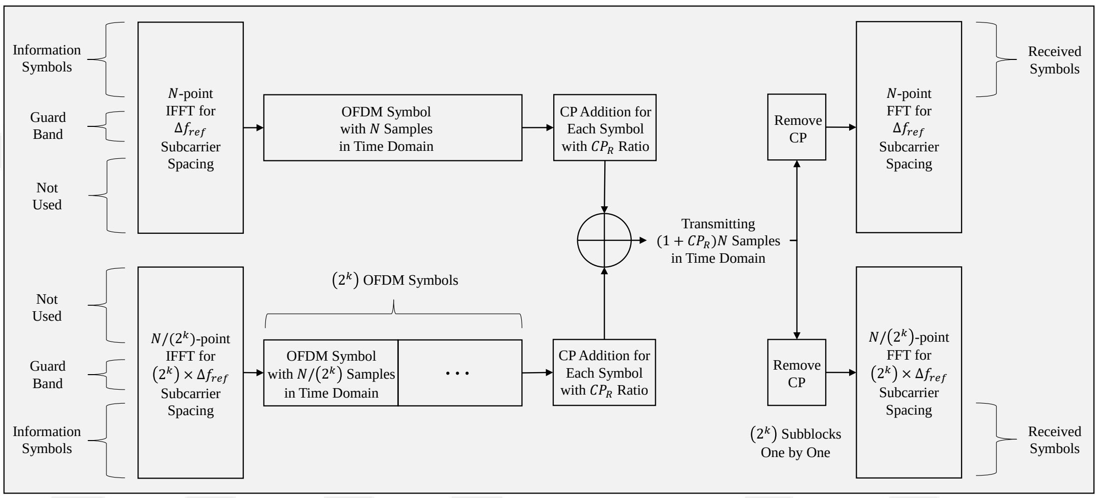
In this section, various inter-numerology interference (INI) and signal-to-interference ratio (SIR) results as a function of multi-numerology parameters, guard allocation and user power levels are provided through computer simulations based on the block diagram in Fig. 3.7.

3.1.6.1 Assumptions and System Model

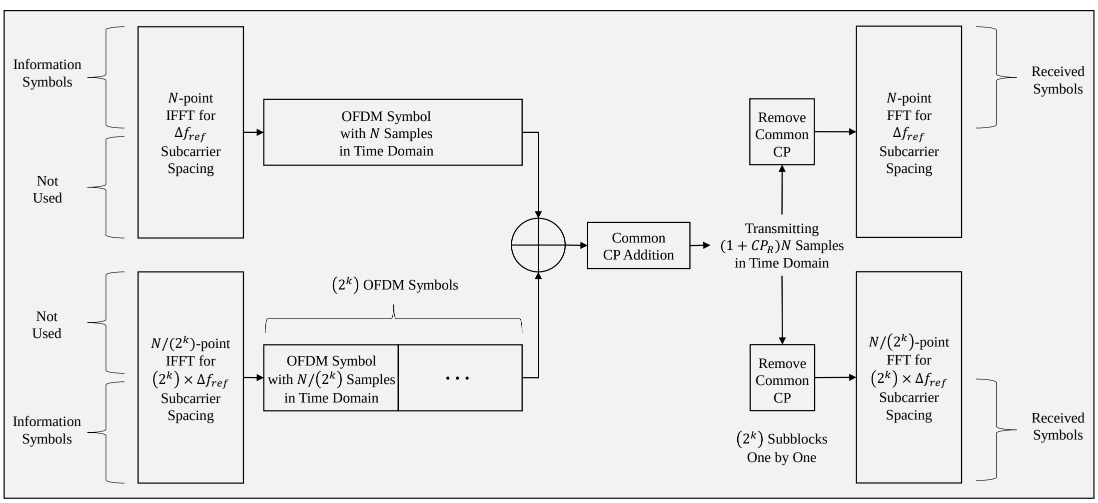
It is assumed that user equipments (UEs) are synchronous to each other. We allocate UEs or bandwidth (BW) Parts (BWPs) with same numerologies contiguously in the frequency domain. It is also assumed that the subcarriers of UEs are sidelobe overlapped to each other and each numerology block that consists of multiple carriers is shared by multiple UEs. OFDM is employed and each UEs have different power levels in Section 3.1.6.4 and equal power levels in other subsections.

Independent random binary phase shift keying (BPSK) symbols are generated separately for two-numerology structure. For the first numerology, which has $\Delta \mathrm{f}_{\mathrm{ref}}$ kHz subcarrier spacing, N-point inverse fast Fourier transform (IFFT) is employed. The second numerology has $2^{\mathrm{k}} \times \Delta \mathrm{f}_{\mathrm{ref}}$ kHz subcarrier spacing and uses $N/(2^k)$-point IFFT, where 2^k is the scaling factor and k is a positive integer. Here, the second half of the IFFT inputs for the first numerology and the first half of the IFFT inputs for the second numerology are zero-padded to separate two numerologies in frequency domain. After each IFFT operation, CP samples are added with a ratio of CP_R to every OFDM symbol. There are 2^k OFDM symbols with the second numerology corresponding to one OFDM symbol with the first numerology. Thus, the number of samples for each of the numerologies are the same, and they can be added to form a composite signal at the transmitter.

Wireless channel and noise are ignored to just focus on the INI in the simulation results. At the receiver side, CP samples are removed from each OFDM symbol. N-point fast Fourier transform (FFT) is used for the first numerology over full



(a) There is a guard band between numerologies. Individual CPs are preferred.



(b) There is not any guard band between numerologies. Common CP is preferred.

Figure 3.7: Block diagram for the simple implementation of multi numerologies. The scaling factor of Δfs is chosen as 2^k, where k is a positive integer.

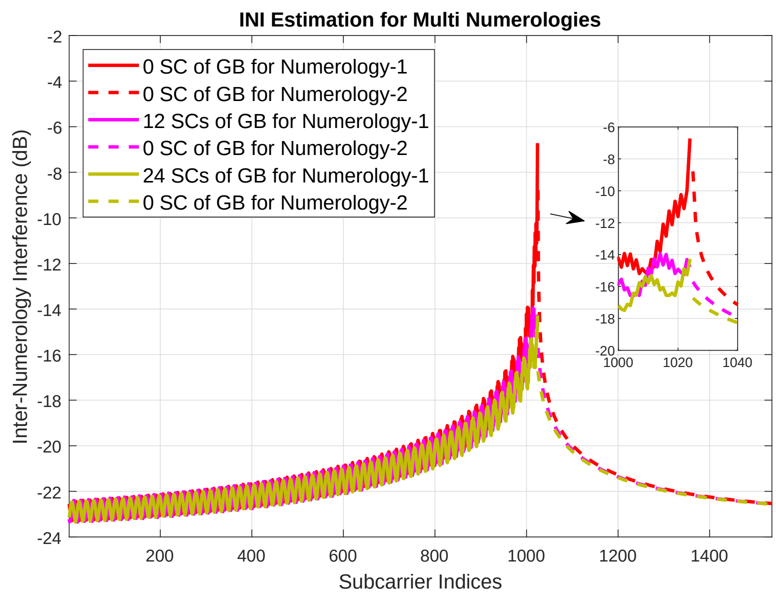
composite signal. However, only $N/(2^k)$ samples of the composite signal to make them input into $N/(2^k)$-point FFT for the second numerology. 2^k subblocks are constituted by dividing the composite signal into 2^k parts and these subblocks are processed one by one. The first half of the FFT output for the first numerology and the second half of the FFT output for the second numerology are taken to obtain received symbols.

Interference estimations for each of the used subcarriers are done separately. Monte Carlo method is applied and the number of independent tests is 500 with different set of random data in each of these tests. Thereafter, the average interference on the subcarriers are estimated.

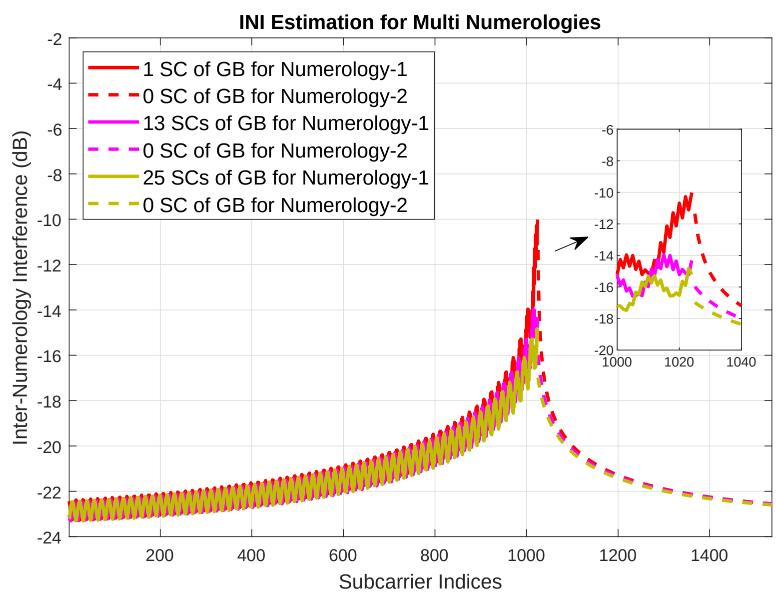
3.1.6.2 Subcarrier Spacing and Guard Band Effects with Individual CPs

There are four cases in the simulation results presented in Fig. 3.8 and Fig. 3.9. Number of usable subcarriers are half of the IFFT sizes in each case. In Fig. 3.8 and Fig. 3.9, INI results are plotted like that there is not any guard bands between the edge subcarriers of two numerologies when there are actually guard bands. The reason of this representation is to make a comparison with different amount of guard bands easily.

Simulation results show that there is more INI at the edge subcarriers of different numerologies and the effect of guard bands are more prominent for the edge subcarriers. Subblocks of the second numerology are constituted by dividing the composite signal. Hence, the symbols of the first numerology causes an interference on the second numerology at the receiver side.

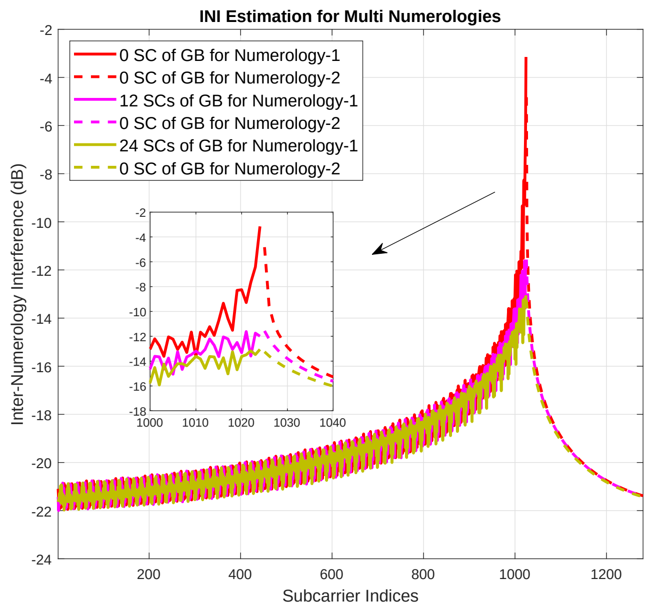


(a) Case 1: Guard bands are 0 kHz, 180 kHz and 360 kHz.

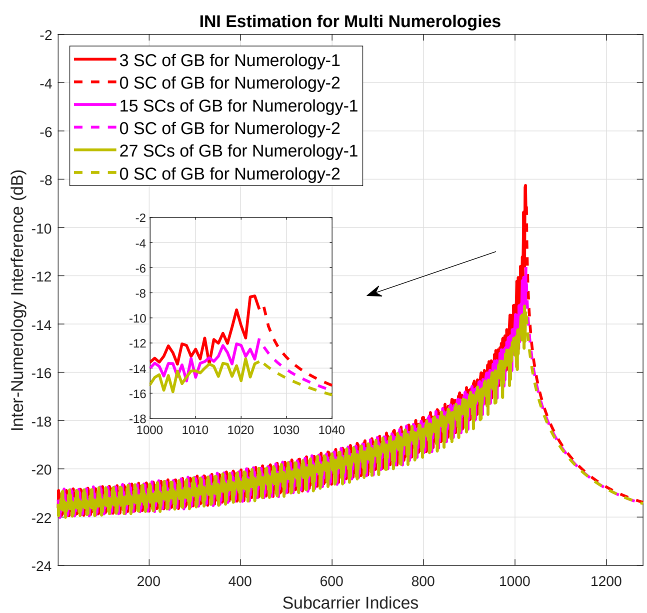


(b) Case 2: Guard bands are 15 kHz, 195 kHz and 375 kHz.

Figure 3.8: Simulation results for two different cases with different guard band amounts between numerologies. Numerology-1 has 15 kHz Δf and Numerology-2 has 30 kHz Δf.



(a) Case 3: Guard bands are 0 kHz, 180 kHz and 360 kHz.



(b) Case 4: Guard bands are 45 kHz, 225 kHz and 405 kHz.

Figure 3.9: Simulation results for two different cases with different guard band amounts between numerologies. Numerology-1 has 15 kHz Δf and Numerology-2 has 60 kHz Δf.

3.1.6.3 Common CP Effects

Individual CP addition causes an extra interference for the numerology with smaller Δf as shown in Fig. 3.8 and Fig. 3.9. However, in common CP implementation, INI on every (2^k)th subcarrier is zero for the numerology with smaller Δf as it can be seen in Fig. 3.10. It is an important advantage for the short symbol duration numerology. Simulation results support the explanations that are given in Section 3.2.2.

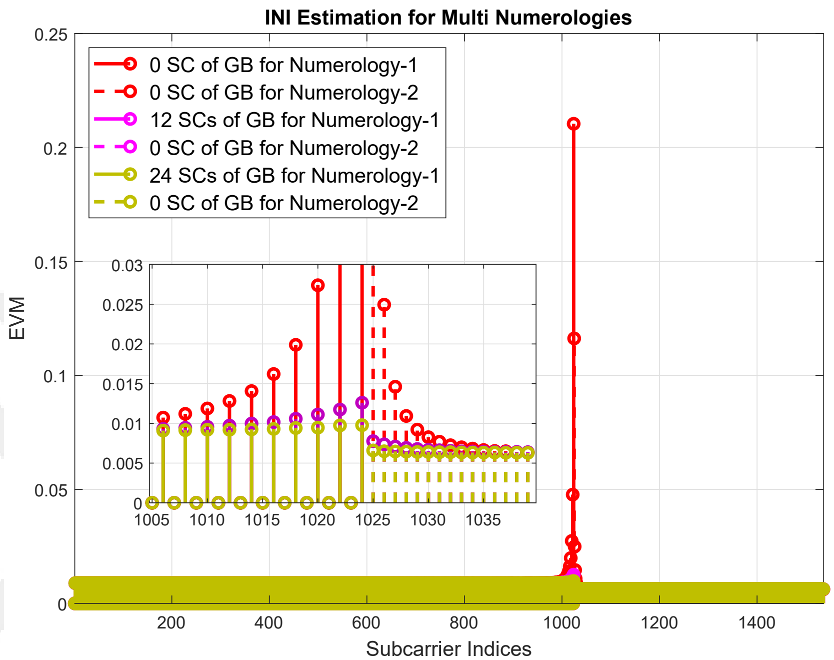
3.1.6.4 Power Difference Effects

In simulations, power offsets (PO) of the UEs alternate between 0 dB, 3 dB, and 7 dB. For Fig. 3.11(a), increasing the power level of the NUM-2 edge UE 3 dB results with 5.7 dB SIR decrement in the NUM-1 edge UE. PO increment also affects the NUM-1 inner UEs with 4.8 dB. However, there is more than 10 dB SIR difference between the edge UE and inner UEs for NUM-1.

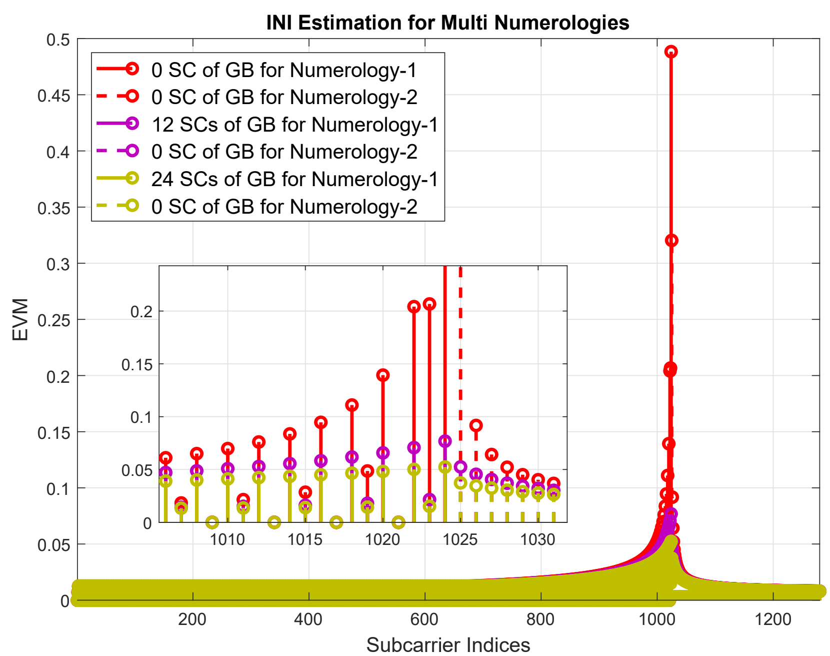
For Fig. 3.11(b), increasing the power level of the NUM-1 and NUM-2 UEs symmetrically results with a small SIR increment in the edge UEs of two numerologies. However, inner UEs are affected by the power levels of edge UEs in proportion. These results show that edge user scheduling algorithm presented in Section 3.2.5 is an effective solution for multi-numerology systems.

3.1.6.5 Discussions on the Results

The effects of INI cannot be ignored considering the presented simulation results. There should be mechanisms to control this new interference. Several trade-off situations need to be analyzed while developing these mechanisms.

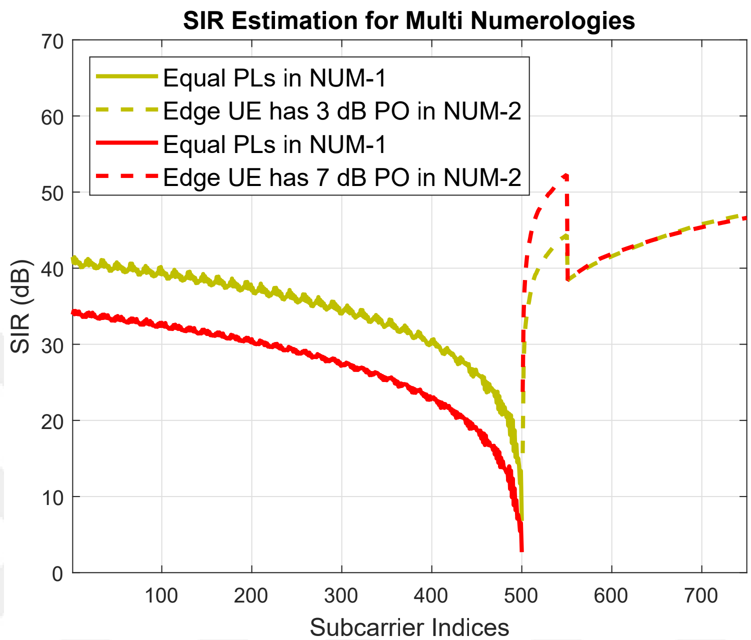


(a) Numerology-1 has 15 kHz Δf and Numerology-2 has 30 kHz Δf.

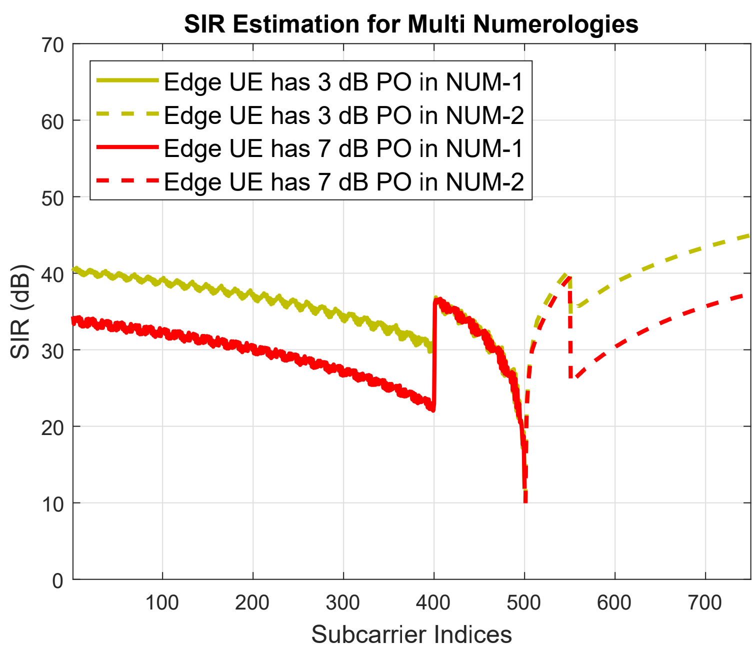


(b) Numerology-1 has 15 kHz Δf and Numerology-2 has 60 kHz Δf.

Figure 3.10: Simulation results for common CP implementation. Guard band amounts between numerologies are 0 kHz, 180 kHz and 360 kHz.



(a) Edge subcarriers of NUM-2 has higher PLs than the other subcarriers in NUM-1 and NUM-2.



(b) Edge subcarriers of NUM-1 and NUM-2 have higher PLs than the inner subcarriers of NUM-1 and NUM-2. There is not any POs between the edge subcarriers.

Figure 3.11: Power difference analysis. NUM-1 has narrow subcarriers with 15 kHz and NUM-2 has wide subcarriers with 30 kHz.

3.2 Research Opportunities for Multi-Numerology Systems

Multi-numerology structures that were included in the Third Generation Partnership Project (3GPP) New Radio (NR) standardization were studied in literature from different aspects. Relationships between multiple numerologies and user/service requirements are provided in [3, 4, 55] from the numerology selection perspective. Non-orthogonality of multi numerologies are investigated in [56–59]. Various INI estimation and cancellation methods are provided in [45, 56]. Moreover, INI reduction techniques are proposed in [2, 45, 51, 56, 60–63]. Algorithm examples for the advanced scheduling methods of multiple numerologies explained in [4, 18, 64–66]. A summary for the subjects of these studies are presented in Fig. 3.12 and details for the literature are provided in next subsections.

As it can be seen from the previous sections, the main flexibility causative for NR is mostly focused on the new frame with multi-numerology. Different UE and service requirements can be met using multiple numerologies. In other words, multiplexing numerologies provides the flexibility needed by NR.

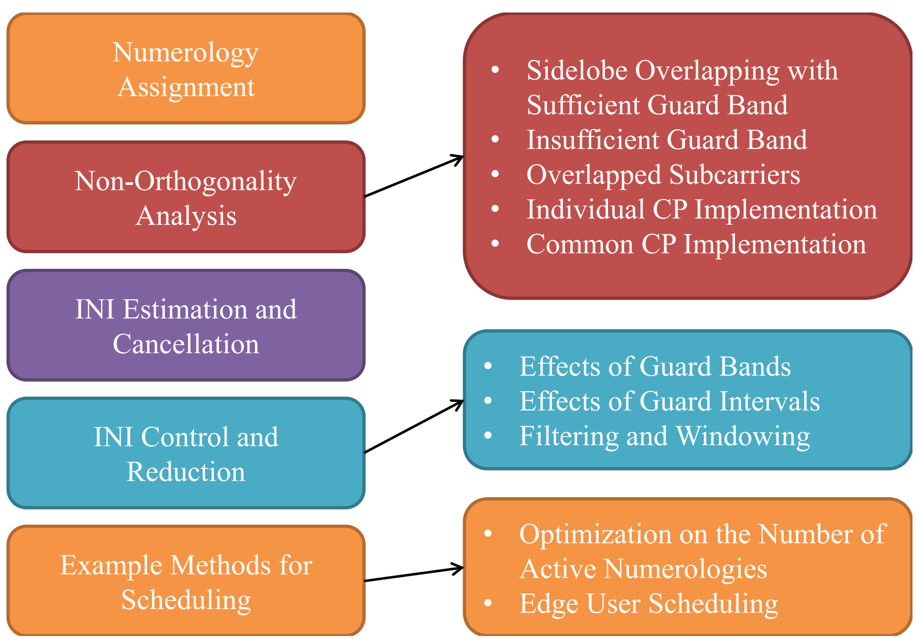


Figure 3.12: Various research opportunities for multi-numerology systems.

This section presents various research opportunities and exemplary multi-numerology methods that exploit the flexibilities in NR design pointed out in the previous sections. Many new research studies exploit this degree of freedom.

3.2.1 Numerology Assignment Methodologies

Numerologies of UEs cannot be decided arbitrarily. There is a need for a numerology selection mechanism to employ multi-numerology systems with multi UEs. In this subsection, we provide some details on that subject.

Active BWPs and the corresponding numerologies can be selected using different methodologies. Various trade-offs between distinct performance metrics that include spectral efficiency, INI, flexibility, and complexity can be considered while deciding on active BWPs and so numerologies.

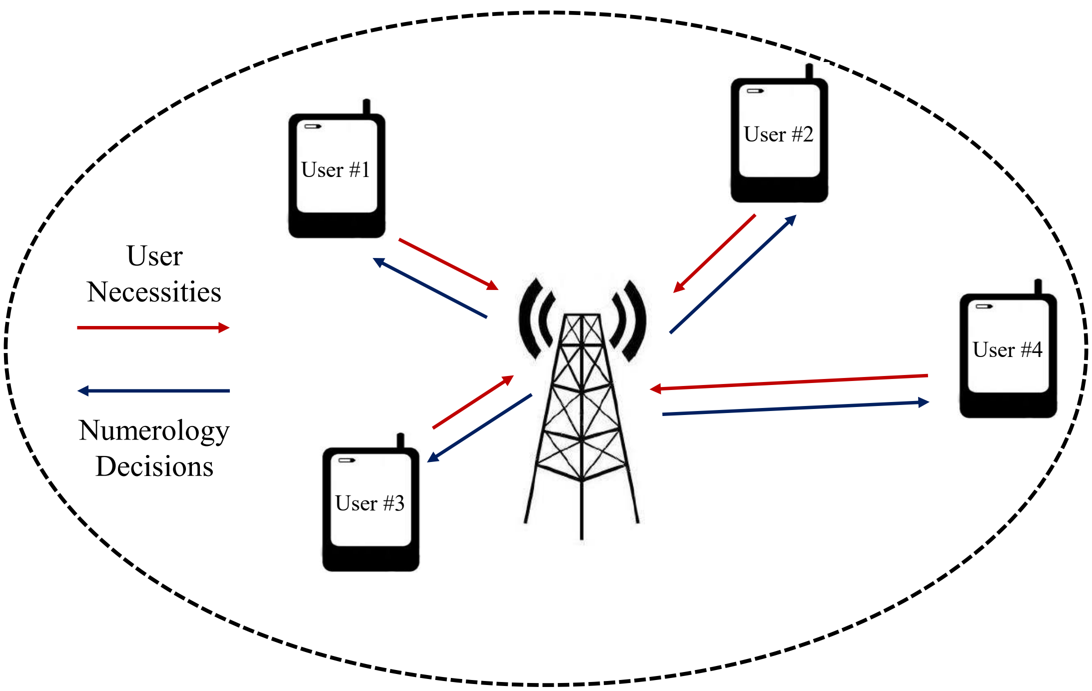


Figure 3.13: Simple representation of numerology selection methodology in a cell serving users with various necessities [4]. User necessities can be gathered by BS at different or same times but numerology decisions are made at the same time.

For one active BWP at a time case, an example numerology selection methodology is proposed in [4] that uses a heuristic algorithm to configure numerologies suitable for each user. Fig. 3.13 illustrates this resource allocation optimization methodology. The proposed method also provides an active BWP switching mechanism. Δf, CP duration (T_{CP}), and spectral efficiency requirements of all users in a cell are input to the algorithm.

It is possible to increase the number of numerologies in beyond 5G. Offering more numerologies simultaneously ensures that all user and service requirements are satisfied, but this requires more sophisticated numerology selection mechanisms. To reduce computational costs, BSs may use two-step numerology selection methods in the future. The first step decides on the most suitable numerology set between different sets. Then, the second step determines the best numerologies from the set that is selected in the first step. Additionally, different numerology selection methods may become available for multiple active BWPs.

In [64], a heuristic solution is proposed while considering the optimization of the data block allocation as a Knapsack problem. Optimal numerology assignment methodology can be also developed for multiple numerologies.

3.2.2 Non-Orthogonality in Multiple Numerologies

In this subsection, different implementation structures are presented in the scope of non-orthogonality in multiple numerologies. INI changes tremendously regarding the non-orthogonality under different implementations.

Relationships between different scenarios for inter-numerologies are summarized in Fig. 3.14. Synchronous communications means there is a slot-based synchronicity. In addition, overlapping of multiple numerologies is pulse-based and sidelobe-based. If there is a non-orthogonality for the edge subcarriers, there can be full or partial orthogonality for the inner subcarriers of multiple numerologies. Non-orthogonality of inter-numerologies need to be analyzed for each of the subcarriers separately. Several example demonstrations are shown in Fig. 3.15.

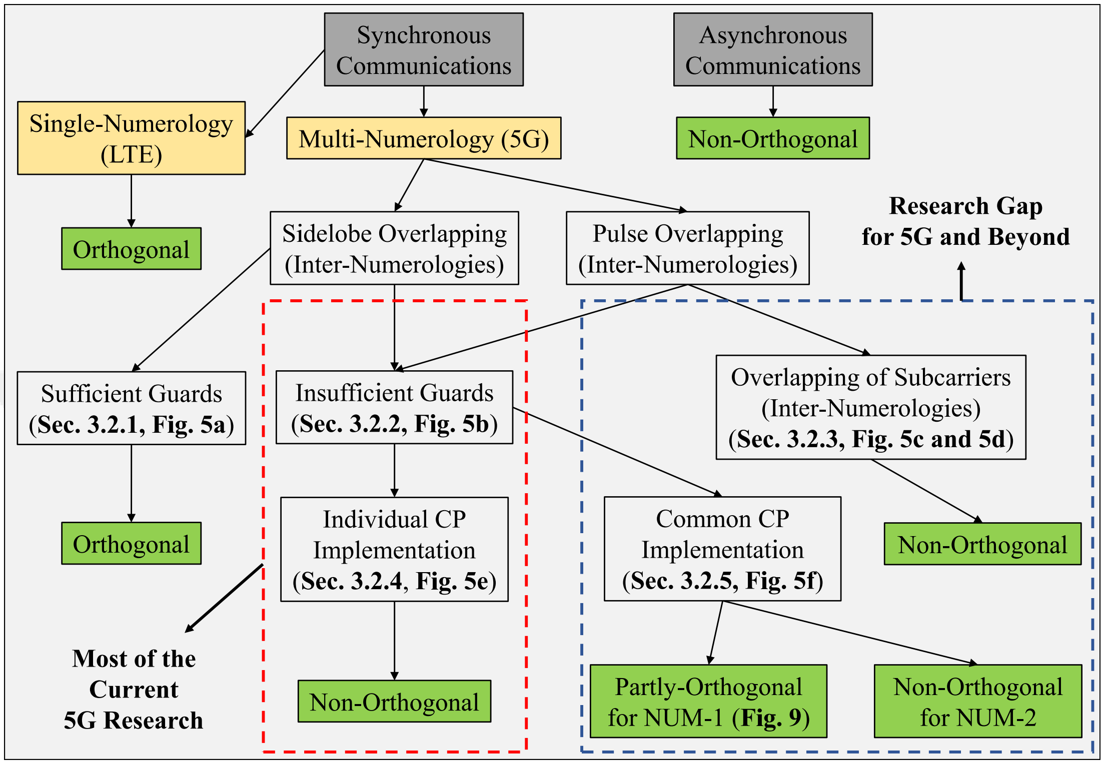


Figure 3.14: Non-orthogonality and partial orthogonality of inter-numerologies for different OFDM-based scenarios. NUM-1 has narrow subcarriers and NUM-2 has wider subcarriers.

3.2.2.1 Sidelobe Overlapping with Sufficient Guard Band

Non-orthogonality can result either from pulse-based or sidelobe-based overlapping numerologies for the synchronous communications. In the case of sidelobe overlapping subcarriers, the main reason of non-orthogonality is out-of-band (OOB) emission. We can use large guard bands between different numerologies to move away from the spectral leakage and reduce INI. Resource elements within the same numerology are orthogonal to each other, but resource elements of any two numerologies with different Δfs are only orthogonal to each other if sufficient guards exist among them [2, 56].

Deciding about the required guard bands between multiple numerologies for different scenarios is an important research area. The amount of guard bands affects spectral efficiency inversely proportional.

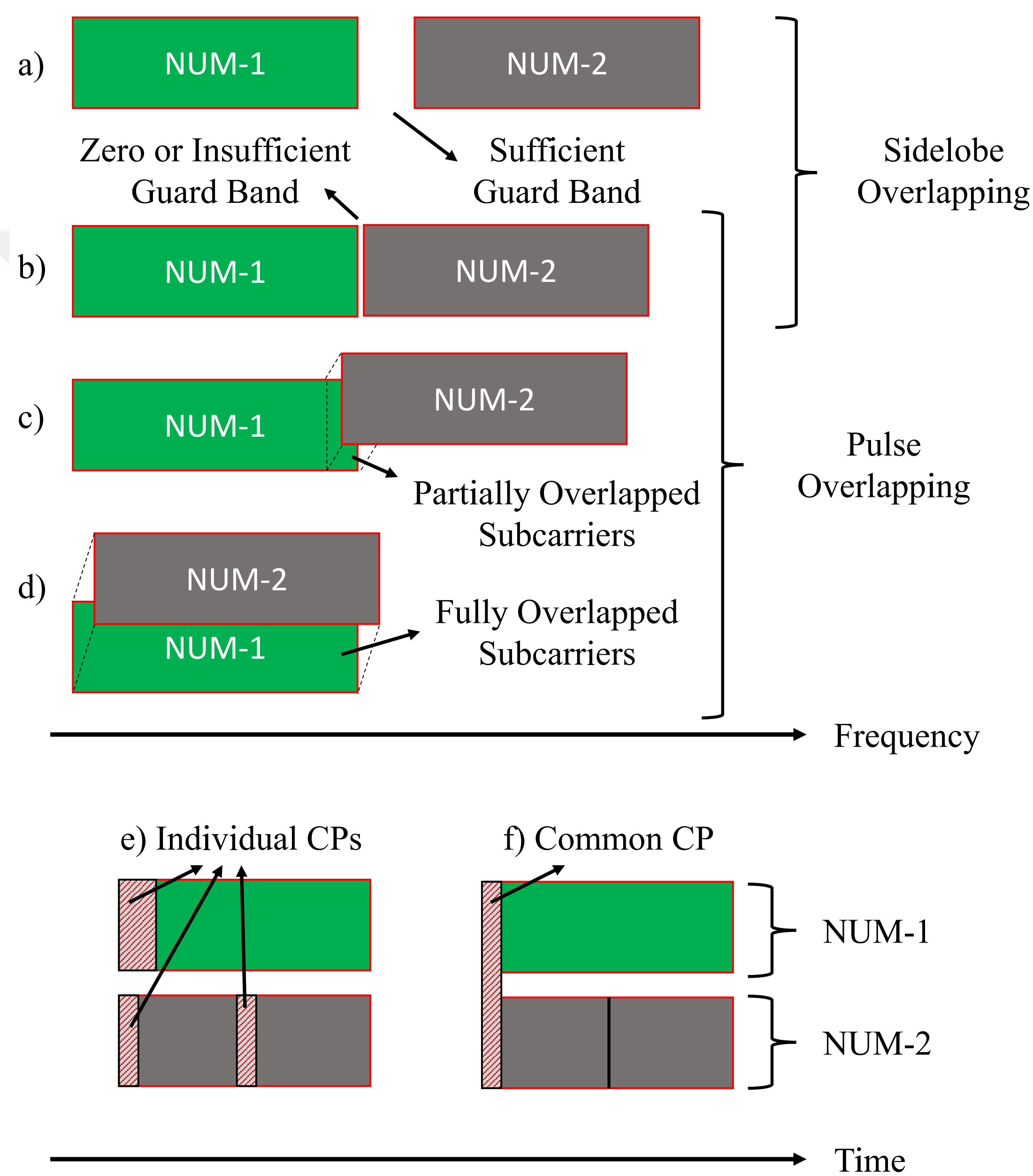


Figure 3.15: Frequency and time domain demonstrations of the scenarios given in Fig. 3.14. Numerology-1 and Numerology-2 are presented as NUM-1 and NUM-2, respectively. Subcarrier spacing is shown with SCS.

3.2.2.2 Insufficient Guard Band

If the guard amount between multiple numerologies is insufficient or it is a zero-guard case [2], inter-numerology non-orthogonality is inevitable. Most of the studies for the 5G multi-numerology systems can be classified under this scenario.

OOB emission increase INI effects especially for the edge subcarriers of each numerologies. Side lobes decrease from edge to inner subcarriers in all multi-numerology scenarios. Additionally, separation of the composite signal at the receiver unintentionally increase INI during the separation of the composite signal. This situation is discussed more in the next subsections.

Different CP implementation techniques can be employed to decrease INI effects in the scenarios that have insufficient guards. Alternative INI reduction techniques like filtering and windowing can be preferred as mentioned in Section 3.2.4. It is also possible to use advanced scheduling techniques like in Section 3.2.5.

3.2.2.3 Overlapped Subcarriers

Inter-numerology non-orthogonality can be originated from overlapping of subcarriers in a fully or partially manner. In [57], authors proposed a numerology-domain non-orthogonal multiple accessing (NOMA) system with fully-overlapping multi-numerology structures. However, it is also possible to overlap only small amount of subcarriers that belong to multiple numerologies. For the single-numerology systems, partially-overlapping subcarriers scenario is studied in [67]. It is also possible to make a similar system in the multi-numerology domain. Example demonstrations are shown in Fig. 3.15(c) and Fig. 3.15(d).

NR allows overlapping of BWPs using different numerologies in time-frequency grid [46]. Numerology-domain NOMA system designs can be developed to exploit this gap in 5G. However, receiver complexity increase for the scenarios with the overlapped subcarriers.

3.2.2.4 Individual CP Implementation

CP implementation techniques have effects on non-orthogonality in multi numerologies [56–58]. Individual CP usage for each OFDM symbol is preferred in 3GPP standardization for 5G NR [44]. However, there is an important disadvantage of employing individual CPs.

A composite signal is formed with summing time domain signals of different numerologies at the end of transmitter side as shown in Fig. 3.7(a). There are more than one symbol for the shorter symbol duration numerologies corresponding to one symbol of the other numerology that has a longer symbol duration as shown in Fig. 3.15(e). Therefore, CPs of the shorter symbol duration numerologies corrupt orthogonality of long symbol duration numerology during FFT process at the receiver side.

3.2.2.5 Common CP Implementation

For the common CP usage, a composite signal is formed with summing time domain signals of different numerologies before CP addition process as shown in Fig. 3.7(b) and Fig. 3.15(f). One CP is added to the composite signal at the end of transmitter. Hence, the disadvantage of employing individual CPs is prevented because orthogonality is not corrupted during FFT process at the receiver side. There is less INI because of the partial orthogonality for long symbol duration numerology with the common CP implementation. However, there is not any difference between two implementations regarding the short symbol duration numerology.

Common CP also can be useful from the perspectives of spectral efficiency and latency. Advantages of zero-interference subcarriers can be exploited for different purposes like channel estimation. ultra reliable and low latency communications (uRLLC) users can be scheduled at the short symbol duration numerology side with common CP implementation because there is less INI and this implementation provides more reliable communications. Moreover, latency can be reduced by using a shorter common CP in suitable scenarios [68]. Based on all these advantages, it can be said that common CP implementation may be one of the research areas for 5G beyond technologies. Additionally, common CP needs to be arranged according to wireless channel of different UEs and common CP selection of multiple users is also an important research area.

3.2.3 INI Estimation Models and Cancellation Methods

INI can be simply defined as a leakage between different numerology structures. The amount of INI can vary depending on Δf, BW, guards, CP usage type, filtering/windowing usage, and user power levels. All of the related parameters need to be analyzed together to form estimation models for INI. There are some important studies about INI estimation in the literature as listed in Table 3.7 but they do not include all of the aspects for the INI sources. In these studies, also INI cancellation methods are proposed to remove estimated INI at the receiver.

Authors of [56] shows that no-CP case can be used to estimate structured INI. Common CP implementation can be considered as a similar scenario as stated in Section 3.2.2 [69]. Structured INI can be exploited during the INI cancellation process. The analytical expression of the INI power is established for windowed OFDM systems in [45].

INI estimation can be used as a feedback to all other adaptive systems that include numerology selection, adaptive guards, filtering/windowing decision, and advanced scheduling methods. Interference models can be very useful for adaptive decision on different algorithms for multi-numerology systems.

3.2.4 INI Control and Reduction Techniques

Various INI reduction techniques that prevent INI and effects of them are explained in this subsection. Effects of guards analyzed in [2, 51, 60, 63]. Different filtering techniques are provided in [56, 60–62]. Moreover, windowing methods

Table 3.7: Comparison of INI analysis studies in the literature.

Study	INI Analysis	Guard Band Effects	Windowing Effects	Filtering Effects	Alternative CP Utilization
[56]	✓	✓		✓	No CP case
[45]	✓	✓	✓		
[70]	✓	✓		✓	
[71]	✓	✓			
[69]	✓	✓			Common CP
[72]	✓	✓	✓		
[73]	✓	✓			

are discussed in [45, 60].

3.2.4.1 Effects of Guard Bands Between Multi Numerologies

This subsection deals with the adjustment of frequency domain guards with respect to estimated INI after numerologies are selected. In 3GPP standards, guard band choices can be flexible [50]. Adaptive guard band concept for different numerologies becomes a crucial research area at this point.

As it is well known, the OFDM signal is well localized in the time domain with a rectangular pulse shape, which corresponds to a sinc pulse in the frequency domain. Sincs cause significant OOB emission and guard bands are needed between two adjacent subbands with different numerologies to handle the interference.

The OOB emission increases as the symbol duration decreases. Therefore, more guard band is required for the numerologies with higher Δf. For the edge subcarriers of two adjacent numerologies, signal to interference plus noise ratio (SINR) decrease is more significant compared to the decrease in remaining subcarriers. Most of the interference comes from the edge subcarriers [74]. Grouping services in BWPs reduces the amount of necessary guards and eases scheduling when such fast numerology variations become necessities. Moreover, passing OFDM signal through power amplifiers causes non-linear distortions. The peak-to-average power ratio (PAPR) and OOB emission increase as the number of active subcarriers increases. As a result, more guard band is needed for the transmissions with wider occupied numerology BWs.

3.2.4.2 Effects of Guard Intervals for INI Elimination

In addition to guard bands between different numerologies, the guards in time and frequency domains must be jointly optimized to boost the spectral efficiency [51]. The guard times can be utilized flexibly, similar to guard bands. Combining time-frequency guard flexibility yields that empty resource elements can virtually be placed anywhere. Interpreting this at a multi-user level reveals that the uplink (UL) slot of one UE and the downlink (DL) slot of another UE can be scheduled to consecutive time or frequency resources with little guard time and band. This poses serious requirements in pulse shaping, making localized pulses and interference rejection techniques critical.

3.2.4.3 Filtering and Windowing in NR

INI cannot be handled only using guards but also with the filtering and windowing approaches that require additional guards. Applying proper filtering and windowing methods are left for the implementation of standardization. Allocating users optimal guards minimizes but not completely eliminates the interference on the received signal in a non-orthogonal system. The receiver may also engage in filtering and windowing to further eliminate the remaining interference, but doing so using conventional methods requires additional guards. The assigned optimum guards may not be sufficient if minimum latencies are required.

3.2.5 Scheduling Techniques for Multiple Numerologies

3.2.5.1 Optimization on the Number of Active Numerologies

Authors of [4] find the efficient number of active numerologies that should be simultaneously employed by users. The algorithm aims to minimize various overheads to provide a practical solution satisfying different service and user requirements using multi-numerology structures. All of the numerologies that are defined in standards do not need to be used all the time.

Basically, the amount of total guard band in the lattice increases with increasing number of numerologies. Hence, there is a trade-off between the spectral efficiency and multi-numerology system flexibility. Although not imposed by the standard [44], they allocate BWPs configured to use the same numerologies consecutively in an effort to reduce guard bands and computational complexity.

3.2.5.2 Edge User Scheduling for Multiple Numerologies

Edge users of multiple numerologies experience unfairness because most of the INI is concentrated at the edges of numerologies. Intensive INI at the edges causes low reliability for edge UEs. Proper scheduling mechanisms can increase fairness and reliability for these UEs.

In [18], fairness of UEs at the numerology edges is increased by minimizing the INI effects while maintaining spectral efficiency with fixed guard bands. They use three inputs that include service type, power level, and BW of a UE. Their only focus is on edge UEs in the proposed algorithms. The other UEs can be scheduled randomly in frequency domain. Hence, frequency dependent scheduling flexibility does not lose. The main aim is that minimization of the power difference between edge users of multiple numerologies as shown in Fig. 3.16. Performance analysis results for power difference scenarios are provided in Section 3.1.6.4.

Contrary to [18], authors of [51] aim to minimize guard necessities with a fixed

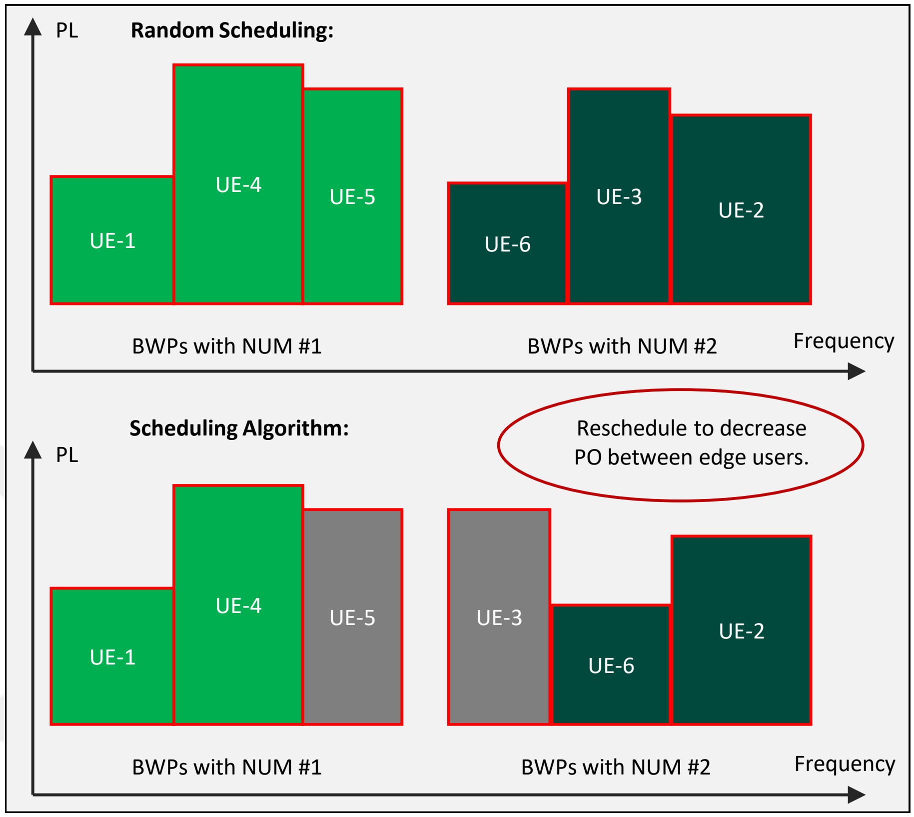


Figure 3.16: Example demonstration for the edge user scheduling algorithm. Power levels are shown with PL.

SIR and fairness in their scheduling algorithm. In their case, spectral efficiency can be increased due to the fewer guard necessities between different numerologies under desired SIR.

3.2.6 Possible Waveform Parameter Options for 6G

Apparently, the number of configurable parameters and numerologies for a single waveform may increase with 6G [75]. There may be more parameter variety than the 5G numerologies (e.g., flexibility in subcarrier spacings) [4]. Different lattice domains can be exploited with or without time-frequency. These domains provide new types of numerology parameters (e.g., beamwidth parameter for space domain). Hence, variety of numerology parameters increases. In the future generations, also different types of CP structures can be employed along with multiple

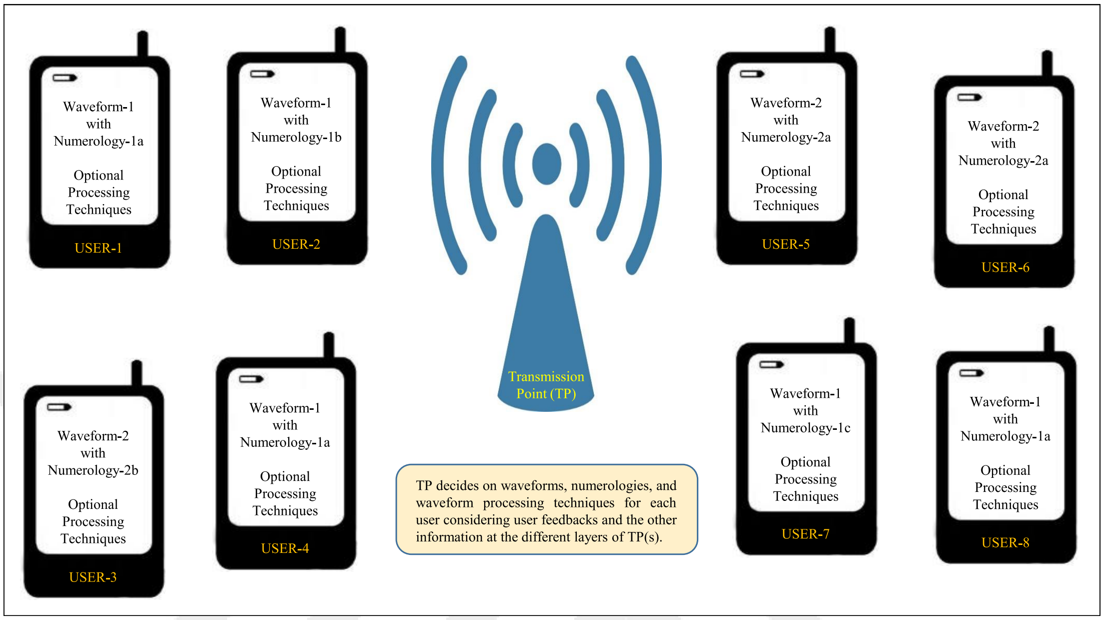


Figure 3.17: Different parameter assignments for each user in the same coverage area. It is assumed that coexistence of multiple waveforms in the same frame is also possible with multiple numerologies and additional waveform processing techniques.

numerologies [69]. Moreover, CP parameter can take more values independent from the subcarrier spacing. There can be different waveform processing methods in 6G, so these methods can bring new parameter types. Parametrization of new techniques will increase the number of waveform parameters. Additionally, multiple waveforms may be utilized together in the same frame for the next generation of wireless communications standards [76]. For example, it is possible to use different waveforms together for beyond 52.6 GHz [1]. Coexistence of various standards may also trigger the designs of multiple waveforms in a frame. Different waveforms can have specific numerologies with several types of parameters. Therefore, there will be considerable amount of waveform parameters in 6G and options will exponentially increase with the number of waveform types. An example usage of multiple waveforms and numerologies with some processing techniques is illustrated in Fig. 3.17. There is a necessity of configurable parameter richness to meet the potential future requirements of 6G networks flexibly.

A projection of 5G NR is combined with potential waveform structures to

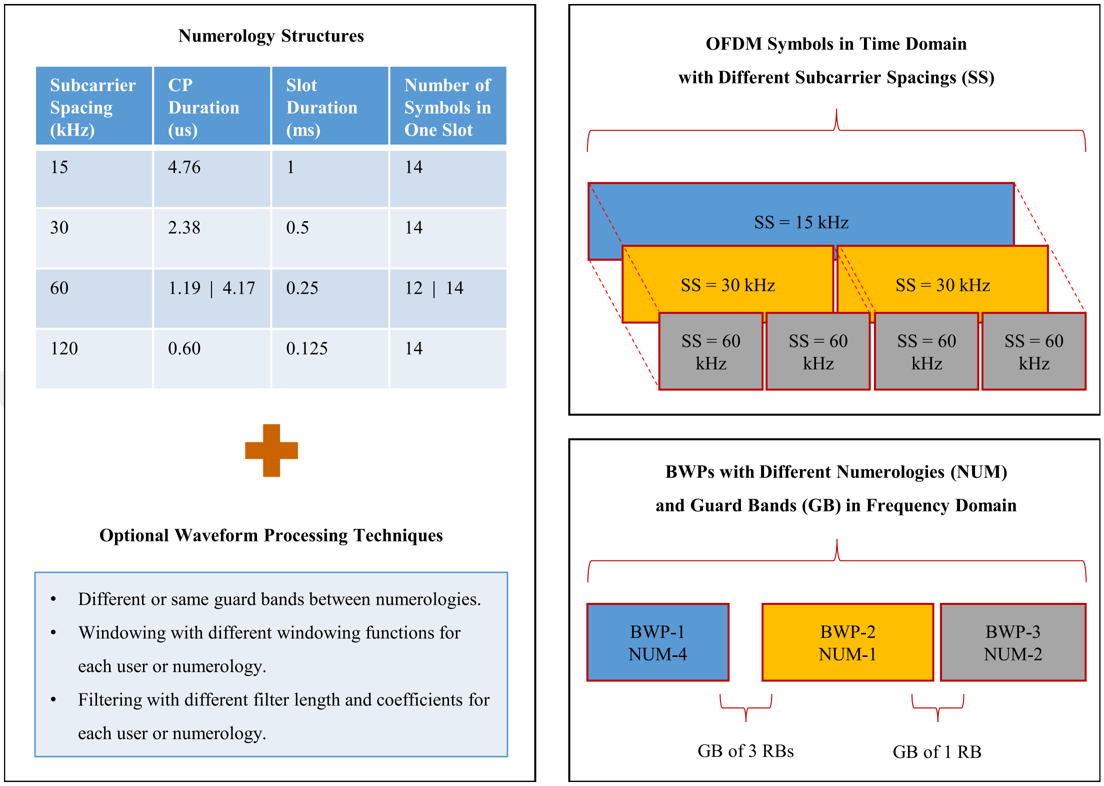


Figure 3.18: The list of numerology parameters and additional parameter types for CP-OFDM in 5G NR with example demonstrations.

forecast the waveform parameters in 6G. It is shown that there will be numerous waveform parameter options in the future. TPs will use all of these waveform parameter options while assigning them to different users with the optimal decisions. Possible differences between 5G and 6G waveform parameters are summarized in Table 3.8.

Multi-numerology based CP-OFDM waveform is standardized in 5G NR. There are also optional waveform processing techniques like guard utilization, windowing and filtering in 5G NR as exemplified with Fig. 3.18. All of the optional waveform processing techniques have different type of parameters with various implementation structures. The number of numerologies and processing options will increase in 6G and the coexistence of multiple waveforms in the same frame may also be possible for 6G.

Table 3.8: Possible differences between 5G and 6G waveform parameters.

	5G Waveform Parameters	**Possible 6G Waveform Parameters**
Numerology Structures	**(1)** Time-frequency lattice domains. **(2)** Subcarrier spacings of 15 kHz, 30 kHz, 60 kHz and 120 kHz. **(3)** Fixed CP ratio but two options for 60 kHz subcarrier spacing.	**(1)** There may be different lattice domains with or without time-frequency. **(2)** Different domains provide new types of numerology parameters. **(3)** Common CP utilization [14] can be preferred to make CP ratio flexible. **(4)** CP parameter can take more values independent from the subcarrier spacing. **(5)** There may be more parameter variety than the 5G numerologies [4]. **(6)** For the case of multiple waveforms, each waveform may have separate numerology options on the same or different lattice structures.
Waveform Processing	**(1)** Inter-numerology guard bands. **(2)** Roll-off factors for windowing. **(3)** Filter coefficients for filtering. **(4)** Different types of parameters for the other processing techniques.	**(1)** Waveform processing methods need to be enhanced because of more INI effects. **(2)** For new lattice structures, new INI management techniques need to be developed. **(3)** New type of interferences if multiple waveforms are utilized in the same frame. **(4)** New waveform processing techniques to control, reduce and exploit IWI. **(5)** Parametrization of each new technique will increase the number of waveform parameters.

New attempts to increase flexibility generally will increase the number of parameter types in 6G. Some possible challenges can be listed as follow:

- There may be more numerology options in 6G but it will increase INI effects. Hence, waveform processing techniques need to be enhanced. This situation will give rise the increment for the number of possible new parameters.
- New types of CP utilization methods can be preferred in 6G, such as common CP [14]. It makes CP ratio more flexible but number of possible CP values increases compared to the numerology designs in 5G systems.
- If different lattice domains are used in 6G rather than the time-frequency, new types of waveform parameters will be included in the numerology sets. Therefore, the number of numerology options will increase. Additionally, the current INI management techniques will be useless for different lattice domains. Then, new waveform processing techniques and the related parameters need to be defined. This case will also increase the number of possible waveform parameters.
- Utilizing multiple waveforms in a single frame may be possible for 6G. Lattice structures can be different for each waveform as an important challenge. Besides, there may be different types of numerology parameters for multiple waveforms. Additionally, IWI needs to be controlled by new waveform processing techniqes and the related parameters. Waveform parameters will increase in all of these cases for 6G.

3.2.6.1 Multiple Numerologies

In one of the first studies on multiple numerologies [20], channel-aware numerology assignments are done for multiple users with CP-OFDM. However, multi-numerology structure of 5G NR is flexible in order to consider different feedbacks including channel structures of users. Different frame parameters under four numerologies are provided for data transmission of 5G NR in Fig. 3.18 [14]. Numerologies can have various parameters that are dependent or independent of each other. In 5G NR, there is only one main adjustable parameter which is a subcarrier spacing. The other parameters are generally dependent on it because of the practicality.

6G systems probably will come with more numerology structures that provides more flexibility. If the number of waveform related adjustable parameters increase with 6G, then there will be more options for multiple numerologies [4]. For example, adjustable CP duration and utilization are important concepts for 6G [69]. Using one common CP for different numerologies may be one of the new concepts in 6G and it changes the number of numerology options noteworthily [14].

Furthermore, possible implementation structures for multi-numerology CP-OFDM vary with different bandwidth part (BWP) operations in 5G NR [46]. BWP defines a fixed band with the same numerology. It is a bridge between numerologies and 5G NR scheduling. BWP operations are flexible, e.g., users with the same numerologies can be located contiguously in the frequency domain rather than creating several non-adjacent BWPs with the same numerology. Similarly, there are many different BWP implementation options or radio access network (RAN) slicing methods in 5G and beyond systems. The number of scheduling-related implementations and methods will likely increase in 6G.

3.2.6.2 Waveform Processing Techniques

Windowing usage, filtering usage, and inter-numerology guard utilization are example waveform processing techniques for cellular communications systems [77]. More waveform processing techniques can be developed in 6G to address prospective requirements. Multiple numerologies and the other non-orthogonality sources increase the importance of waveform processing techniques [14]. These techniques require various adjustable parameters. For example, several prototype filters in the literature including rectangular, raised-cosine, Gaussian and so on, are provided in [19]. There is a flexibility to apply windowing with different or same roll-off factors on the subframes for each numerology or composite signal of multiple numerologies at the transmitter. Receiver windowing is the another option. Roll-off factor optimization is analyzed in [21]. Different filters, the related coefficients, and roll-off factors increase the number of options for waveform processing techniques. Coexistence of 6G and the other standards will have even more options, especially if there are multiple waveforms in the same frame.

3.2.6.3 Multiple Waveforms

In addition to multiple numerologies and waveform processing techniques, one of the future technologies is coexistence of multiple waveforms in the same frame together with multiple numerologies and processing techniques. In [78], frequency-domain non-orthogonal multiple access (NOMA) structure with two sets of orthogonal signal waveforms (CDMA and OFDMA) is presented. OFDM and OFDM-IM are used together as another NOMA scheme in [79] and [80]. Probably, there will be more studies on multi-waveform concept in 6G.

If there are multiple waveforms in the same coverage area [76], it means that there will be a tremendously high number of options for the waveform parameters. Thus, the number of parameter options will double many times, depending on the number and types of waveforms. In addition, there will be more types of numerology structures if 6G waveforms use different lattice domains.

Chapter 4

Waveform Parameter Assignment

Multi-numerology waveform concept is one of the fundamental topics in 5G communications systems. It provides flexibility while meeting the requirements of new generation of cellular communications. Besides, waveform parameter assignment to users and services becomes a new research opportunity. This chapter aims to draw attention to the waveform parameter assignment subject regarding resource allocation and scheduling. In this respect, a review on waveform parameter assignment is presented around different multi-numerology waveform papers in the literature. Moreover, numerology assignment, waveform processing, and the related joint optimization issues are discussed as a case study of waveform parameter assignment with multiple numerologies in 5G New Radio. Additionally, the novel solutions are proposed for the waveform parameter assignment.

Fig. 4.1 shows an example demonstration for the single-numerology and multi-numerology communications. The users do not communicate with a base station (BS) with different numerologies in a single-numerology system. Forcing to use only one numerology does not provide a high flexibility to meet several requirements of different users and services [4]. Diversifying the number of parameters increases the flexibility [81]. Hence, multi-numerology waveforms enhance the

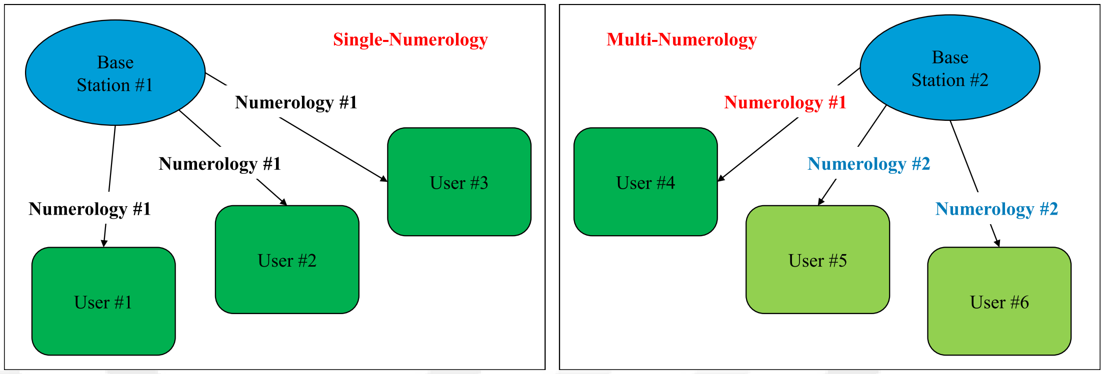


Figure 4.1: An example demonstration for the communications with a single-numerology and multi-numerology waveform.

flexibility. However, there is a non-orthogonality problem between multiple numerologies because of the subcarrier spacing variations [69]. If windowing, filtering, or inter-numerology guard bands are not employed, orthogonality cannot be ensured for multi-numerology OFDM systems [14, 45]. Therefore, there is an important trade-off situation regarding the flexibility and inter-numerology interference (INI) in 5G NR. Different trade-offs for the INI are shown in Fig. 4.2.

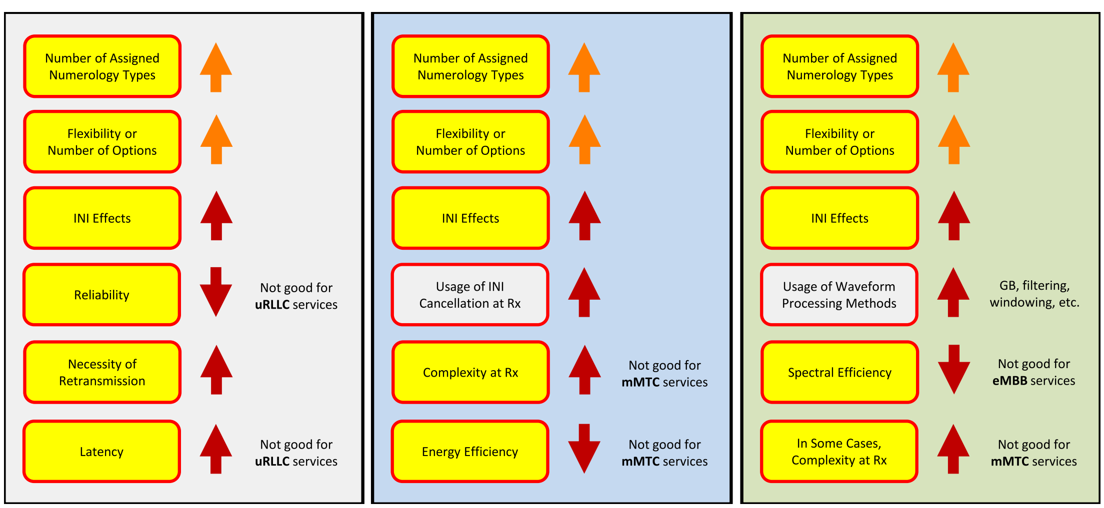


Figure 4.2: Several trade-off situations considering the INI.

4.1 A Novel Waveform Parameter Assignment Framework

5G NR comes with more waveform parameters than the previous generations. Moreover, there are new problem sources like INI. The importance of controlling mechanisms in MAC layer (e.g., parameter optimization, scheduling, radio resource control, evaluating feedback signals and measurements) increase. Through multi-numerology based 5G systems, waveform studies become directly related with scheduling, resource allocation and radio access network (RAN) slicing [4, 17, 18, 51, 55, 63, 66, 82–91]. Waveform parametrization and waveform parameter assignment are important topics from this perspective. Details of the relationships for different studies are provided in the next sections.

This section mainly aims to present a vision on waveform parameter assignment considering the current waveform design in 5G NR. The objective of the section is to draw attention to the waveform parameter assignment by employing the available waveform design more efficient without designing a new waveform. At that point, multi-numerology concept plays a crucial role for the waveform parametrization. Hence, waveform parameter assignment literature is reviewed from the multi-numerology perspective. After that, case studies for the optimizations in numerology assignment, waveform processing, and joint methods are discussed to reveal the relationships between multi-numerology concept and waveform parameter assignment in 5G NR.

4.1.1 Problem Definition

Two main problems can be analyzed related with the waveform parameter assignment [17]: 1) A necessity of optimal parameter assignment strategy for each single user while meeting user requirements one by one; 2) A necessity of optimal parameter assignment strategy for multiple users while meeting their individual requirements together. Meeting several requirements of one user can be difficult

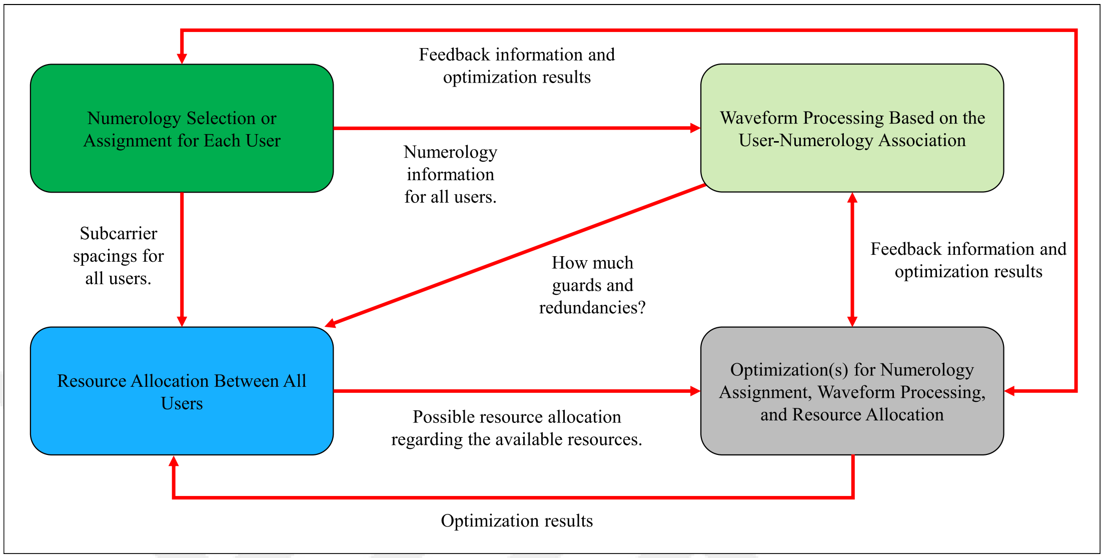


Figure 4.3: Illustrations of the given subproblems and their example relationships.

in some cases. Moreover, multiple users can have more challenging requirements to be met in the same frame of a waveform. These two main problems can be solved separately [4,51,55,63,85,86]. However, they are not independent problems so it is also possible to solve them together [17, 88, 89].

The subproblems of the given main two problems can be listed as: 1) Numerology selection or assignment for each user, 2) Waveform processing based on the user-numerology association, 3) Resource allocation between all users, 4) Optimization(s) for numerology assignment, waveform processing, and resource allocation. Figure 4.3 illustrates these problems. These subproblems can be solved independently or jointly. For example, waveform processing techniques like adaptive inter-numerology guard bands and subframe windowing with different roll-off factors can be designed based on the assumption of perfect user-numerology association [4, 51, 55, 63, 85, 86]. However, it is more realistic to develop this type of waveform processing techniques together with adaptive user-numerology association methods because there can be a different waveform processing technique or parameter necessity while numerologies of users are changing [17, 88].

More requirements need more flexibility. Flexibility brings more parametrization necessity. Then the high number of parameters makes the given optimization problems more difficult. The assignment of waveform parameters for each user is done at TP considering user feedbacks and the other information acquired in different layers. However, multiplexing waveforms with different parameterization may give rise to several penalties that include new forms of interferences, such as inter-numerology interference (INI) and inter-waveform interference (IWI), scheduling complexity, and signaling overhead [14]. As a consequence, various optimization mechanisms are developed in the literature to compensate or exploit the adverse effects (e.g., INI) of utilizing multiple waveform parameters in 5G and beyond. Example resource allocation optimization techniques are proposed in [4] and [66]. Waveform parameter assignment will be a more difficult task in 6G because of the increasing number of configurable parameters and requirements. From the optimization perspective, providing a flexible structure with a high number of controllable waveform parameters can not always be the best solution for users that have several requirements in a coverage area of one TP. A balance should exist between the constructive and destructive impacts of employing different types of waveform parameters together [4]. Furthermore, more difficult scenarios can be realized, such as waveform parameter assignment in coordinated multiple TPs with multiple users. Joint parameter assignment for all users in different cells is not an easy problem. Hence, next generation TPs require powerful waveform parameter assignment mechanisms with proper optimizations so that an efficient resource allocation is ensured in 6G systems.

4.1.2 Previous Works

We can relate different multi-numerology studies [14] with the waveform parameter assignment subject. Multi-numerology studies can be grouped as 1) general multi-numerology concept, 2) inter-numerology interference (INI) and non-orthogonality issues, 3) time-domain analysis of multi-numerology signals, and 4) scheduling and resource allocation. Figure 4.4 shows the relationships between different topics for multi-numerology waveforms. Waveform parameter assignment can be done regarding the information of requirements and frame design

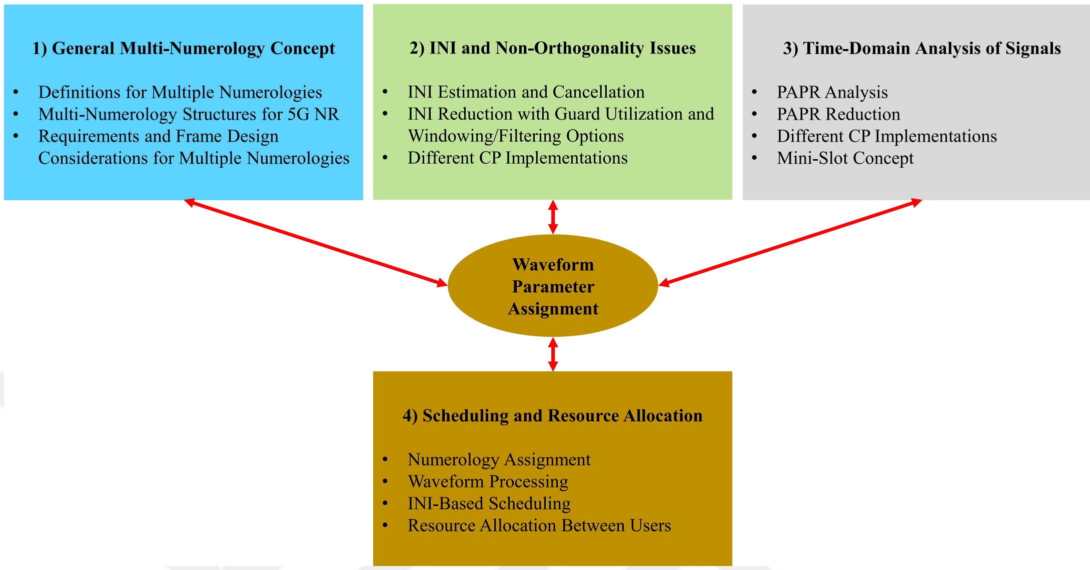


Figure 4.4: All of the multi-numerology based research topics are directly associated with waveform parameter assignment subject because the other topics cannot be investigated without waveform parameter decisions.

considerations for multiple numerologies (Group-1). Therefore, relationships between the multi-numerology structures defined in standards and different requirements with frame design consideratios should be established properly. Meanwhile, INI analysis and the related non-orthogonality issues (Group-2) are important feedbacks for waveform parameter assignment. INI is a strong drawback considering the resulting non-orthogonality. Time-domain analysis of multi-numerology signals (Group-3) has also effects on the waveform parameter assignment algorithms. Scheduling and resource allocation units (Group-4) include all of these feedback mechanisms and waveform parameter assignment algorithms to solve the problems that are defined in Section 4.1.1.

For Group-1 studies, general concept on multi-numerology structures are discussed in [2, 47, 60, 62]. Research opportunities for multi-numerology waveform are given in [14]. In [4] and [3], requirements and frame design considerations for multiple numerologies are explained. Requirement analysis is very important for the feedback of solution mechanisms regarding the optimization problems. If the user and service requirements are mapped into the waveform parameters correctly, all of these requirements can be met in a better way. Requirements should be matched with the suitable waveform parameters like in [4]. Otherwise, employing multi-numerology concept is not meaningful.

For Group-2 studies, INI analysis and the related non-orthogonality issues are discussed in [45, 56, 69–73]. INI cancellation methods are provided in [45, 56, 72, 73]. Multi-numerology waveforms provide a high flexibility however their main disadvantage is INI effects. Reduction or cancellation of INI enhance reliability and then the capacity. Besides, INI analysis is one of the main feedbacks for the waveform parameter assignment algorithms.

For Group-3 studies, PAPR reduction methods for multi-numerology OFDM signals are developed in [92] and [93]. Moreover, PAPR analysis is provided in [94] based on the multiple numerologies. Different CP implementations are discussed in [14] and [69]. Using only one CP for the composite signal that is formed by subframes of different numerologies provides several advantages like higher spectral efficiency for the shorter CP cases rather than the fixed individual CPs of multiple numerologies. CP implementation variety has direct effects on the waveform parameter assignment.

For Group-4 studies, multi-numerology based scheduling and resource allocation papers are investigated under five subgroups that are listed below. In Section 4.1.3, some of these studies are revisited to give waveform parameter assignment perspective in more detail. As a short summary, Table 4.1 shows the differences between the related studies in multi-numerology literature for scheduling and resource allocation.

1. Numerology assignment
2. Waveform processing
3. INI-based scheduling
4. Resource allocation between users
5. Joint optimization

Table 4.1: Comparison of the multi-numerology based scheduling and resource allocation studies.

Study	Numerology Assignment	Waveform Processing	INI-Based Scheduling	Resource Allocation	Joint Optimization
[82]				✓	
[83]				✓	
[51]		✓			
[63]		✓			
[84]				✓	
[85]	✓				
[86]	✓				
[87]			✓	✓	
[88]	✓		✓	✓	✓
[89]			✓	✓	✓
[55]	✓				
[90]				✓	
[4]	✓				
[18]			✓		
[17]	✓	✓			✓
[66]				✓	
[91]				✓	

Numerology Assignment: In most of the studies under multi-numerology waveform literature, numerology assignment is given as an assumption to make the other optimizations. Some of the studies present joint optimization with the numerology assignment like in [17, 85, 88]. [17] uses machine learning (ML) methods to optimize the numerology assignment and guard band selection between different numerologies jointly. In [85], the authors assume that there is a direct mapping between numerologies and service types. The paper optimizes the numerology configuration and the DL-UL duplexing ratio in a TDD. The focus of [88] is the joint optimization of bandwidth allocations and numerology assignments for four users. There are also pure numerology assignment optimization studies in the literature [4, 55, 85, 86]. [4] makes optimal numerology assignment regarding the requirements and frame design considerations. The authors try to find effective number of multiple numerologies. In [86], the authors find the best one subcarrier spacing for all users. Adaptive numerology selection method is developed for V2X service in [55].

Waveform Processing: Adaptive guard band concept is analyzed in [63] and [51] for multiple numerologies. Putting guard band between different numerologies has important effect on INI but using large guard bands decrease spectral efficiency. Moreover, it is possible to use different amount of guard bands between different numerology pairs. [17] investigates the ML usage for the guard band decisions. Additionally, INI analysis studies also include guard band usage in the INI equations.

INI-Based Scheduling: INI is an important feedback information for scheduling decisions because it is the main disadvantage of multi-numerology systems. In different studies, INI is used as an input for scheduling mechanisms [18, 87–89]. INI can be called as inter-band interference (IBI) in some of these studies.

Resource Allocation Between Users: Most of the multi-numerology scheduling studies in the literature are focused on the resource allocation [66, 82–84, 87–91]. The main aim of them is the optimization of bandwidth allocations. They are not directly related with the waveform parameter assignment but resource allocation and waveform parameter assignment should be handled together jointly.

Joint optimization: Numerology assignment, waveform processing, the amount of INI, and resource allocation can be jointly optimized. Some of the studies make optimizations for some of them together [17, 85, 88, 89]. A summary of the literature is presented in Table 4.1.

In the literature, generally numerology assignment is given as an assumption to make the optimizations for waveform parameters. Some of the studies present joint optimization with the numerology assignment like in [17, 85, 88]. In [17], ML methods are utilized to optimize the numerology assignment and guard band selection between different numerologies jointly. In [85], the authors assume that there is a direct mapping between numerologies and use cases. The paper optimizes the numerology configuration and the DL-UL duplexing ratio in a TDD.

The focus of [88] is the joint optimization of bandwidth allocations and numerology assignments for four users. There are also pure numerology assignment optimization studies in the literature [4, 55, 85, 86]. In [4], optimal numerology assignment is done regarding the requirements and frame design considerations to find effective number of numerologies. In [86], the authors find the best single subcarrier spacing for all users. Adaptive numerology selection method is developed for V2X service in [55]. Adaptive guard band concept is analyzed in [49, 51, 63] for multiple numerologies. Putting guard band between different numerologies has important effect on INI but using large guard bands decrease spectral efficiency. Moreover, it is possible to use different amount of guard bands between different numerology pairs. Most of the multi-numerology scheduling studies are focused on the resource allocation [66, 82–84, 87–91]. The main aim of these studies is the optimization of bandwidth allocations rather than waveform parameter assignment. However, resource allocation and waveform parameter assignment should be handled together jointly.

4.1.3 Waveform Parameter Assignment and Optimization

3GPP standards give the BS and UE manufacturers the freedom to implement any additional algorithm they desire as long as it is transparent to the receiver [77]. Scheduling algorithms are also left implementation-dependent. In this context, waveform parameter assignment can be done flexibly with different optimization steps. In this section, details of various example case studies for waveform parameter assignment are provided.

Numerology assignments will be done via bandwidth part (BWP) selections in 5G NR. Each BWPs has one specific numerology and BWP operations in frequency domain are implementation-dependent. They are controlled by BS. One BWP can belong to a single user or multiple users. It is also possible to make a BWP for one service. In this subsection, the focus is on the numerology assignment rather than BWP operations. Therefore, BWP issues are not discussed in the remaining parts.

An example case study for the numerology assignment for users and services is given in [4]. They firstly map the user and service requirements to numerology parameters in a specific parameter set for 5G NR. It is assumed that there is a feedback mechanism from users to base station regarding the requirements as shown in Figure 4.5. Then, they use the scheduler to find the best suitable numerologies from a parameter set for each users and services. This solution makes all users satisfied but it is not realistic. Increasing the number of effective numerologies in a system brings the necessity of more redundancies. Hence, the capacity is affected negatively.

To make more realistic system, the authors of [4] remove the least selected numerology from a parameter set and repeat the numerology assignment step without the eliminated numerology. They try to decrease redundancy in the system while maintaining the flexibility as much as possible. At the next steps, they check the amount of redundancy, and then stop or continue to eliminate numerologies that are selected less frequently. This method finds an optimum point considering the redundancies and system flexibility. However, waveform processing techniques are not included while optimizing the numerology assignments.

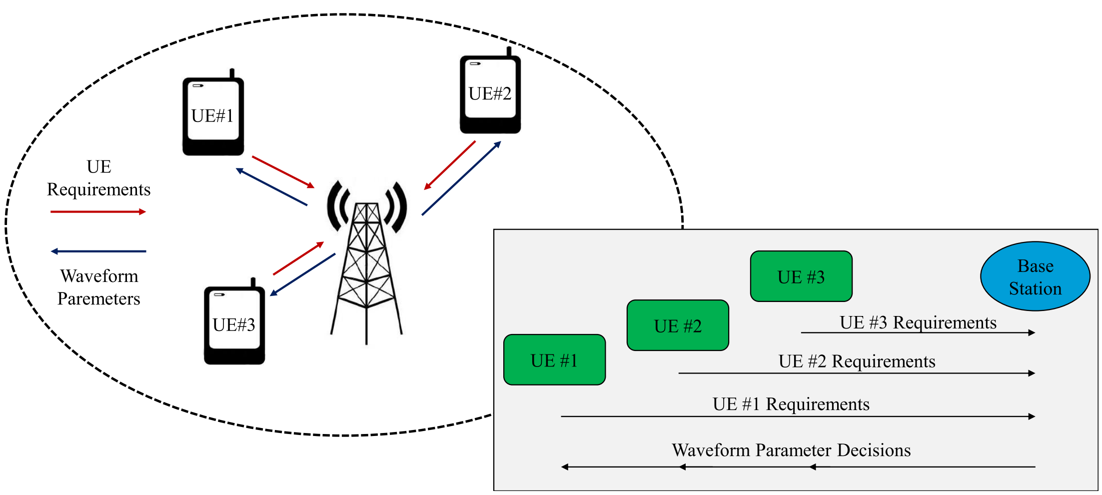


Figure 4.5: An example demonstration for the numerology assignment to UEs.

5G NR optional waveform processing methods include windowing and filtering for each numerology subframes or composite signal subframe. Windowing can be at the transmitter or receiver. Additionally, inter-numerology guard band is optional and it can be in fixed or adaptive manners. For example, [51] is one of the adaptive guard band algorithm examples. The authors adaptively change the guard bands between multiple numerologies considering the average desired SINR and power levels of each users. On the contrary, employing fixed amount of guard bands rather than adaptive ones is not an optimum method but it decreases the scheduling complexity.

In [51], it is assumed that optimal numerology assignment is done before applying adaptive guard band algorithms. However, it is not a realistic scenario because different amount of guard bands can have effects on the numerology assignment recursively. Therefore, there is a need for joint optimization methods.

Optimization methods for waveform parameter assignment generally effect each others recursively. These optimization can be done in multiple steps or one joint step. Joint optimization research is exemplified in [17] using machine learning (ML) approach. The number of numerologies and the amount of inter-numerology guard bands are decided using channel- and service-based features. They do not make direct user-numerology association because it requires a high number of classes in the system. Also, windowing parameter is not included because of the same reason. It is not an easy task but all of these numerologies and parameters need to be optimized together jointly in an ideal scheduling mechanism for 5G NR.

If there are many waveform parameter options in one coverage area, it provides a flexible structure considering the different requirements of users. However, the variety of waveform parameter options comes with a price like INI and similar impairment sources. Employing multiple waveforms in 6G may also cause additional interferences. Several performance indicators (or metrics) are affected while handling the different types of additional interferences. This situation brings difficult dilemma problems.

Performance metrics of reliability, latency, spectral efficiency and complexity are affected by multi-numerology implementations, directly or indirectly. For example, the number of numerologies that are assigned to the users change the amount of INI in a directly proportional way. Reliability decreases if there are INI effects. To compensate INI effects, re-transmission schemes can be used at the expense of additional delays, increasing latency. INI reduction techniques or waveform processing techniques can be utilized to decrease INI effects, however, these techniques generally reduce spectral efficiency. Indeed, some of the INI cancellation techniques can be used but they may increase complexity of the receiver units. As it can be seen from these examples, different trade-off situations need to be handled with proper resource allocation optimizations if multiple numerologies and waveform processing techniques are employed for different users. If there are multiple waveforms, the problem becomes more difficult.

All the users should be assumed to be in the same coverage area. Waveform parameter decisions cannot be given for a single user independently of the other users, as they are indirectly related with each other due to various constraints, like limited radio spectrum. Illustrations of the several subproblems and their example relationships are shown in Fig. 4.3. Waveform and numerology assignment for each user, waveform processing, resource allocation, and all related optimizations effect each other. Collaboration during the solutions of these problems is necessary and as stated before, the level of this collaboration will increase in 6G. The given subproblems can be solved with different waveform parameter assignment, optimization and supplementary methods. A general framework for these methods is presented in the next subsections.

4.1.3.1 Waveform Parameter Assignment

Waveform parameter assignment units should decide on the user parameters by considering the optimization restrictions to provide the possible maximum flexibility regarding different user requirements. Optimization restrictions are achieved at the optimization unit of the waveform parameters for all users. Optimization unit is discussed in the next subsection. The aim of waveform parameter assignment unit is to meet different requirements of all users separately as much as possible under the given optimization restrictions if there is any.

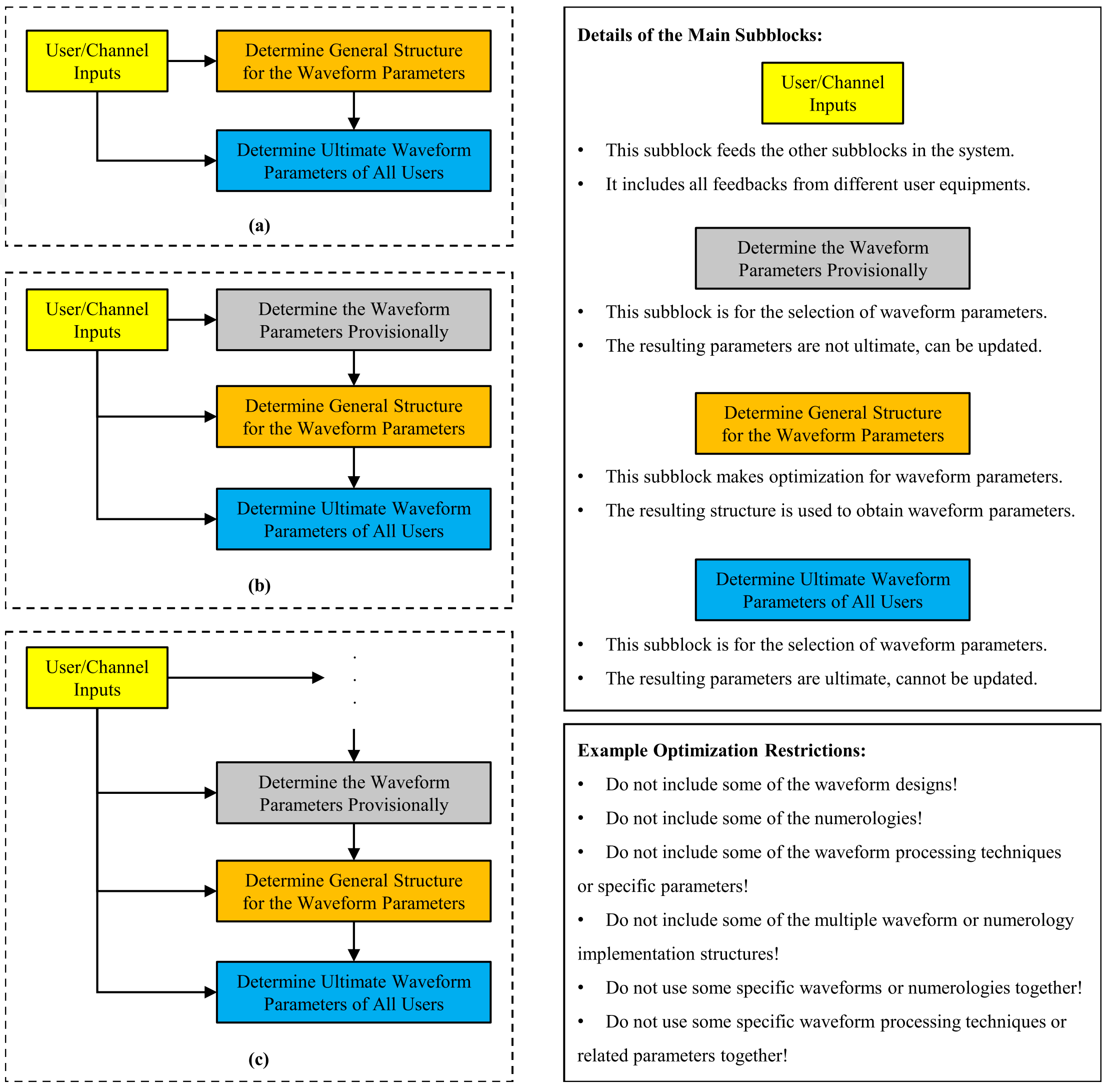


Figure 4.6: General structures of the framework for waveform parameter assignment and resource allocation optimization mechanisms. These mechanisms can include a) two iteration steps, b) three iteration steps, and c) more than three iteration steps.

Waveform parameter assignment is repeated in every cycle, as shown in Fig. 4.6 with different structures. Assignment unit can be run as the first step or as the second step. If it is run as the second step, the first step should be a pre-optimization unit. However, the last step is always the determination of ultimate waveform parameters in all structures. The previous decisions of waveform parameter assignment units can be defined as provisional decisions.

All of the parameter assignment units can work with different flowcharts or with a same flowchart. For example, some of the waveform parameters can be decided in the first iteration and the other parameters can be determined in the next iterations with different flowcharts. Alternatively, all assignment units can work with the same flowchart and can decide on all of the waveform parameters in each iteration step. For the first alternative, options or class labels (for ML) need to be designed application-specific because each assignment unit can provide different types of class labels.

As a case study, a user-numerology association method in [4] can be given. In this study, user channels and use cases are associated with the most suitable numerology from different numerology sets. This step is shown with the first waveform parameter assignment unit in Fig. 4.6(b). After the first step, less assigned numerologies are detected and removed from the numerology set. It brings an optimization restriction and decreases INI effects by forbidding some of the numerologies. As a last step, user-numerology association step is repeated one more time to determine ultimate numerologies for users.

4.1.3.2 Optimization for Waveform Parameters

We can assign the waveform parameters of different users directly but there are some constraints. It will not be a practical and efficient solution without proper optimizations. The main objective of the optimization unit is to create a balance between several performance metrics and find optimum points regarding these metrics. This balance can be provided by meeting requirements of different users together with some sacrifices instead of meeting different requirements of all users separately without any sacrifices. Penalty functions need to be defined to increase the success of general performance for the cellular communications.

Similar to waveform parameter assignment units, optimization units in different steps can also be designed as one type or more. A designer needs to decide on the number of steps for different structures. As an example, a general structure for multiple numerologies can be determined by deciding on the number of numerologies as a first optimization unit like in [17] and as shown with Fig. 4.6(a). After one cycle of waveform parameter assignment unit, a general structure for waveform processing techniques can be obtained in the second optimization unit. Alternatively, different types of optimization units can be combined in one type of unit, and then the unit can be employed in each cycle of the optimization.

Only one cycle of optimization unit is preferred in [17]. Increasing the number of optimization steps provides a better general performance regarding all requirements of different users in a coverage area. However, it can also increase computational complexity of the related radio resource management (RRM) units. Hence, there should be a meaningful reason for increasing the steps of optimization units under different scenarios. An efficient work load distribution is needed between waveform parameter assignment units and optimization mechanisms to obtain ultimate optimal waveform parameters.

4.1.3.3 Supplementary Methods

In addition to waveform parameter assignment and resource allocation optimization methods, different techniques, like INI cancellation [45] and resource allocation based scheduling [18], can play indirect roles to help and simplify the parameter assignment strategies by changing the results of various performance metrics. The work distribution for waveform parameter assignment units and optimization units is changed with these types of practical supplementary methods.

In [18], INI effects at the numerology edges are decreased and also ultra reliable low latency communication (uRLLC) users are scheduled at the inner subcarriers of different numerologies to move away from intensive INI effects at the numerology edges. This method enables providing to make waveform parameter assignment process more simple through proper optimizations. Hence, the number of steps for waveform parameter assignment strategies is reduced inherently.

The design criteria of decision strategies can change regarding different supplementary methods. INI modelling and trade-off analysis through different waveform processing techniques are some other example research topics that are helpful for waveform parameter assignment and corresponding resource allocation optimization methods. Moreover, it can be said that all of the RRM techniques are correlated with the waveform parameter assignment with proper optimizations in some way.

Three mechanisms of the proposed framework that are given as subfigures of Fig. 4.6 are compared in Table 4.2. For 6G, the last mechanism, Fig. 4.6(c), may be more suitable because there will be very large number of waveform parameters and 6G requirement variety will be high. As an important challenge, there will be many optimization necessities so that work load distribution between the optimization units should be balanced carefully. Hence, complexity per unit can be kept under control. Moreover, optimization unit redundancy should be prevented to limit the general complexity.

4.2 The Role of Machine Learning in Waveform Parameter Assignment

ML and conventional methods can be used while waveform parameter assignment units and resource allocation optimization units are run alternately to obtain ultimate optimal waveform parameters. Understanding the role of ML is useful to constitute efficient waveform parameter assignment systems in 6G communications. In general, the aim of ML usage for the waveform parameter assignment can be listed as follow:

Table 4.2: Differences of three mechanisms for the general waveform parameter assignment and optimization framework.

	Advantages and Disadvantages	**Scenarios**
Fig. 4.6(a)	• Low complexity in general considering the number of units. • High complexity in a single optimization unit. • Low performance regarding the meeting requirements if there are large number of waveform parameters.	• Reasonable if there are small number of waveform parameters. • It is also preferable when the requirement variety is low.
Fig. 4.6(b)	• Medium complexity in general considering the number of units. • Variable complexity in optimization units. • Medium performance regarding the meeting requirements if there are large number of waveform parameters.	• Reasonable if the number of waveform parameters is not high. • It is also preferable when the requirement variety is medium.
Fig. 4.6(c)	• High complexity in general considering the number of units. • Variable complexity in optimization units. • High performance regarding the meeting requirements if there are large number of waveform parameters.	• Reasonable if there are large number of waveform parameters. • It is also preferable when the requirement variety is high.

- ML can establish useful and unnoticeable relationships in waveform parameter assignment domain.
- It is possible to obtain fast significant solutions when ML methods are preferred.

4.2.1 Previous Works

Waveform parameter assignment from a large number of parameter options for each user and the resource allocation optimization requirements considering all users (in a single TP or multiple TPs) are two critical challenges. Different solutions can be provided for these problems with traditional methods or new technologies such as machine learning (ML). In ML, learning process is carried out by using data and the system does not need to be explicitly programmed. It provides promising results for different wireless communications research areas as exemplified in [95–98]. If there is a large number of parameter options, dilemma, or trade-off, ML based solutions can be helpful because ML can establish useful and unnoticeable relationships without heuristic engineering design and theoretical analysis. Designing a classical method sometimes is not an easy task in practice for a problem that requires to establish relationships considering a large number of parameter options. The importance of ML lies in the process of obtaining the classical model based solutions faster than before. It may be helpful to use ML and conventional methods together in complex scenarios with heterogeneous structures.

The use of ML for 5G is discusses in several studies. For example, artificial neural networks are investigated in [95] to be employed for solving various problems with unmanned aerial vehicles (UAV)-based wireless networks, wireless virtual reality (VR), mobile edge caching and computing, co-existence of multiple radio access technologies (RAT), and Internet of Things (IoT). In [95], resource allocation and management problems are given for specific applications of UAV networks [99, 100], VR concept [101, 102] and multi-RAT systems [103]. Several ML-based scheduling mechanisms are utilized for resource allocation and management [104], interference management [105] and dynamic multichannel access [106]. However, existing 5G resource allocation and management works that employ ML are not focused on waveform parameter assignment and optimization.

A discussion on the ML-enabled methodologies for 6G networks and the possible new challenges of ML in 6G are presented in [107]. One of the new challenges is transformation of the "network softwarization" to "network intelligentization". Moreover, "intelligent PHY layer" for 6G will include self-learning and self-optimization capabilities [107]. 6G networks will employ ML to optimize and automate many operations [108]. ML will play a more important role during the standardization of 6G [7]. In 5G, ML can have a supporting role, however, it will be a leading role for ML in 6G. If 5G is called as "connected things", 6G can be called as "connected intelligence" [107]. A number of existing works has studied 6G and they are summarized in the previous chapters. To the best of the authors' knowledge, this is the first study that focuses on the waveform parameter assignment and optimization for 6G.

There are three main types of ML schemes - supervised learning (SL), unsupervised learning (UL), and reinforcement learning (RL). SL requires class labels in the training stage. On the contrary, UL process does not use class labels but utilizes a clustering type of algorithms, e.g. specifing the class distinctions with learning more about the input data. RL employs feedback mechanisms to improve the ML system consistently. These schemes can be employed for different optimization aims in wireless communications. Additionally, there are several state-of-the-art concepts such as deep learning (DL) and edge computing. DL is a special case of ML and it consists of multi-layered neural network (NN) models. Edge computing is a distributed computing framework to process data on the device itself rather than a centralized data processing. It is possible to use main ML schemes for DL and edge computing algorithms. Furthermore, DL can be used for the edge computing. Besides, federated learning (FL) is one way of the edge learning across multiple decentralized devices.

Relationships between ML and the wireles networks are discussed comprehensively in several studies such as [95–98]. A set of network design and optimization schemes to make wireless networks intelligent regarding being self-aware, self-adaptive, proactive and prescriptive is introduced with big data concept in [109]. An overview of the emerging studies on DL-based solutions for different network layers are provided in [110–112]. Signal identification for emerging intelligent radios and end-to-end learning from spectrum data are investigated in several papers [113–116]. ML-aided channel estimation is studied from different perspectives such as OFDM, NOMA and MIMO in [117–119]. Beam management with ML for highly mobile mm-wave systems [120], beam selection with ML [121], beam allocation with ML in multi-user massive MIMO systems [122] and antenna selection with ML [123] are some other useful researches in the literature. ML for vehicular networks is discussed in [124] and [125]. A ML vision and an overview of ML architectures for network traffic control are introduced in [126] and [127]. For edge computing learning, mostly FL is used to schedule wireless networks. Scheduling policies for FL in wireless networks [128], FL-based multichannel random access [129], joint power and resource allocation with FL for vehicular communications [130] and FL for UAVs-enabled wireless networks [131] are several previous works on edge computing learning.

4.2.2 The Role of Machine Learning

Designing a classical method sometimes is not an easy task in practice for a problem that requires to establish relationships considering a large number of options. Hence, ML plays an important role to establish useful and unnoticeable relationships without heuristic design and theoretical analysis. It does not mean that ML methods are superior to conventional methods. However, ML methods can make the design process easier compared to developing non-ML techniques. ML methods learns from data without requiring a specific design. If there are optimal classical methods for all stages of the design units, ML may not provide extra advantages but this scenario is not valid for our case. Therefore, it is more preferable to use ML and conventional methods together in a hybrid way.

ML methods can be employed efficiently to decide on general structures during optimization steps for waveform parameter assignment. The other steps also can be designed with ML methods but there are too many parameter options as class labels in waveform parameter assignment steps. It causes a difficulty in training and reduces success rates. The number of waveform parameter options or class labels for one assignment/optimization unit should not be higher than a desired level if this unit is designed with ML model. The model needs to have more complex rules and the boundary samples have more influence for a large number of class labels. Using a large number of class labels for one ML model is not preferable as this introduces an imbalanced learning problem and degrades prediction accuracy. In imbalanced dataset has disproportional ratios of observations in the class labels. Because of this, a class with insufficient number of samples is hard to learn. Additionally, the complexity for the learning process also increases dramatically for a large number of class labels. Therefore, ML models should have less number of class labels and the work distribution needs to be designed considering this hypothesis. If ML methods are employed during optimization steps, most of the work load should not be shifted to the optimization units, as this increases the number of class labels in ML models. The number of optimization steps can also be adjusted to reduce the number of class labels in each step. The work distribution for parameter assignment units and optimization units should be adjusted considering the role of ML. Conventional methods need to be preferred if there is not an efficient work distribution between the units. Additionally, edge computing can be used for different steps of waveform parameter assignment and optimization. For example, edge computing can be preferred to minimize the class labels for each user's parameter assignments after the necessary optimization steps. Learning with the edge computing can enhance the practicability of employing ML in parameter assignment steps. Also, some parts of the optimizations can be done using edge computing for a better work distribution between the other steps.

Analysis of ML usage in the proposed framework is summarized in Table 4.3 and Table 4.4. ML plays an important role especially in optimization of parameter assignments. There will be more optimization necessities for 6G because

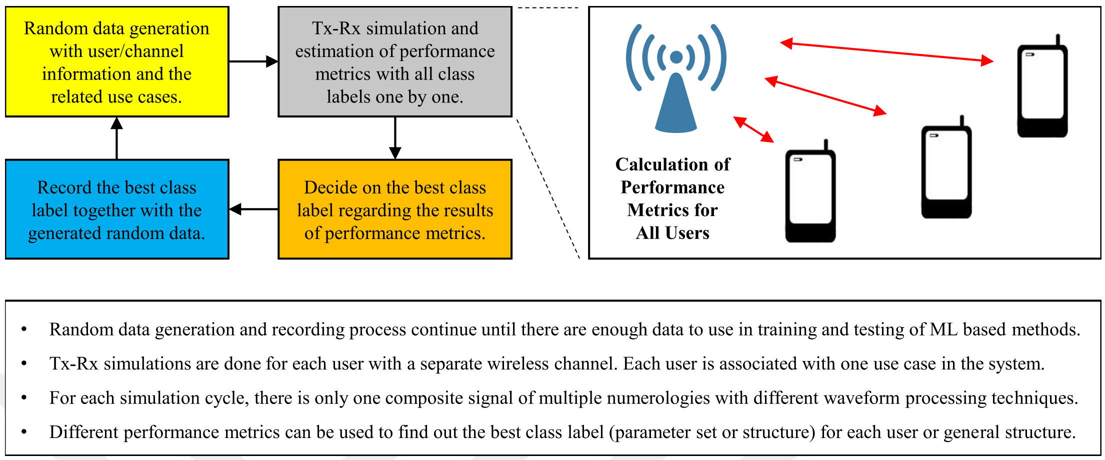


Figure 4.7: Block diagram for the simulation based dataset generation.

of the possible high number of waveform parameters. Hence, the role of ML in optimization of parameter assignments for 6G will be more than 5G. This is one of the possible challenges in 6G from the ML perspective. The increasing number of waveform parameter options makes ML usage more feasible for optimization steps. Additionally, another ML challenge is the large number of class labels for direct waveform parameter assignment roles. Difficulty in ML training, more complex rules, imbalanced learning problem and high computational complexity are the potential 6G challenges for waveform parameter assignment steps.

4.2.3 Datasets for Machine Learning

There are many issues for the use of ML techniques for wireless communications. However, one of the most important issues is the availability of datasets to make ML works. It is crucial to have large datasets while making ML systems functional [132]. In the literature, there are only limited datasets for many of the wireless communications research opportunities. ML systems need large datasets during the training and testing stages. Data-driven learning process cannot be possible without a dataset. Therefore, the role of datasets is given together with the ML role in this study.

In practice, it is not feasible to constitute a measurement based dataset that

Table 4.3: Analysis of ML usage in the proposed framework.

	ML Usage Scenarios
Parameter Assignment Roles	• If there are too many parameter options as class labels in parameter assignment steps, difficulty in training and low success rates. • The model needs to have more complex rules and the boundary samples have more influence for a large number of class labels. • A large number of class labels for one ML model introduces an imbalanced learning problem and degrades prediction accuracy. • The complexity for the learning process also increases for a large number of class labels. • ML can play a role in waveform parameter assignment for 5G systems because the number of waveform parameters is limited. • Parameter assignment with ML in 6G networks may not be feasible because of the tremendous number of potential class labels. • After the optimization steps, edge computing can be preferred to minimize the class labels for each user's parameter assignments.

Table 4.4: Analysis of ML usage in the proposed framework.

	ML Usage Scenarios
Optimization Roles	• ML can be employed efficiently to decide on general structures during optimization steps for waveform parameter assignment. • For ML-based optimization steps, the work distribution should be adjusted to reduce the number of class labels in each step. • Some parts of the optimizations can be done using edge computing for a better work distribution between the other steps. • Trying to solve an optimization problem with only one ML model sometimes makes the problem more difficult. • ML plays an important role in optimization of waveform parameter assignments for 5G and 6G. • There will be more optimization necessities for 6G because of the possible high number of waveform parameters. • A high number of parameters makes ML more feasible for optimization steps but not for parameter assignment roles directly. Because, generally there is a large number of class labels during the waveform paprameter assignment step. In that case, the model needs to have more complex rules and the boundary samples have more influence for a large number of class labels.

includes data for too many different scenarios. Simulation based dataset generation methodologies can be preferred as shown in Fig. 4.7. After forming the types of class labels in different units, functional datasets can be prepared with simulations and automatic class labeling methods to use these datasets in the training of ML based units. An example simulation based dataset generation methodology and an automatic class labeling method for the purpose of supervised learning is shown in Fig. 4.7. Details are given in the next section with a case study. At the end, obtained class labels are recorded in a dataset along with the randomly generated data. This dataset can be used for ML purposes after the feature engineering processes that include data cleaning, preprocessing, feature extraction, feature selection and feature reduction if necessary. The simulation based datasets can also be used as an initialization point and a priori info for reinforcement learning models.

4.2.4 ML-Based Decision of Optimal Waveform Parameter Subsets

A supervised ML based method is developed with a case study example to provide an optimal waveform parameter subsets before the assignment of waveform parameters for each user. For example, the proposed method decides on the efficient number of numerologies that can be assigned to users. However, it does not make a direct user-numerology association. In this case study, the main focus is on finding the optimal waveform parameter subsets by utilizing ML algorithms. A simple model is shown in Fig. 4.8(a).

4.2.4.1 Class Labels for the Dataset

It is assumed that each class label corresponds to one set of waveform parameters. Therefore, more than one thousand classes can be considered for 5G cellular systems with different numerology assignments and waveform processing parameters. The number of classes may increase exponentially for 6G especially if there

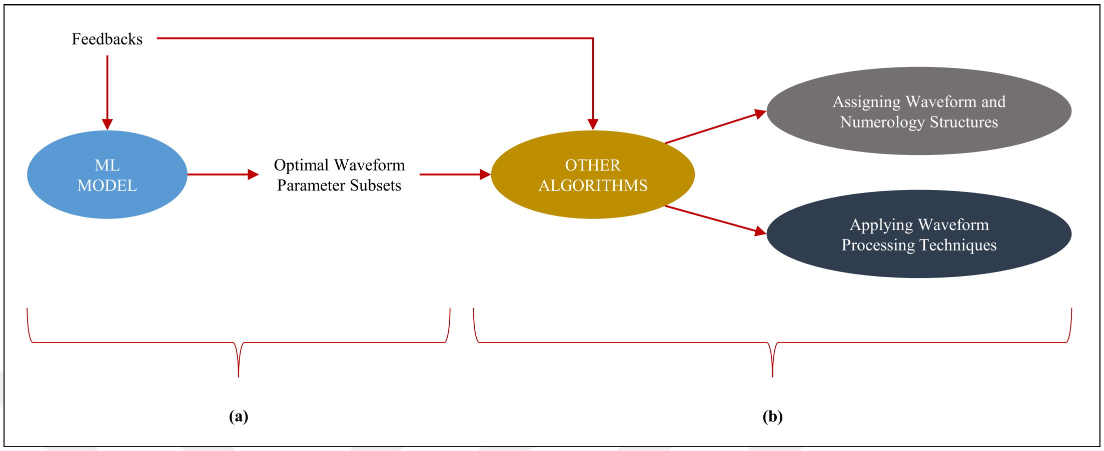


Figure 4.8: Example demonstrations for a) decision on general structure for the configurable waveform parameters and b) assignments of user-based waveform parameters.

are multiple waveforms. In this case, a multidimensional look-up table may be necessary.

The number of class labels changes the learning problem difficulty, affects the training complexity and requires a larger dataset. Also, a larger dataset is needed when there are more class labels. Due to these restrictions, only ten classes are taken in this case study for the sake of simplicity.

It is assumed that there are four numerology related options - using four numerologies, three numerologies, two numerologies, and only one numerology at a time. In other words, a subset is decided for the efficient number of numerologies in a frame. In addition, three guard band options are defined as the waveform processing techniques. Windowing and filtering options are not included. The class labels and short descriptions for the case study are provided in Fig. 4.9(b).

There are three and four type of numerologies in the first and second row classes in Fig. 4.9(b). If the number of distinct requirements in one coverage area is rich, these classes may suitable to meet the requirements under this scenario. Third and fourth row classes are more compatible for a scenario that the number of distinct requirements is limited. Classes in different columns vary with INI effects on the requirements.

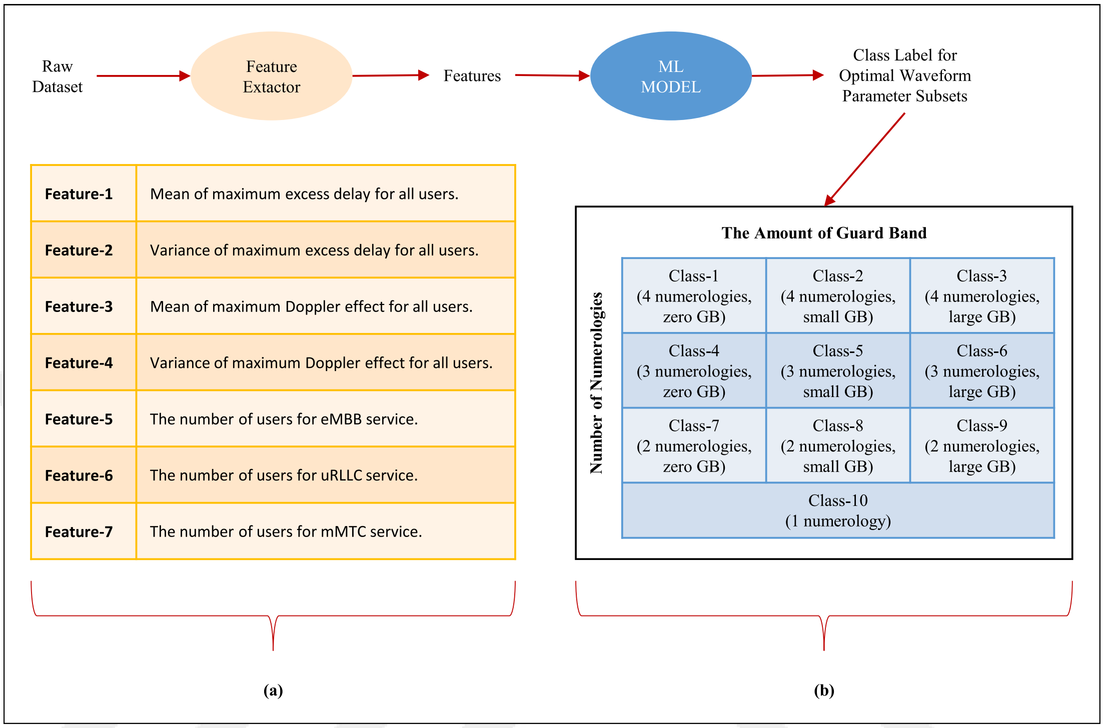


Figure 4.9: Details of the features and class labels that are included in the dataset.

4.2.4.2 Feature Extraction

For all users, independent random data is generated under different scenarios (e.g. thousands of random scenarios) based on the channel information in [133] and use cases that include eMBB, uRLLC and mMTC. Scenarios are defined with the parameters of random maximum excess delay, random maximum Doppler effect, and random service type (eMBB, uRLLC, or mMTC). Users can be associated with one of the use cases and different Rayleigh fading channel models are used for each user. Hence, the proposed ML system model can be assumed as channel-aware and service type-aware.

Short definitions of the extracted seven features include mean of maximum excess delay, variance of maximum excess delay, mean of maximum Doppler effect, variance of maximum Doppler effect, the number of users for eMBB, the number of users for uRLLC and the number of users for mMTC as shown in Fig. 4.9(a). The first four features give information about the channels of users in general.

The remaining three features are obtained related with use case statistics. All of the features aim to describe requirement trends in one coverage area for a TP. ML model is trained considering these requirement trends and the available classes.

In the future cellular systems, there will be more use cases. In addition, there will be more different types of new channel models for 6G, especially for millimeter wave systems. New models will increase the number of scenario parameters and then the feature characteristics.

4.2.4.3 Simulation Based Automatic Class Labelling

After the feature extraction process, a simulation based automatic class labelling is done before training ML models. This process is realized using the calculation of several performance indicators that include signal to interference plus noise ratio (SINR), spectral efficiency, and flexibility. A multi-numerology waveform transceiver simulation is employed to obtain the calculation of these performance indicators. [44] is taken as a reference for multiple numerologies. Additionally, flexibility is defined as a metric that changes directly proportional to the number of numerologies.

For the automatic class labelling process, different waveform options (ten classes in this case study) are tested one by one in separate simulations for the same inputs and features. Three performance indicators are obtained for each simulation. A single performance value is calculated using three indicators with different priorities and weights. These priorities and weights change considering the service type majority. For example, the spectral efficiency metric has more priority for eMBB but the SINR metric has more priority for uRLLC. If there are a high number of users with all type of services, then the flexibility metric has also a priority because the overall system needs to meet with many different requirements together. At the end, performance values for each simulation are compared and the best one is decided. This decision gives the optimal class label that has specific waveform options.

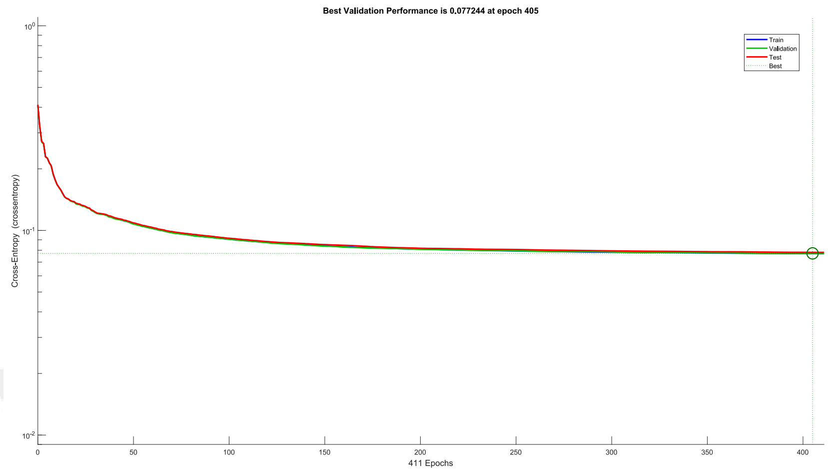


Figure 4.10: Convergence curve for NN networks with 20 hidden neurons using Bayesian regularization backpropagation algorithm.

4.2.4.4 Simulation Results

While training and testing ML models, 114420 samples with seven features and one class label are used for each random scenario. The dataset is divided as training, validation, and testing with 60%, 20%, and 20% ratios, respectively.

MATLAB platform is employed in the simulations. For the ML traning and hyperparameter optimizations, 'fitcecoc' and 'patternnet' functions are preferred in MATLAB. Several classifiers are trained and tested during the simulations. Success rates change between 60% and 65% for ten classes. Additionally, if neighbour classes in Fig. 4.9(b) are grouped together, the success rates vary between 90% and 93% for the same classifier models. For example, if the decision for number of numerologies is three or four, it can be acceptable while neighbour classes are grouped.

Confusion matrices are provided in Fig. 4.12 for several classifiers. Receiver operating characteristic (ROC) and convergence curves for NN networks with 20 hidden neurons using Bayesian regularization backpropagation algorithm are shown in Fig. 4.10 and Fig. 4.11, respectively. Success rates are not high but they are promising.

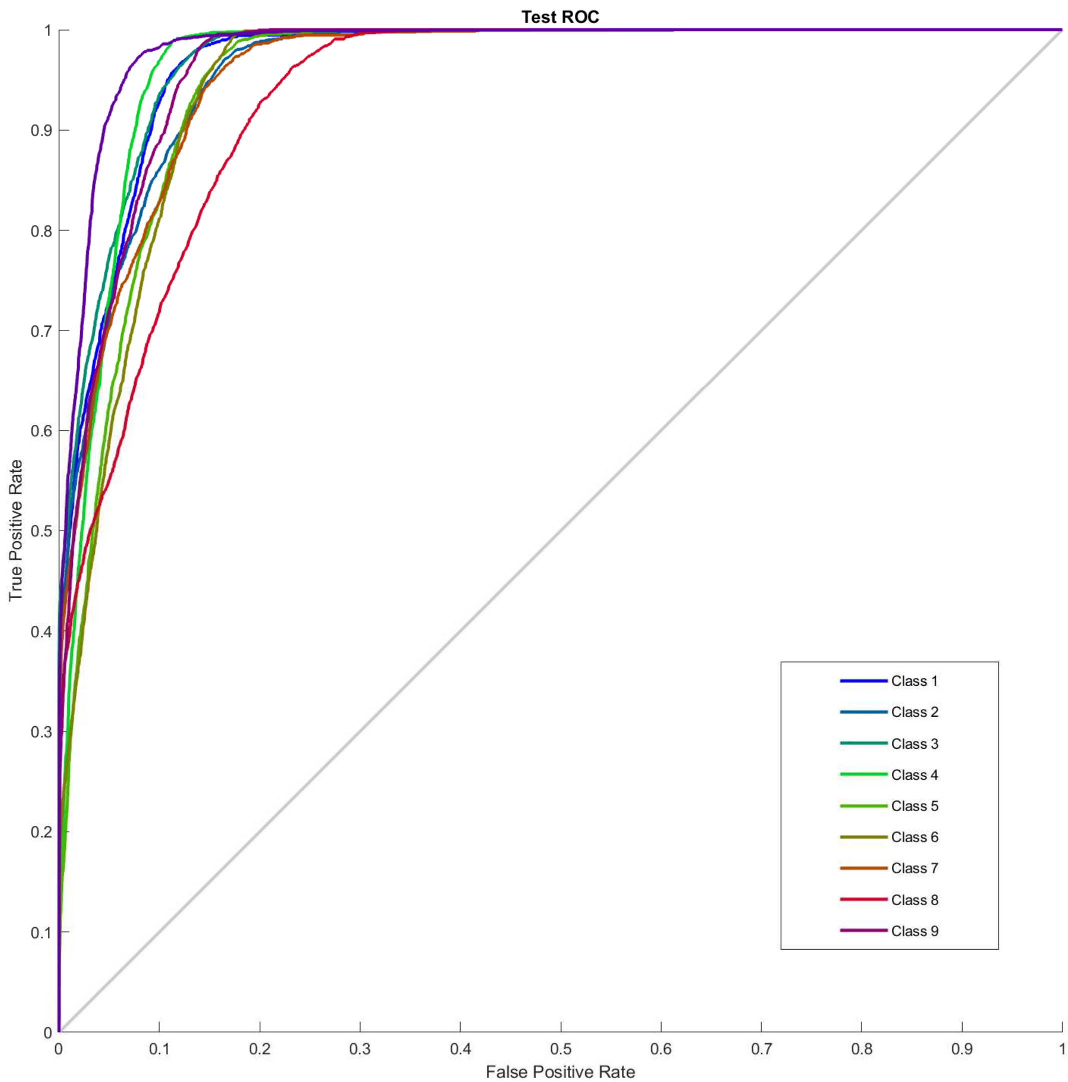
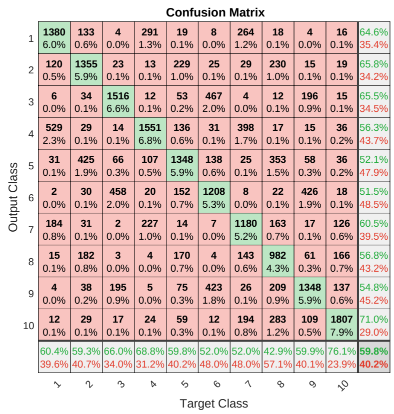
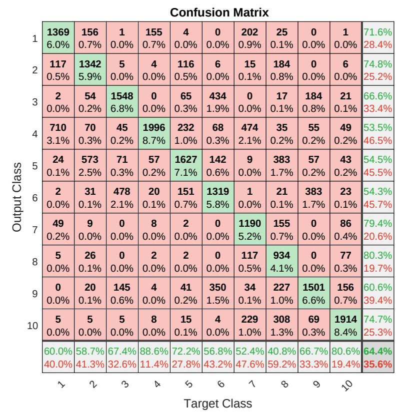


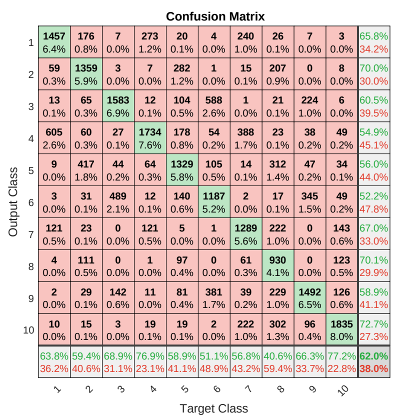
Figure 4.11: ROC curve for NN networks with 20 hidden neurons using Bayesian regularization backpropagation algorithm.



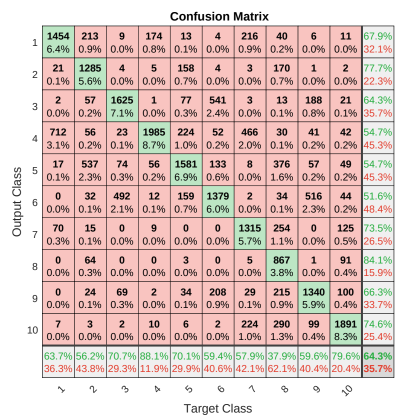
(a) Confusion matrix for KNN classifier with five neighbors.



(b) Confusion matrix for decision tree classifier.



(c) Confusion matrix for NN networks with 20 hidden neurons using scaled conjugate gradient backpropagation algorithm.



(d) Confusion matrix for NN networks with 20 hidden neurons using Bayesian regularization backpropagation algorithm.

Figure 4.12: Confusion matrices for the simulation results in MATLAB platform.

4.2.4.5 6G Projection of the Proposed Case Study

In the previous sections, it is emphasized that the increasing number of waveform parameter options makes ML usage more feasible for optimization steps rather than the direct parameter assignment roles without optimizations. Hence, optimization units for waveform parameter assignment should be discussed more for ML roles. The proposed case study is a basic example for ML usage in pre-optimization of waveform parameter assignment problems of 5G and 6G.

As discussed previously, numerology options, CP utilization methods, lattice domains and waveform types may be diversified with the next generation cellular systems. If the number of class labels is increased tremendously in 6G, the solution of the parameter assignment problems will be more difficult.

Under the assumption of large number of new parameter options in 6G, the following potential ML challenges may be listed for the adjustment of future waveform parameters:

1. There will be more interferences (INI and IWI) because of the increasing number of parameter options.
2. New processing techniques and the related parameters will be needed for the interference management.
3. The number of steps for parameter assignment and optimization in the proposed framework will increase.
4. There will be a need for better optimization algorithms in general.
5. A more efficient work distribution will be required between different steps in the proposed framework.
6. The role of ML will increase and more ML models will work together under an optimized work distribution.
7. The number of useful features should be improved to enhance the accuracy of ML models.

8. Feature selection and/or reduction can be applied after feature extraction.
9. More powerful methods like DL and edge computing will be integrated to the ML role.
10. Edge computing algorithm structures can be designed to reduce the work load at TPs. Hence, FL-based edge computing solutions can be preferred.
11. There will be a need for better and larger datasets to make ML mechanisms more functional.
12. More user inputs as new feedbacks will be included for the datasets.
13. New mechanisms for the evaluation of user feedbacks will be designed.
14. Data cleaning and preprocessing may need to be used on the raw dataset.
15. 6G frames need to implemented to form useful datasets with simulation based automatic class labelling system.

4.3 Optimization for the Efficient Number of Multiple Numerologies

4.3.1 Problem Definition

There are three main questions that this section aims to answer:

1. How many and which mixed numerologies should be used together in one transmission time interval (TTI) duration?
2. What are the effects of different numerology sets for the mixed numerology based frame structures?
3. How can be a flexibility metric defined from the frame design perspective?

Table 4.5: Numerology Structures in 5G. 480 kHz subcarrier spacing is removed from 3GPP Release 15 later on.

Type of Numerology	Numerology Parameters			
	$\eta_{spectral}$	Δf (kHz)	# of Symbols in One Subframe	T_{CP} (μs)
Type-A1	93.3%	15	14	4.76
Type-A2	93.3%	30	28	2.38
Type-A3	93.3%	60	56	1.19
Type-A4	80.0%	60	48	4.17
Type-A5	93.3%	120	112	0.60
Type-A6	93.3%	240	224	0.30
Type-A7	93.3%	480	448	0.15

To the best of authors' knowledge, these questions don't have answers in the literature. Another important point is that there is a very strong relationship between these questions.

As is known, only one numerology can be employed for one TTI duration in LTE. Using one numerology for all situations can be considered as an efficient way but user and application specific systems need more flexibility to meet correlated requirements provided in the previous chapters. An effective solution is, employing different numerologies which are not fixed for each of the users from the flexibility perspective without considering the other performance metrics. However, there is a need for a balance between flexibility and the other performance metrics because there are various trade-offs.

For 5G, three numerologies for three main service classes are not enough because there are also user requirements. Due to this reason, seven fixed numerologies are defined for 5G, and the list of them is given in Table 4.5. The number of numerologies is seven for the moment but may increase further in the future systems.

The number of different type of numerology structures preferred by users is needed to be decided in every TTI duration for a meaningful system. Besides, a different type of numerologies can be used in different amounts in accordance with the service and user requirements. Sometimes, a less number of numerologies can be enough to meet the requirements. It should be noted that the assumption is that services are not mapped to the numerologies in a fixed manner, and bandwidth allocations for the numerologies can be different.

Basically, the number of mixed numerology structures have effects on the performance metrics of spectral efficiency, scheduling complexity, computational complexity, and signaling overhead.

Spectral efficiency defined in Eq. 4.1 generally decreases depending on the increase in the number of mixed numerologies and flexibility because there should be some guards between different numerologies to prevent inter-numerology interference (INI). Rather than flexibility, spectral efficiency can be more important under some scenarios. In such cases, the number of mixed numerology structures should be chosen less.

$$\eta_{spectral} = \frac{T_U}{T_U + T_{CP} + T_G} \times \frac{B_U}{B_U + B_G} \tag{4.1}$$

In Eq. 4.1, T_G is guard periods, B_U is usable bandwidth, and B_G is guard bands.

In this paper, it is assumed that the mixed numerologies are orthogonal to each other. However, we have an intention conducting a study provide another algorithm for non-orthogonal conditions in near future. Spectral efficiency analysis needs to be reconsidered for the non-orthogonal case.

In addition, flexibility comes with some other constraints including scheduling complexity, computational complexity, and signaling overhead which can be called as network operator requirements. Increasing the number of numerologies reduces the channel dependent scheduling complexity compared to LTE systems. Also, signaling overhead and computational complexity reduction is important for feasibility. The base station has to inform the users with enough details about the spectral structure of mixed numerologies. This process increases the control signaling overhead. For the multi-numerology systems, different-sized Fast Fourier Transform (FFT) blocks need to be employed together. This situation brings additional higher computational complexity to the system.

Considering the disadvantages of using the high number of mixed numerology structures, flexibility performance of a frame needs to be optimized to meet the key requirements and necessities of different users and services.

Another point is that, if we extend and enrich the numerology set, we can increase the probability of providing more suitable numerologies for the different necessities of users. It is possible to increase average user satisfaction by selecting more suitable numerologies from a larger numerology set without changing the number of used numerologies together. However, a larger numerology set generally includes less common numerologies, and it causes various difficulties in the scheduling processes.

4.3.2 Assumptions and System Model

In this study, CP-OFDM with mixed numerology structures is analyzed. According to [44], seven numerology structures are defined for 5G new radio (NR). Some of the main parameters of these numerology structures are presented in Table 4.5. Here, ten one-millisecond subframes constitute one frame like in LTE systems. The number of symbols in one slot and the number of slots in one subframe are not given in the table but the number of symbols in one subframe is presented. There can be 7 or 14 symbols in one slot for the first three types of numerology structures on the table. However, the number of symbols in one subframe is same in this situation independent of the number of symbols in one slot. CP durations are calculated considering that there are not any guard periods between adjacent symbols. Spectral efficiency values, $\eta_{spectral}$, are calculated without any guard periods and guard bands using Eq. 4.2 where T_U is usable symbol duration, and T_{CP} is CP duration. All results are presented in Table 4.5. Additionally, there are 12 subcarriers with different sized subcarrier spacings, Δf, in each of resource blocks which use different bandwidths.

$$\eta_{spectral} = \frac{T_U}{T_U + T_{CP}} \tag{4.2}$$

Three different numerology sets are used. First set is the numerology structures defined in Table 4.5. Also, alternative types of numerologies are tested employing the other numerology sets especially if a longer CP duration is needed. The related simulation results are presented in Section 4.3.4.

Different scenarios, service requirements, user requirements, and numerology structures that are given in this section are going to be correlated to each other in the next section.

4.3.3 Numerology Assignment Algorithm

To make an optimization on the flexibility, firstly it must be estimated. As far as we know, there are not any algorithms available in the literature for this purpose. That is why a new heuristic flexibility metric algorithm is developed in this paper.

Our flexibility metric, F, is estimated using Eq. 4.3 which employs Eq. 4.4 to provide a satisfaction result of only one user, S_u. Actually, the flexibility metric is equal to the average satisfaction of all users. The flexibility metric is calculated with the average user satisfaction ratio in every TTI duration.

$$F = \sum_u \frac{S_u}{U} \tag{4.3}$$

In Eq. 4.3, U is the number of users in the same coverage area.

$$S_u = \sum_k \frac{P_k}{K} \tag{4.4}$$

In Eq. 4.4, P_k is the user satisfaction for the necessity of k, and K is the number of key necessities. P_k is estimated by Eq. 4.5 for each of the key necessities for every single user. Hence, S_u can be also called average satisfaction result for all necessities of a user.

$$P_k = \begin{cases} 1 & I_{l,u,k} = N_{u,k} \\ 0 & D_k + 1 \geq M \\ 1 - \frac{D_k+1}{M} & D_k R_k \leq A_k < (D_k + 1)R_k \end{cases} \tag{4.5}$$

In Eq. 4.5, $N_{u,k}$ is the necessity function to determine ideal result for necessity k of a user u, $I_{l,u,k}$ is the l'th numerology selection from a set of numerologies for user u and necessity k, A_k is found with Eq. 4.6 and it is the difference regarding to ideal solution for necessity k, R_k is the reference value for necessity k, D_k is found with Eq. 4.7 and it is the normalized value of A_k for necessity k, and M is a limit value for the resolution of the algorithm.

$$A_k = |I_{l,u,k} - N_{u,k}| \tag{4.6}$$

$$D_k = \frac{A_k}{R_k} - [\frac{A_k}{R_k} mod(1)] \tag{4.7}$$

In our algorithm, the flexibility metric is estimated based on P_k values. The P_k values vary between 0 and 1. The higher P_k, the more user satisfaction will be for the related key necessity. Additionally, there can be maximum $M + 1$ different type of P_k values in the algorithm. If M is increased, the resolution for the satisfaction estimation also increase. However, a higher resolution brings more computational complexity.

As stated previously, if all users have their ideal numerology structures, then the number of numerology structures will be equal to the number of users. In this situation, F will be 1, and it represents the most flexible system. All users can be satisfied 100% in this way as an ideal system.

Eq. 4.8 finds the best numerology selection, $I^*_{l,u}$, from a set of numerologies for user u by employing Eq. 4.4.

$$I^*_{l,u} = \underset{I_{l,u}}{\operatorname{argmax}} \, S_u \tag{4.8}$$

4.3.4 The Efficient Number of Multiple Numerologies

Algorithm 1 is proposed for the estimation of an efficient number of mixed numerology structures. Also, algorithm flowchart is shown in Fig. 4.13. More user satisfaction is equal to more flexibility, and flexibility metric is employed to decide on the efficient number of mixed numerology structures in one coverage area.

The best numerology selection process is repeated up to the number of members in a numerology set. For every stage, the usage of all numerologies is counted

Algorithm 1 Heuristic algorithm to decide on the efficient number of mixed numerologies

function OPTIMIZATION(I, U, N, M)
▷ I is the numerology set, and N is the set of necessities ▷ L is the number of numerologies in I
  for i = 1 **do** L_{start}
    for u = 1 **do** U
      $I^*_{l,u} = argmax(I, N, M)$
    end for
    Estimate F, and V using a fixed guard band, C
    Sort the number of numerology selections.
    Decide on the new numerology set, I, by removing the least used numerology.
  end for
  return The numerology selections of all users for a reasonable case which maximizes the overall satisfaction for a given numerology set.
end function
function ARGMAX(I, N, M)
  for l = 1 **do** L
    Estimate $S_{u,l}$
  end for
  $S_u = max(S_{u,l})$
  return $I^*_{l,u}$
end function

and sorted in a descending order. By this way, the least preferred numerology is removed from the numerology set in each stage. Then, Eq. 4.8 is performed again with the new set of numerologies which has a less number of numerology structures. The best numerologies for each of the users can be decided again at every stage. Meanwhile, overall satisfaction, V, is estimated using Eq. 4.3, Eq. 4.9, and Eq. 4.10 for the best numerology selections. In Eq. 4.9 and Eq. 4.10, η_{BW} is the spectral efficiency related with bandwidth usage of all numerologies employed in that stage. In Eq. 4.10, B_G is the total guard bands used between different numerology structures to prevent or decrease INI.

$$V = \eta_{BW} \times F \tag{4.9}$$

$$\eta_{BW} = \frac{B_U}{B_U + B_G} \tag{4.10}$$

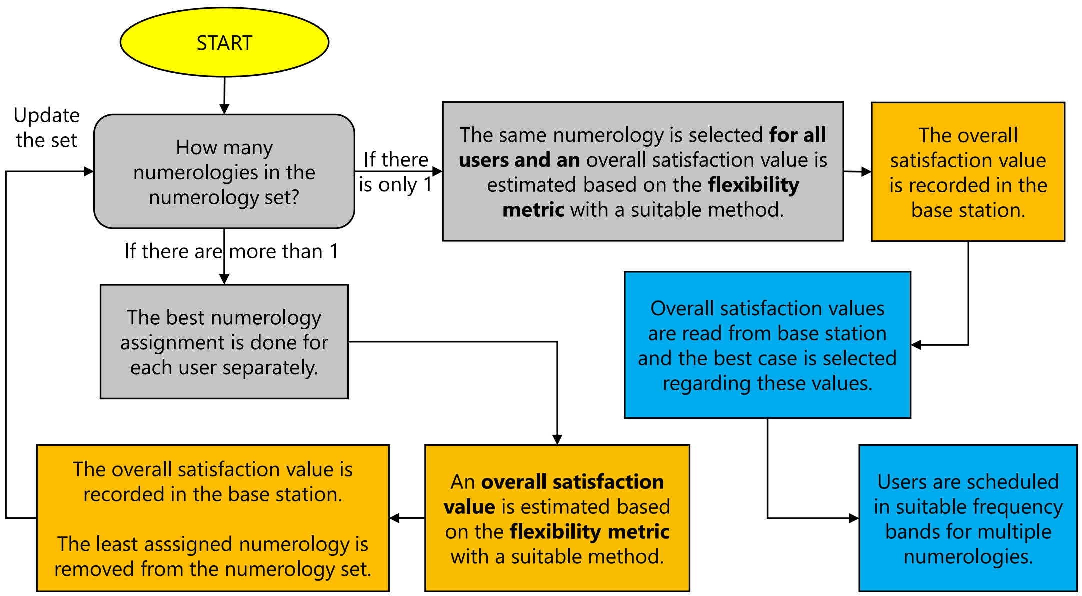


Figure 4.13: Algorithm flowchart to decide on the efficient number of mixed numerologies.

The more numerologies mean the more flexibility along with the more B_G. A larger B_G causes decrease in the spectral efficiency of the system. Therefore, overall spectral efficiency changes while the number of mixed numerologies in the current stage is varying. V becomes maximum on one point while changing the number of mixed numerologies in each stage. When this point is found, it gives a reasonable result for the number of current mixed numerologies. At the end, the overall satisfactions are maximized on different points while changing the number of mixed numerologies. These points are the most reasonable points for the given numerology set but they cannot be accepted as optimum points for all numerology sets. The positions of the points can vary from one numerology set to another. The related simulation results are given under different scenarios in the next section.

Additionally, the proposed heuristic algorithm is designed in a simple manner considering the complexity and implementation feasibility perspective.

4.3.5 Results and Discussion

Simulation results are obtained for 12 scenarios given in the previous chapters. Necessity weights differ from one scenario to another. Different users' necessities, $N_{u,k}$, are randomly generated regarding the related scenario. For example, a larger subcarrier spacing necessity is relatively high in "Highway" scenario.

Some algorithm parameters which are referred in Section 4.3.3, and 4.3.4 are presented in Table 4.6. In Eq. 4.5, resolution steps are obtained by $1/M$ which is 0.05 in our simulations. For example, if there is a difference of 15 kHz between the numerology and user necessity for the subcarrier spacing, P_k is estimated as $1 - 0.05 = 0.95$ or if there is a difference of 30 kHz, it is estimated as $1 - 0.1 = 0.9$ to present the user satisfaction out of 1.

U, K, and M parameters have effects on the complexity of the proposed algorithm. If they are increased, algorithm complexity also increases. The number of numerologies in a numerology set also affects the algorithm complexity. More numerologies bring more complexity.

Fixed guard bands, C, are placed between the consecutive numerologies. Because of that total guard bands, B_G, increase linearly with the number of numerology structures. Actually, the relationships between INI, spectral efficiency, the number of mixed numerologies, and adaptive guard bands between the consecutive numerologies need to be analyzed but they are not included in this study.

Table 4.6: Simulation Parameters

The number of users in a coverage area	U	200
The number of key necessities	K	3
The limit for the algorithm resolution	M	20
Reference value for the spectral efficiency necessity	R_1	5%
Reference value for the subcarrier spacing necessity	R_2	15 kHz
Reference value for the T_{CP} duration necessity	R_3	1 μs
Fixed guard bands between two numerologies	C	50 kHz

In the computer simulations for this study, the following three different numerology sets are used:

1. 5G numerology set given in Table 4.5 with 7 numerologies
2. Alternative numerology set given in Table 4.7 with 36 numerologies
3. Alternative numerology set given in Table 4.8 with 12 numerologies

Table 4.7: Alternative Numerology Set with 36 Numerologies. Only 19 of them are shown in the table.

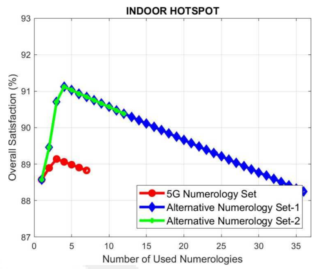
Type of Numerology	Numerology Parameters			
	$\eta_{spectral}$	Δf (kHz)	# of Symbols in One Subframe	T_{CP} (μs)
Type-B1	80.0%	15	12	16.67
Type-B2	**93.3%**	**15**	**14**	**4.76**
Type-B3	80.0%	30	24	8.33
Type-B4	**93.3%**	**30**	**28**	**2.38**
Type-B5	**93.3%**	**60**	**56**	**1.19**
Type-B6	**80.0%**	**60**	**48**	**4.17**
Type-B7	80.0%	120	96	2.08
Type-B8	90.0%	120	108	0.93
Type-B9	81.7%	120	98	1.87
Type-B10	**93.3%**	**120**	**112**	**0.60**
Type-B11	75.0%	240	180	1.39
Type-B12	80.0%	240	192	1.04
Type-B13	85.0%	240	204	0.74
Type-B14	90.0%	240	216	0.46
Type-B15	95.0%	240	228	0.22
Type-B16	75.8%	240	182	1.33
Type-B17	81.7%	240	196	0.94
Type-B18	87.5%	240	210	0.60
Type-B19	**93.3%**	**240**	**224**	**0.30**

Table 4.8: Alternative Numerology Set with 12 Numerologies

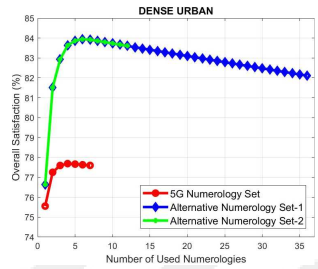
Type of Numerology	Numerology Parameters			
	$\eta_{spectral}$	Δf (kHz)	# of Symbols in One Subframe	T_{CP} (μs)
Type-C1	80.0%	15	12	16.67
Type-C2	**93.3%**	**15**	**14**	**4.76**
Type-C3	80.0%	30	24	8.33
Type-C4	**93.3%**	**30**	**28**	**2.38**
Type-C5	**93.3%**	**60**	**56**	**1.19**
Type-C6	**80.0%**	**60**	**48**	**4.17**
Type-C7	80.0%	120	96	2.08
Type-C8	90.0%	120	108	0.93
Type-C9	81.7%	120	98	1.87
Type-C10	**93.3%**	**120**	**112**	**0.60**
Type-C11	**93.3%**	**240**	**224**	**0.30**
Type-C12	**93.3%**	**480**	**448**	**0.15**

5G numerology set is indicated with bold rows in Table 4.7 and 4.8 which include Table 4.5. Also, Table 4.7 includes Table 4.8. The same input data are used for all numerology sets, and all tests are simulated 100 times with different input data to increase statistics. Average results of 100 tests are given in Figure 4.14. The results base on the ideal results which are obtained by ideal numerologies of each of the users. The efficient number of numerologies for the simulation results in Figure 4.14 are presented in Table 4.9.

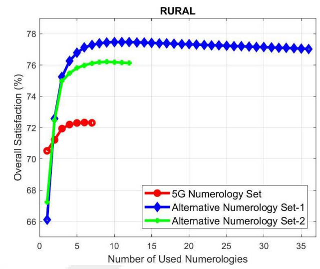
Scheduling can be easier while using the multiple numbers of slots in all subframes for different numerologies but we test also alternative numerology sets which have different numbers of slots in the subframes. In other words, we used the number of slots as 1, 2, 4, 7, 8, 9, 13, 14, 15, etc. instead of 1, 2, 4, 8, 16, and 32. The alternative sets give better flexibility results compared to 5G numerology set. If we remove some of the constraints (e.g. using the multiple numbers of slots in all subframes), total satisfaction increases. It should not be forgotten that user satisfaction can be increased by providing a wider numerology set. Hence, the



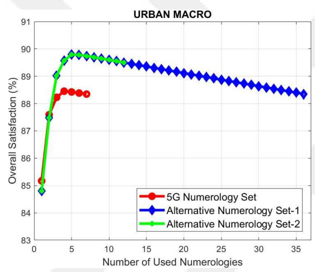
(a) Scenario 1



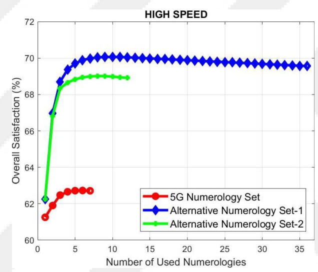
(b) Scenario 2



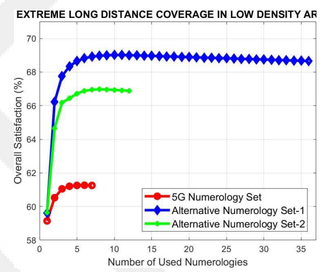
(c) Scenario 3



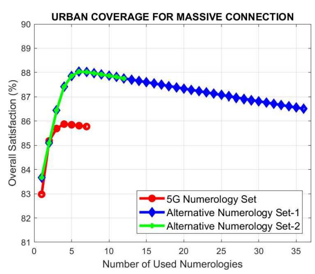
(d) Scenario 4



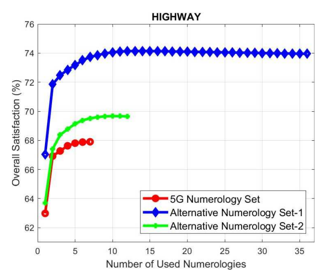
(e) Scenario 5



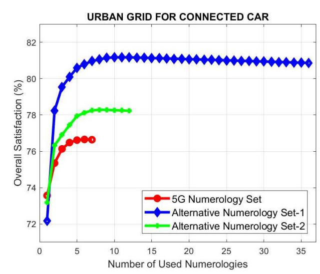
(f) Scenario 6



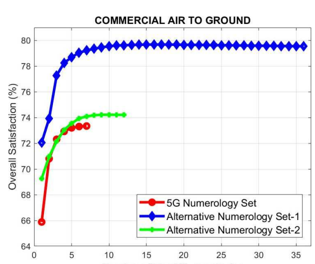
(g) Scenario 7



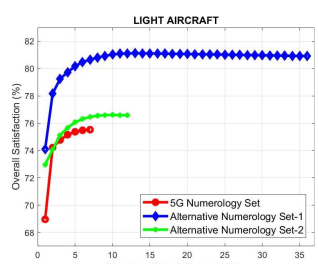
(h) Scenario 8



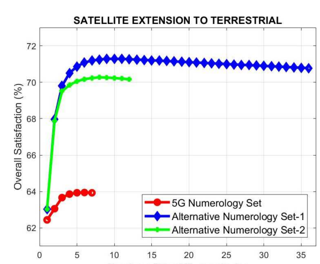
(i) Scenario 9



(j) Scenario 10



(k) Scenario 11



(l) Scenario 12

Figure 4.14: The results for 12 scenarios and three numerology sets. 5G numerology set includes 7 numerologies, the first alternative set includes 36 numerologies, and the third alternative set includes 12 numerologies.

numerology set is also very important parameter from the flexibility perspective. Figure 4.15 shows the number of users for each of the numerologies in case of using the best numerology selections for three numerology sets. Alternative sets offer better choices compared to 5G numerology set despite they include the first set. However, scheduling complexity and algorithm complexity increase when the numerology set is widened.

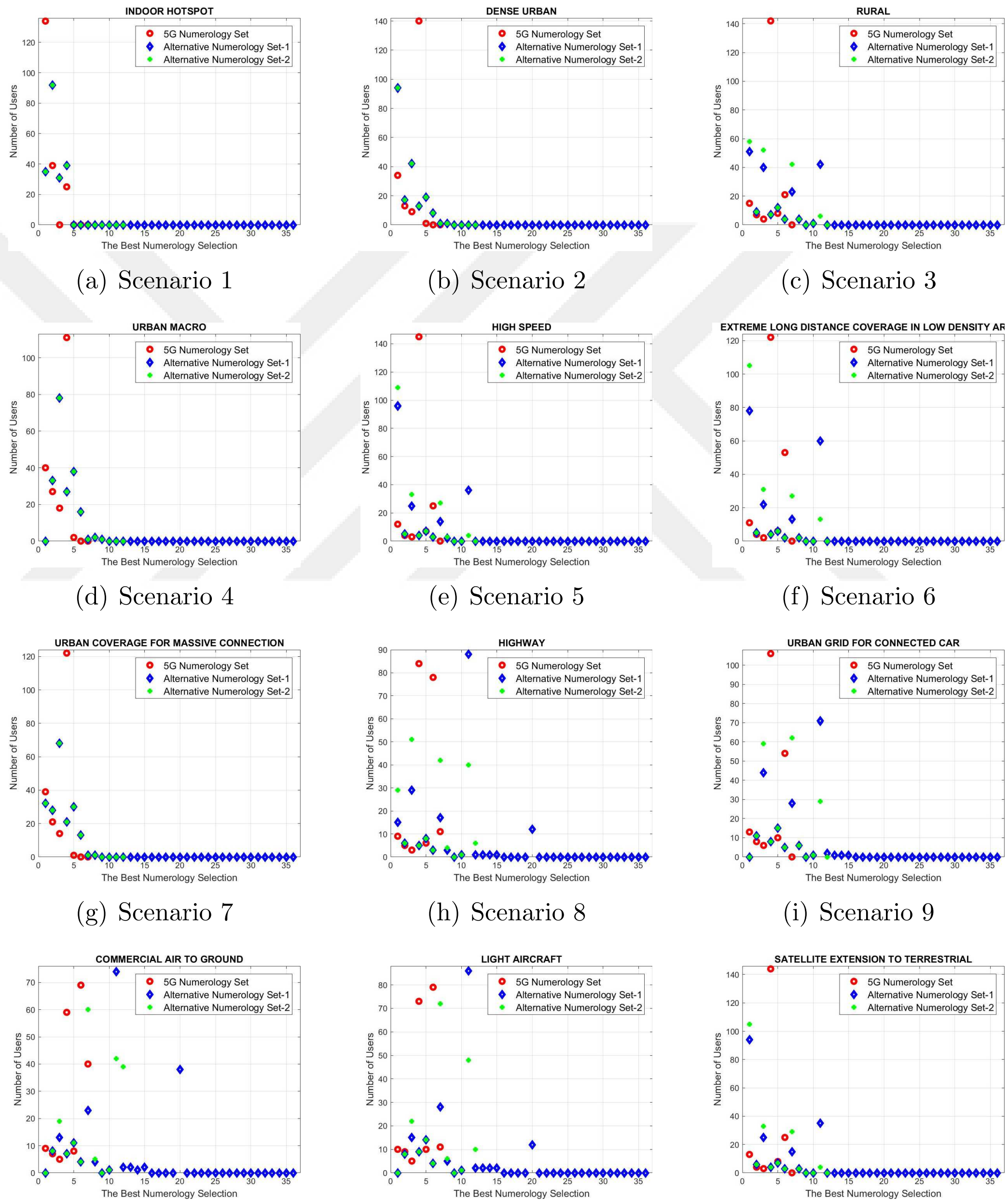
The main reasons for the differences between the results of three numerology sets can be listed as:

1. In the first set, there is not sufficient options if a longer CP duration is needed.
2. The second set covers too many options for a larger subcarrier spacing necessity.

Characteristics of the necessities or input data of all users can be analyzed from Figure 4.15. Figure 4.14 is used to find the efficient number of numerologies, whereas Figure 4.15 shows the most preferred numerology type in a numerology set under different scenarios. Generally, the most preferred numerology type is used when only one numerology needs to be selected.

In addition, as it can be seen from Figure 4.14, flexibility generally is not good when only one numerology is used. Moreover, three numerologies are not enough in many situations but they rarely give good results under some scenarios.

Simulation results support our motivations for the algorithm designs on a flexibility metric and optimization methods related with the mixed numerologies. In many cases, optimization algorithms need to be employed to increase the overall system performance.



(a) Scenario 1 (b) Scenario 2 (c) Scenario 3

(d) Scenario 4 (e) Scenario 5 (f) Scenario 6

(g) Scenario 7 (h) Scenario 8 (i) Scenario 9

(j) Scenario 10 (k) Scenario 11 (l) Scenario 12

Figure 4.15: The number of users for each of the numerologies while using all of the numerologies in three numerology sets under 12 scenarios.

Table 4.9: Efficient Number of Mixed Numerologies for Three Different Sets Under 12 Scenarios

Scenario Code	Optimum Number of Mixed Numerologies		
	Set-A (7 numerologies)	Set-B (36 numerologies)	Set-C (12 numerologies)
1	3	4	4
2	4	6	6
3	6	11	9
4	4	5	5
5	6	10	8
6	6	10	8
7	4	6	6
8	7	14	10
9	6	11	8
10	7	16	10
11	7	13	10
12	6	10	8

Chapter 5

INI-Aware Resource Management

5.1 Reliability Enhancement Using INI-Aware Resource Management

Multi-numerology waveform based 5G New Radio (NR) systems offer great flexibility for different requirements of users and services. However, there is a new type of problem that is defined as inter-numerology interference (INI) between multiple numerologies. This chapter proposes novel scheduling and resource allocation techniques to enhance overall reliability and also provide extra protection for ultra reliable and low latency communications (uRLLC) users and cell edge users against INI. Proposed methods are useful for Internet of Things (IoT) communications and they do not cause additional spectral usage, computational complexity and latency. Practical INI-aware schemes in this chapter include fractional numerology domain (FND) scheduling, power difference based (PDB) scheduling, and machine learning based (MLB) scheduling algorithms. Additionally, waveform parameter assignment can be made more easier with a better resource management techniques that enhance the reliability.

5.1.1 Problem Definition

Reliability is one of the key performance metrics of 5th Generation (5G) systems to show the success probability of a transmission. The requirement of 5G reliability is very high compared to Long-Term Evolution (LTE) systems, e.g. ultra reliable and low latency communications (uRLLC) service needs 99.999 percent (five nines) reliability in 5G [134].

There can be various solutions in different communications layers to provide the required reliability. It is also possible to employ different solutions together. Otherwise, it is very difficult to provide the reliability with five nines. Retransmission schemes are used under media access control (MAC) layer at the expense of additional delays. Physical (PHY) layer solutions like windowing are applied for interference management but they generally come with an amount of spectral efficiency decrement. Increasing computational complexity, latency, and energy consumption are not preferred for Internet of Things (IoT) communications. In this paper, it is aimed to provide reliability without causing any loss in the other performance metrics including computational complexity, latency, energy consumption, and spectral efficiency. Reliability is enhanced by simple resource allocation and management techniques based on interference-aware scheduling.

One of the most remarkable characteristics of New Radio (NR) is its flexibility that is needed for application diversity [2,4]. Requirements of users (also channel-related issues) and different application groups that include uRLLC, enhanced mobile broadband (eMBB), and massive machine type communications (mMTC) can only be met with a flexible wireless system [59]. The importance of service multiplexing is increased with the flexibility perpective of multi-numerology based NR [135, 136]. To support this flexibility, different structures are defined with 5G and one of them is the multi-numerology waveform design that provides suitable waveform parameters for different types of services at a time. A disadvantage of the multi-numerology systems is the inter-numerology interference (INI) that is a leakage between different numerologies, causing many challenges and presents new research opportunities [14]. Therefore, the importance of adaptive interference management grows. For example, INI is more effective at the edge subcarriers of different numerologies and signal-to-interference ratio (SIR) of the edge subcarriers is low as a result [14, 45]. It causes unfairness for the edge subcarriers of multiple numerologies and reliability for the edge subcarriers decreases tremendously. In this paper, INI-aware resource allocation based scheduling techniques are applied against the multiple numerology based interference to enhance reliability.

5.1.2 Previous Works

Classical physical resource block (PRB) scheduling algorithms for the resource allocation of single-numerology LTE systems (without INI) are reviewed exhaustively in [137]. Fairness and reliability based user equipment (UE) scheduling concept has been extensively studied for single numerology systems in the literature [138–140]. For example, proportional fair (PF) is one of the most used methods for a fair scheduling [140]. PF scheduling aims to provide fairness while exploiting good channel conditions and dynamically allocating resources to UEs. There are also INI based reliability enhancement techniques rather than scheduling based methods in the literature [45, 56]. Most of these techniques (e.g. guard usage, windowing, filtering) do not maintain spectral efficiency and use more spectrum to decrease or eliminate INI effects. However, to the best of authors' knowledge, INI-aware resource allocation based scheduling methods without losing from the important performance metrics for reliability enhancement have not been studied intensively under multi-numerology concept. Besides, resource allocation based scheduling methods can be employed together with the other type of reliability enhancement methods to provide more reliability.

In this chapter, fractional numerology domain (FND) scheduling and power difference based (PDB) scheduling concepts are proposed as main contributions. Moreover, machine learning based (MLB) scheduling mechanism is provided as another perspective. INI affects all of the users negatively and reliability enhancement can be provided with different solutions to decrease INI effects but we focus on three ideas under INI-aware resource allocation based scheduling concepts: 1) Protecting uRLLC users from INI more than the other users. 2) Protecting cell edge users from INI more than the other users because cell edge users are already subject to interference from the other cells due to their location like in LTE. 3) Increasing fairness for the edge subcarriers of multiple numerologies because INI is more effective at the edge subcarriers. The proposed practical solutions aim to enhance the reliability, QoS, and fairness for 5G and beyond communications systems with minimal loss from scheduling flexibility and without bringing additional latency and computational complexity, causing extra energy consumption, and decreasing spectral efficiency. Algorithm designs in this paper can be used also with other reliability enhancement techniques. All of the proposed algorithms are easily implementable with the 3rd Generation Partnership Project (3GPP) standard thanks to the flexible structure of 5G NR.

5.1.3 Assumptions and System Model

Table 5.1 shows the 5G numerology parameters including subcarrier spacing (Δf), CP duration (T_{CP}), and slot duration for data channels in NR according to 3GPP standard documents [14] and [44]. These numerology structures are employed with orthogonal frequency division multiplexing (OFDM) and it is assumed that UEs are synchronous to each other. It is also assumed that the subcarriers (SC) of UEs are non-overlapping to each other and each numerology block that consists of multiple carriers is shared by multiple UEs. We allocate UEs or bandwidth parts (BWP) with same numerologies contiguously in the frequency domain like in [14, 46, 134].

Algorithms in this paper assume that user-numerology association procedures have been completed in the previous stages of scheduling [4]. For example, base station (BS) assigns NUM-1 to UE-1, 7, 9, 4, 5; and NUM-2 to UE-6, 8, 3, 10, 2 in Fig. 5.1. The proposed INI-aware algorithms may be employed as a feedback

Table 5.1: Numerology Structures for Data Channels in NR

Δf (kHz)	T_{CP} (μs)	Slot Duration (ms)	# of Symbols in One Slot
15	4.76	1	14
30	2.38	0.5	14
60	1.19 | 4.17	0.25	12 | 14
120	0.60	0.125	14

of user-numerology association methods but this paper focuses on the resource allocation of each UEs under the predetermined numerologies.

In [45], a theoretical model for INI is provided for CP-OFDM waveform systems as a special case of Windowed OFDM (W-OFDM). INI analysis for a subblock of the numerology with a smaller subcarrier spacing (NUM-1) gives Eq. 5.1. The result of this equation is the amount of INI that is caused by the other subblock of the numerology with a larger subcarrier spacing (NUM-2). Beside, INI analysis for the subblock of NUM-2 caused by the subblock of NUM-1 gives Eq. 5.2. These models are taken as a reference in our paper. The detailed derivations of Eq. 5.1 and Eq. 5.2 can be found in [45].

$$\begin{aligned} P_u{}^{(1)}(k) \approx \frac{|\rho^{(2)}H^{(2)}(u)|^2}{N^{(2)}N^{(1)}} \Bigg[\left| \frac{sin\left[\frac{\pi}{N^{(1)}}\Delta k^{(1)} \alpha N_T{}^{(2)}\right]}{sin[\frac{\pi}{N^{(1)}}\Delta k^{(1)}]} \right|^2 \\ +(\alpha - 1) \left| \frac{sin\left[\frac{\pi}{N^{(1)}}\Delta k^{(1)} N_T{}^{(2)}\right]}{sin[\frac{\pi}{N^{(1)}}\Delta k^{(1)}]} \right|^2 \Bigg] \end{aligned} \tag{5.1}$$

$$P_u{}^{(2)}(k) \approx \frac{|\rho^{(1)}H^{(1)}(u)|^2}{N^{(2)}N^{(1)}} \left| \frac{sin\left[\frac{\pi}{N^{(1)}}\Delta k^{(2)} N^{(2)}\right]}{sin[\frac{\pi}{N^{(1)}}\Delta k^{(2)}]} \right|^2 \tag{5.2}$$

Here, $P_u{}^{(i)}(k)$ is the INI power on the k'th subcarrier of NUM-i that is caused by the u'th subcarrier of the other subblock. $\rho^{(i)}$ is the power adjusting factor for the subblock with NUM-i. $H^{(i)}(u)$ is the channel frequency response on the u'th

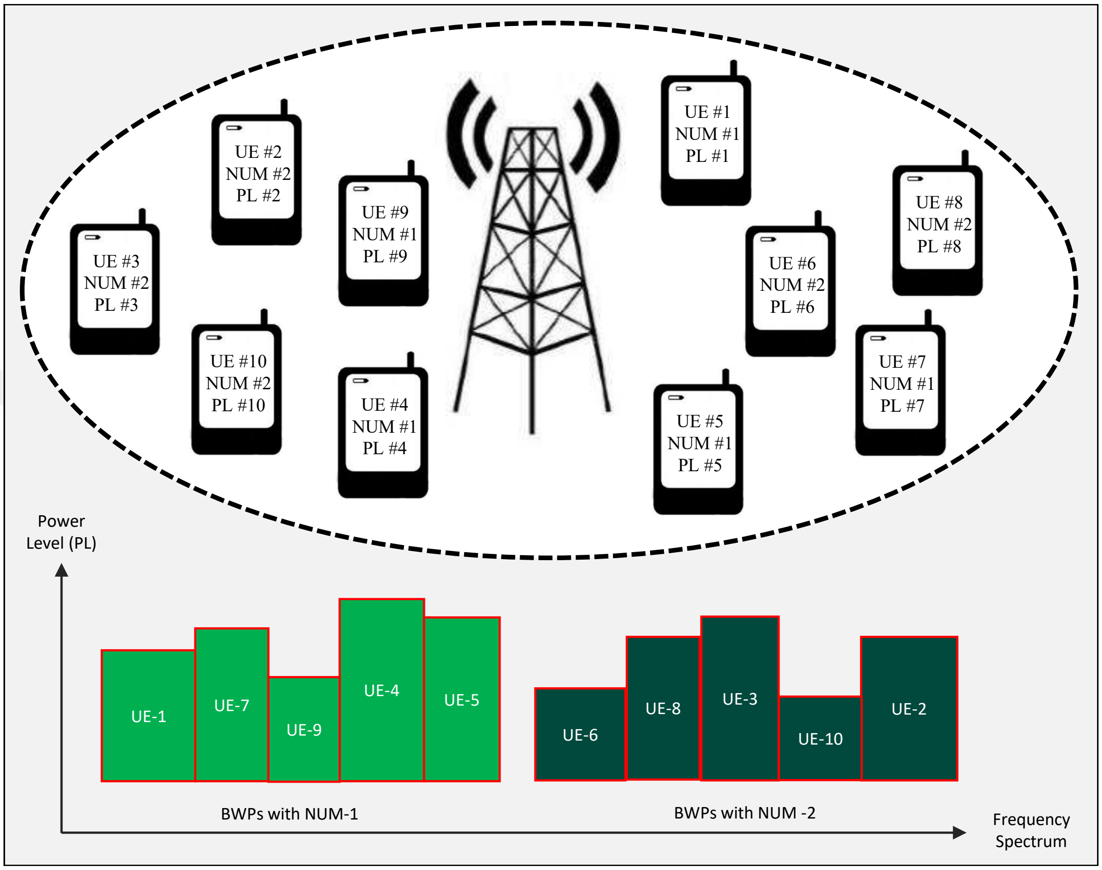


Figure 5.1: An example resource allocation in frequency spectrum for the multiple numerologies (NUM) with different user PLs.

subcarrier of the subblock with NUM-i. $N^{(i)}$ is the Discrete Fourier Transform (DFT) length and ${N_T}^{(i)}$ is the symbol duration (regarding the number of samples) for OFDM symbols. $\Delta k^{(i)}$ is spectral distance between the subcarrier k of the subblock with NUM-i and the interfering subcarrier of the other subblock. α is the number of rectangular overlapping windows.

Increasing spectral distance between subcarriers with different numerologies decreases INI effects. Then, using a guard band between different numerologies is one way to decrease INI in return to spectral efficiency. The 3GPP standards make guard band choices flexible with high granularity [14]. Various amounts of guard bands are used while comparing results in the next sections. Moreover, it is assumed that each UEs have different power levels (PLs) as shown in Fig. 5.1 and this variation is exploited in the proposed PDB scheduling algorithms.

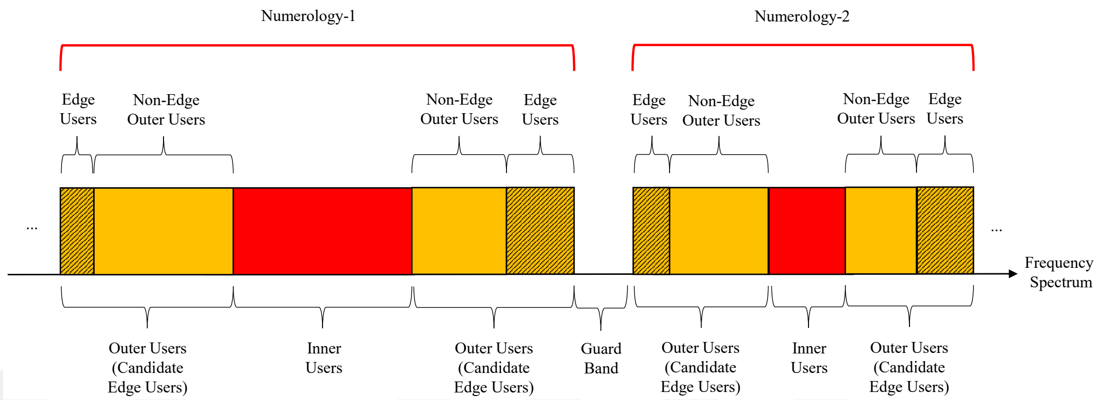


Figure 5.2: Fractional numerology domain (FND) structure.

FND is a novel resource allocation structure. In the proposed structure, there are inner and outer users for each subblocks with different numerologies as shown in Fig. 5.2. All of the outer users are also candidate edge users. Additionally, outer users are divided into non-edge outer users and edge users. INI effects decrease from edge users to inner users. Fractional regions of each subblocks are used while applying scheduling algorithms. These regions are not fixed parts.

It is assumed that UEs have independent and identically distributed multipath Rayleigh fading channels and perfect channel state information (CSI) is obtained at the receiver sides. Additionally, re-use factor is one in all cells like in LTE systems. Hence, inter-cell interference is more effective in the cell edges.

5.1.4 Fractional Numerology Domain Resource Management

Users can be scheduled using the FND concept to protect some of the users from INI effects more. Inner parts of the numerology subblocks are not affected by INI in comparison to outer parts of the subblocks. Therefore, extra protection against the INI effects can be provided by locating some of the users who need more reliability into inner parts of the numerology subblocks. In the next subsections, two ideas are presented to ensure that uRLLC users and cell edge users are protected from INI effects more as also shown in Fig. 5.3.

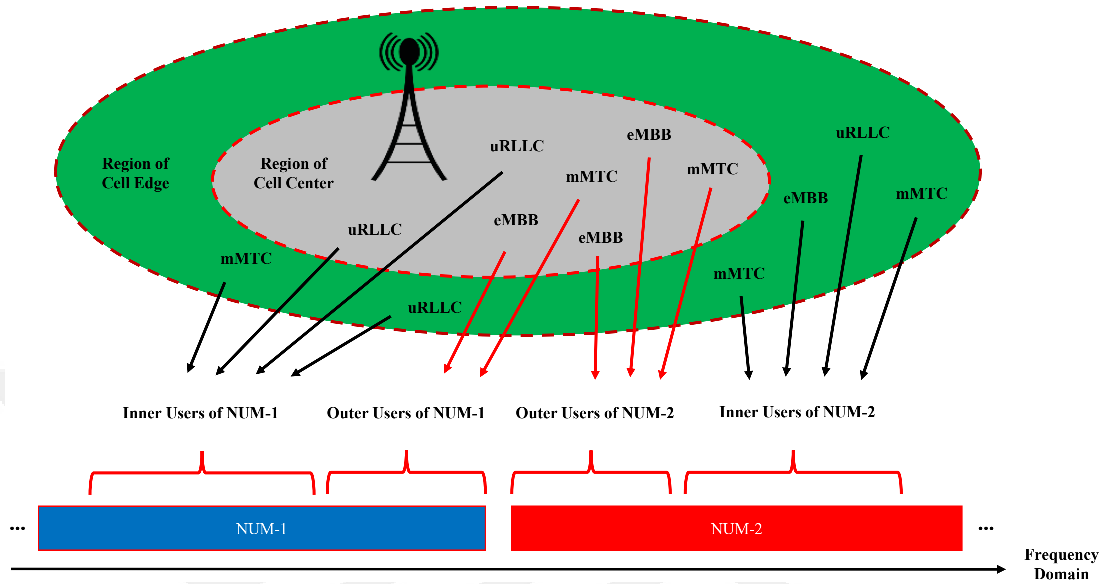
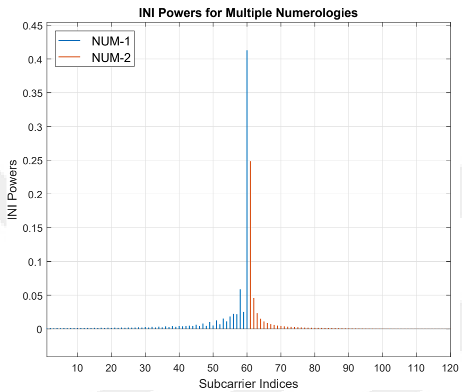


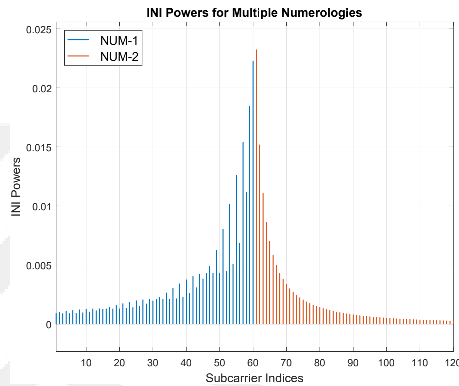
Figure 5.3: Protection for uRLLC users and region of cell edge users. It is assumed that there are inter-cell interference in the region of cell edges. Inner regions of the subblocks are safer than the outer regions.

INI analysis results regarding Eq. 5.1 and Eq. 5.2 for multiple numerologies with different subcarrier spacings and guard bands are presented in Fig. 5.4. Guard band (GB) usage increases spectral distance between the numerologies and it decreases INI. However, the amount of INI is calculated more at the numerology edges in all scenarios. Total INI and INI variation between inner and outer users decrease with the usage of GB in return to corresponding spectral efficiency. Additionally, if subcarrier spacing difference between the numerologies increase, it effects INI negatively.

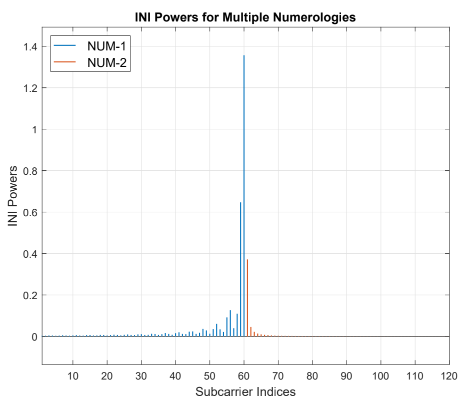
Eq. 5.3 is derived to calculate the total regional INI effects on different subcarriers of a subblock. It is obtained for the total amount of regional INI caused by the other subblock with a different numerology. Here, a and b define a region in one subblock. This region can be only one subcarrier or whole subblock. $P^{(i)}(a, b)$ gives the total interference power at the target region of a subblock with NUM-i. $Z^{(j)}$ presents the number of contiguous subcarriers in the other subblock with NUM-j and it is assumed that $0 \leq a \leq b < Z^{(j)}$.



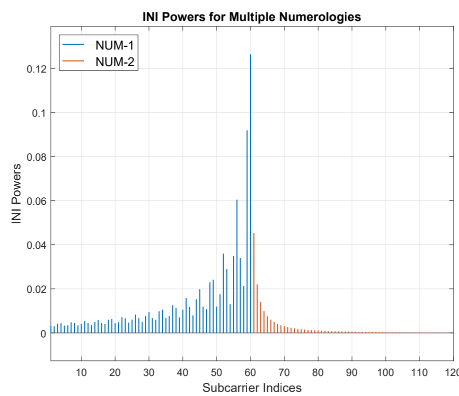
(a) NUM-1 has narrow SCs with 15 kHz and NUM-2 has wide SCs with 30 kHz. There is not any GBs between the numerologies.



(b) NUM-1 has narrow SCs with 15 kHz and NUM-2 has wide SCs with 30 kHz. There are four SCs as GBs between the numerologies.



(c) NUM-1 has narrow SCs with 15 kHz and NUM-2 has wide SCs with 60 kHz. There is not any GBs between the numerologies.



(d) NUM-1 has narrow SCs with 15 kHz and NUM-2 has wide SCs with 60 kHz. There are four SCs as GBs between the numerologies.

Figure 5.4: INI analysis results regarding Eq. 5.1 and Eq. 5.2 for multiple numerologies with different subcarrier spacings and guard bands.

Table 5.2: Total INI Powers on Each User or Subblock Regarding Eq. 5.3 for different guard bands between two numerologies. NUM-1 has narrow SCs with 15 kHz and NUM-2 has wide SCs with 30 kHz. UE-5 and UE-6 are located at numerology edges in frequency domain. UEs have equal number of SCs.

	NUM-1				
	INNER PART		OUTER PART		
	UE-1	UE-2	UE-3	UE-4	UE-5
INI Power (GB: 0 SCs)	0.0139	0.0193	0.0301	0.0544	0.6205
INI Power (GB: 6 SCs)	0.0122	0.0161	0.0239	0.0390	0.0937
INI Power (GB: 12 SCs)	0.0108	0.0139	0.0193	0.0301	0.0544
INI Power (GB: 24 SCs)	0.0084	0.0108	0.0139	0.0193	0.0301
INI Power (GB: 36 SCs)	0.0069	0.0084	0.0108	0.0139	0.0193

Table 5.3: The remaining part of Table 5.2.

	NUM-2				
	OUTER PART			INNER PART	
	UE-6	UE-7	UE-8	UE-9	UE-10
INI Power (GB: 0 SCs)	0.3816	0.0233	0.0107	0.0062	0.0041
INI Power (GB: 6 SCs)	0.0725	0.0185	0.0092	0.056	0.0038
INI Power (GB: 12 SCs)	0.0438	0.0150	0.0080	0.0050	0.0035
INI Power (GB: 24 SCs)	0.0233	0.0107	0.0062	0.0041	0.0028
INI Power (GB: 36 SCs)	0.0150	0.0080	0.0050	0.0035	0.0025

$$P^{(i)}(a,b) = \sum_{k=a}^{b} \sum_{u=0}^{Z^{(j)}-1} {P_u}^{(i)}(k) \tag{5.3}$$

Inner users are affected less than edge users for one numerology. Table 5.2 provides total regional INI powers regarding Eq. 5.3 for different users while GB is varying. As it can be seen from Table 5.2, GB usage has more effects at the edges compared to inner parts of numerologies. Reliability of numerology edges always less than the other parts of numerologies in frequency domain. For the five nines reliability, numerology edges are not safe enough even there is a reasonable GB between multiple numerologies.

5.1.4.1 Reliability Enhancement for uRLLC Users

uRLLC users can be assigned to subblocks with different numerologies. There is not a specific 5G numerology that fits best with uRLLC service. Some of the 5G numerologies include large Δf that is better to struggle with inter-carrier interference (ICI) problems and also better regarding low latency requirements. However, T_{CP} changes directly proportional with symbol duration ($1/\Delta f$) in 5G. It may cause inter-symbol interference (ISI) problems because large Δf (short symbol duration and short T_{CP}) is not suitable for long delay spread cases. ISI problems decrease reliability.

We are proposing that uRLLC data should be scheduled at more reliable regions of multiple numerologies considering its importance. We need to protect uRLLC users more compared to the other users. Hence, uRLLC users can be assigned as inner users of suitable numerologies. If all users are associated with uRLLC service exceptionally (e.g., vehicle-to-vehicle communications in highways), all subcarriers (inner and outer) of a subblock can be employed for uRLLC.

5.1.4.2 Reliability Enhancement for Cell Edge Users

Re-use is taken as one in LTE and beyond systems. Therefore, all of the channels can be employed in all cells. It causes an extra interference on the cell edge users. If there is a fractional cell with two clusters as a region of cell edge and region of cell center like in Fig. 5.3, users in the region of cell edge are exposed to inter-cell interference more compared to users in the region of cell center. Reliability is provided better in the region of cell center inherently thanks to path loss effects of the wireless channel.

We do not want to schedule the same user at the cell edges and the numerology edges. Two disadvantages together are too much unfairness for a user. Cell edge users at least need to be protected from INI effects more. Hence, cell edge users are scheduled as inner users of the subblocks with suitable numerologies.

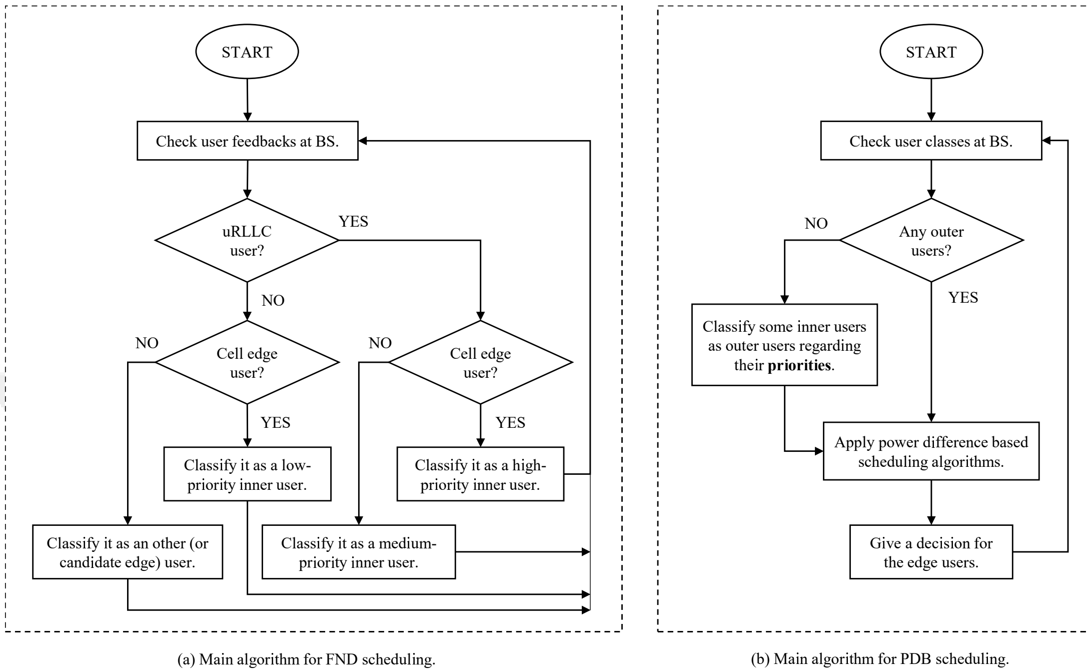


Figure 5.5: Algorithm flowcharts for a) FND scheduling and b) PDB scheduling.

5.1.4.3 User Priorities for INI Protection

It is also possible to enhance reliability for uRLLC users and cell edge users together. For this purpose, uRLLC users and cell edge users can be scheduled to inner parts of the subblocks as far as possible. Three type of special users are listed as 1) association with the uRLLC service, 2) being at the cell edge, 3) being at the numerology edge. If two of them are valid for one user, it is a bad luck. Moreover, if all of these situations are valid for one user, it is the worst case scenario. We cannot control the first two cases but being at the numerology edge can be controlled by the scheduler. At that point, inner users of the subblocks can be decided by starting with the worst case scenario. Some priorities are defined for our algorithms as shown in Fig. 5.5. They can be listed as 1) association with the uRLLC service and being at the cell edge, 2) association with the uRLLC service and being at the cell center, 3) association with the non-uRLLC service and being at the cell edge, 4) association with the non-uRLLC service and being at the cell center. After inner users of subblocks are decided, scheduling of these users on the frequency domain is employed flexibly because the proposed design aims to maintain scheduling flexibility as much as possible. Scheduling each user on specific subcarriers decreases flexibility.

For the non-inner or outer users of subblocks, our scheduling algorithms are described in the next subsection.

5.1.5 Power Difference Based Resource Management

Outer users (candidate edge users) are investigated to find the best suitable edge users of subblocks in this section. Power level (PL) and bandwidth (BW) of a UE are considered as two main inputs for the proposed PDB scheduling methods. Fairness of UEs at the numerology edges is increased by minimizing the INI effects while maintaining spectral efficiency with fixed guard bands. The overall reliability is also enhanced by our novel scheduling methods. We focus only on candidate edge UEs in the proposed algorithms. After the decision of edge users, the other outer UEs can be scheduled flexibly in the frequency domain. Hence, scheduling flexibility does not lose.

In the next subsections, power difference problem for the edge users of numerologies is analyzed. Then, novel algorithms are proposed to increase fairness and reliability by scheduling users at the edges of multiple numerologies more carefully.

5.1.5.1 Power Difference for the Edge Users of Different Numerologies

INI is generally concentrated at the edge SCs of subblocks because of the large side lobes and non-orthogonality of multiple numerologies [14,60]. In addition to the INI problem for the UEs on numerology edges, power difference is another issue for multi-numerology systems [51]. SIR degradation occurs especially at the edge UEs in different numerologies. Power offset (PO) affects SIR negatively. Combined effects of INI and power difference on SIR are given by Eq. 5.4. In these equation, ${SIR_u}^{(i)}(k)$ is SIR on the k'th subcarrier of NUM-i that is caused by the u'th subcarrier of the other subblock. $PL^{(i)}(k)$ is power level on the k'th subcarrier of NUM-i and $PL^{(i)}(u)$ is power level on the u'th subcarrier of NUM-i. If i is 1, j is taken as 2 and if i is 2, j is taken as 1.

$$SIR_u{}^{(i)}(k) = \frac{\left[PL^{(i)}(k)\right]^2}{\left[PL^{(j)}(u)\right]^2 P_u{}^{(i)}(k)} \tag{5.4}$$

Power difference between UEs of different numerologies increases the effects on SIR. Hence, fairness and reliability for the edge UEs of numerologies needs to be provided under different PLs while maintaining the other performance criteria. PO for the edge UEs can be minimized to increase fairness for the edge UEs. Also, minimizing a variance between SIR values for different cases aims the same motivation. SIR values of one UE should not change noticeably with time. Weak UEs are affected easily by high POs like in the near-far problem for a cell. It causes higher SIR variances and low reliability for these UEs. There is a need to balance SIR to preserve the reliability of UEs and protect weak UEs.

A lower PO can also be useful to minimize guard necessities between different numerologies under desired SIR [51]. In that case, spectral efficiency can be increased due to the fewer guards. Authors of [51] aim to minimize guard necessities with a fixed SIR and fairness in their scheduling algorithm. However, we increase fairness and SIR for the weak UEs to protect them under fixed guards and spectral efficiency. Reliability requirement has a higher priority in our scenario.

In this paper, it is assumed that there are multiple users with different PLs in the same numerology. However, all users have different numerology parameters in [51]. They put each user in a specific place regarding their PLs. It causes a low scheduling flexibility. We propose PDB scheduling algorithms that focus only edge users of the subblocks to maximize fairness and reliability for UEs of contiguous multiple numerologies.

There are two goal functions. The first of them is about the interaction between edge UEs of the numerologies and it is more important because most of the INI

Table 5.4: Basic Comparison of the Algorithms

	Advantages	**Disadvantages**
Random Scheduling	The best scheduling flexibility.	Cannot provide fairness especially for edge UEs.
Algorithm 1	Maximizes SIR at the edge UEs. Good scheduling flexibility.	No enhancement for non-edge outer users' SIR.
Algorithm 2	Maximizes SIR at the edge UEs. Additionally, protects non-edge outer users more than Algorithm 1. Increases overall SIR.	A small loss in scheduling flexibility.
Proportional Fair	Increases SIR at the edge UEs compared to random scheduling.	Cannot provide the best SIR for edge UEs while balancing fairness between all UEs.

is concentrated on the numerology edges. We need to maximize SIR at the edge users. The second goal function is focused on the interaction between one edge UE of one numerology and the inner UEs of the other numerology. In this case, we can also enhance SIR on the inner UEs.

The proposed fairness-aware scheduling algorithms are presented in Fig. 5.6. The first part shows a random scheduling case, and the other parts show the proposed scheduling mechanisms. Algorithm 1 maximizes the fairness and reliability of edge UEs. Algorithm 2 checks non-edge outer UEs in addition to edge UEs if the narrow-BW UEs are scheduled at the numerology edges as a decision of Algorithm 1. There are small trade-offs between the proposed algorithms as shown in Table 5.4.

5.1.5.2 Algorithm-1: Scheduling Based on Edge-User Reliability

This method schedules UEs as a function of POs between the UEs for different numerologies. In Fig. 5.6(b), frequency positions of UE-6 and UE-7 are replaced with each other in the same numerology. UE-4 and UE-5 are also switched at the

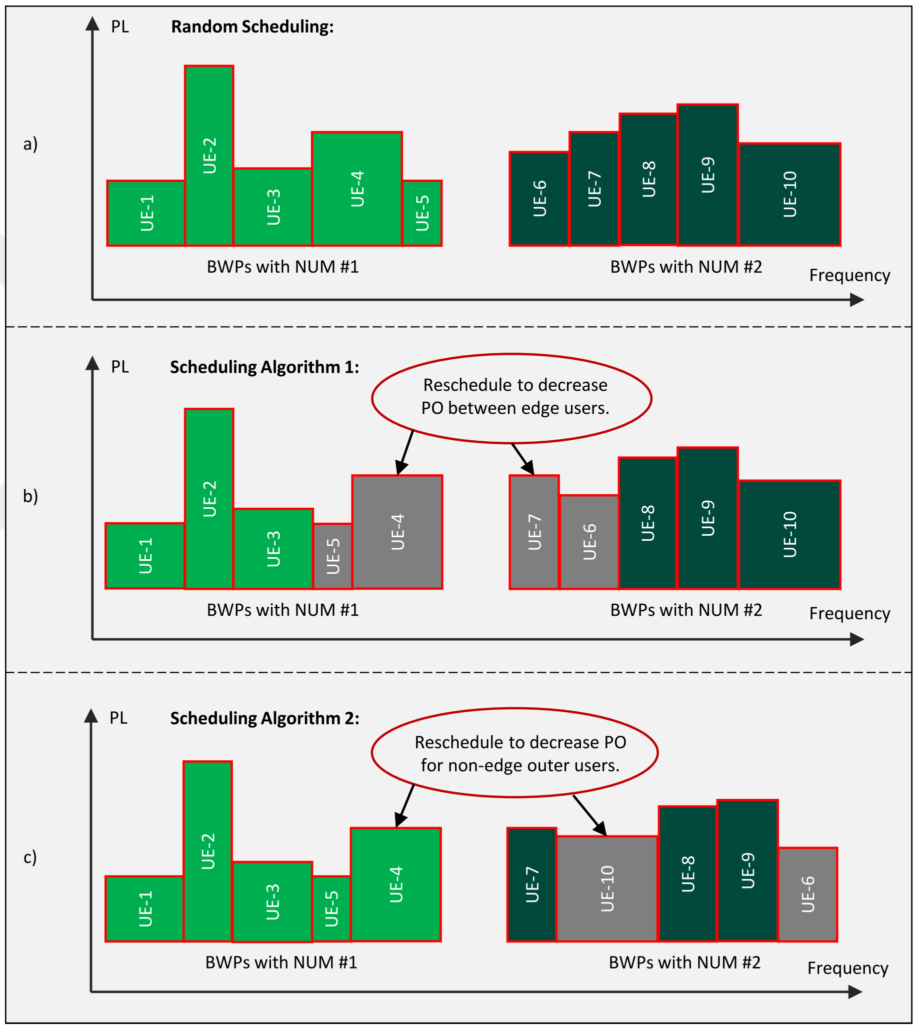


Figure 5.6: Representation of proposed PDB scheduling algorithms to decide on edge users for multi-numerology systems. There is a fixed guard band between two different numerologies. It is assumed that PO between UE-4 and UE-7 is less than PO between UE-4 and UE-10. Moreover, PO between UE-4 and UE-10 is less than PO between UE-3 and UE-6.

NUM-1 side. Hence, the PO between edge UEs (UE-4 and UE-7) are minimized to ensure that SIR is maximized at the subblock edges. Eq. 5.4 shows that PO directly effects SIR values with the INI problem. Additionally, Eq. 5.1 and Eq. 5.2 prove that spectral distance between the subcarriers of different numerologies is very important in INI analysis and numerology edges are closest regions to each other. Hence, most of INI are exposed by numerology edges.

There can be more than two numerologies at a time but our algorithm works based on numerology pairs like in Fig. 5.6. The algorithm needs to be employed for each of the contiguous two numerologies. For this reason, it is assumed that there are two numerologies in the remaining parts of the paper.

There are E non-URLLC users ($u_{1,1}$, $u_{1,2}$, ... ,$u_{1,E}$) for NUM-1, and F non-URLLC users ($u_{2,1}$, $u_{2,2}$, ... ,$u_{2,F}$) for NUM-2. PLs of these users are ($PL_1{}^{(1)}$, $PL_2{}^{(1)}$, ... ,$PL_E{}^{(1)}$) and ($PL_1{}^{(2)}$, $PL_2{}^{(2)}$, ... ,$PL_F{}^{(2)}$), respectively. Then, there are totally ExF possibilities for the PO values between UE pairs with different numerologies. The smallest power difference selection is made using Eq. (5.5) and Eq. (5.6). Then, the resulting UE pair, $(s,t)^*$, can be located at the edges of numerologies to increase reliability for edge UEs.

$$PO(s,t) = |PL_s{}^{(1)} - PL_t{}^{(2)}| \tag{5.5}$$

$$(s,t)^* = \underset{(s,t)}{\operatorname{argmin}}\, PO(s,t) \tag{5.6}$$

where s and t are UEs for NUM-1 and NUM-2, respectively. $PO(s,t)$ is the related power offset value.

5.1.5.3 Algorithm-2: Scheduling Based on Edge-User Reliability with Considering the BWs of UEs

If the edge UEs are scheduled without considering the BWs of UEs, narrow-BW users can be located at the edges of numerologies. In this case, important parts of one numerology's INI effects can continue through more UEs after the narrow-BW edge UE. It causes to focus on more than one UE at the side of narrow-BW edge UE. For example, frequency positions of UE-6 and UE-10 are replaced with each other after applying Algorithm 1 as shown in Fig. 5.6(c). Hence, the PO between UE-4 and UE-10 are minimized to ensure that SIR is maximized through UE-10 that is located next to the narrow-BW edge UE.

Algorithm 2 can be applied after Algorithm 1 if there is a narrow-BW edge UE. The decision to employ Algorithm 2 is given by checking SIR at the outermost subcarrier of a UE next to edge UE. Total SIR value at a specific subcarrier, a, can be calculated using Eq. (5.7). Here, $Z^{(j)}$ presents the number of contiguous subcarriers in the other subblock with NUM-j and it is assumed that $0 \leq u < Z^{(j)}$.

$$SIR^{(i)}(a) = \frac{\left[PL^{(i)}(a)\right]^2}{\sum_{u=0}^{Z^{(j)}-1} \left[PL^{(j)}(u)\right]^2 P_u{}^{(i)}(a)} \tag{5.7}$$

Eq. (5.7) gives total SIR at a subcarrier by all other subcarriers while Eq. (5.4) is calculating SIR at a subcarrier by only one other subcarrier. TH_{SIR} is a threshold value for desired total SIR at one subcarrier and if $SIR^{(i)}(a) < TH_{SIR}$ at the subcarrier of a, it means Algorithm 2 needs to be employed after Algorithm 1 to find the most suitable UE, r^*, that can located next to the edge UE. Eq. (5.8) is used to find r^* by comparing power differences between edge UE of the other subblock and all UEs except edge UE in the current subblock. In other words, Algorithm 1 is repeated to find a single user rather than a user pair. If r^* is searched for NUM-1, there are $F - 1$ possibilities for the PO values. Otherwise, the number of possibilities for the PO values is $E - 1$. Edge UEs that are found in Algorithm 1 are not candidates for r^* in Algorithm 2.

$$r^* = \underset{r}{\operatorname{argmin}}\, A \tag{5.8}$$

where A is PO based on Eq. (5.5) and can be calculated using Eq. (5.9). Here, s_{edge} and t_{edge} are edge UEs that are found with Algorithm 1. The number of r^* can be one or two. If there is only one narrow-BW edge UE, the number of r^* is one. If there are narrow-BW UEs at both numerology edges, the number of r^* is two.

$$A = \begin{cases} PO(r, t_{edge}), & \text{if } r \text{ is using NUM-1} \\ PO(s_{edge}, r), & \text{if } r \text{ is using NUM-2} \end{cases} \tag{5.9}$$

Algorithm 2 causes a small decrement in scheduling flexibility but it protects non-edge outer UEs more than Algorithm 1 and increases overall SIR. If there are large-BW users at the numerology edges, Algorithm 1 is enough and we do not need to employ Algorithm 2. Eq. (5.1), Eq. (5.2), and Eq. (5.4) provide an optimization objective for Algorithm 1 while the same equations and Eq. (5.7) form an optimality background for Algorithm 2. Computational complexity of the proposed algorithms are low since they are practical methods. Alternatively, these algorithms can also be implemented using ML type of decision mechanisms. An example ML concept is presented in the next subsection.

5.1.6 Machine Learning Based Resource Management

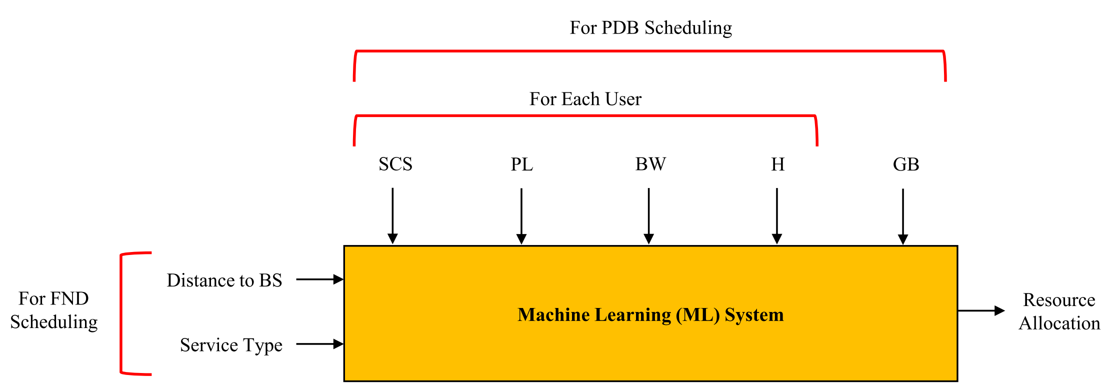


Figure 5.7: An example ML block diagram. Distance to BS and service type are inputs for FND scheduling. Subcarrier spacing (SCS), PL, BW, and wireless channel (H) are used as inputs of PDB scheduling for each UE. Guard band (GB) between two numerologies is used as another input for PDB scheduling.

ML is used for different wireless communications problems in the last years [96,97,110]. ML based (MLB) solutions can provide promising results for different applications of wireless communications. Fig. 5.7 shows an example supervised learning illustration for a MLB scheduling decision mechanism that can be used instead of the proposed algorithms in this paper.

There is a need for a large dataset to train ML systems. Otherwise, ML cannot get high performances compared to the non-ML techniques. Large datasets can be formed as measurement or simulation based methods. Measurement based dataset generation requires too many different measurements under all scenarios. Hence, simulation based dataset generation is more preferable than the measurement based methods. For example, class labels of each input vector for one million random cases need to be decided in a simulation. Maximization on the SIR values of UEs can be used as a decision unit while forming the dataset for each of one million scenarios. Hence, the simulation based dataset can be formed.

After forming the dataset with input vectors and corresponding class labels, supervised training process can be employed for different ML or fuzzy logic methods. Then, the trained models are used as a solution to provide reliability enhancement in our resource allocation based scheduling problem.

5.1.7 Results and Discussion

In the performance analysis simulations, it is assumed that there are five UEs in each numerology like in Fig. 5.6 for the sake of clarity. Some other simulation parameters are provided in Table 5.5.

Δf_{ref} kHz and $2^k \times \Delta f_{ref}$ kHz SC spacings are used for two numerologies, where 2^k is the scaling factor and k is a positive integer. N_{ref}-point and $N_{ref}/(2^k)$-point inverse fast Fourier transform (IFFT) blocks are employed by NUM-1 and NUM-2, respectively. After each IFFT operation, CP samples are added with a ratio of $\boldsymbol{CP_R}$ to every OFDM symbol in each numerology. It is assumed that UEs have independent and identically distributed multipath Rayleigh fading channels and perfect channel state information (CSI) is obtained in receiver. At the receiver side, N_{ref}-point and $N_{ref}/(2^k)$-point fast Fourier transform (FFT) blocks are used by NUM-1 and NUM-2, respectively. The same structure is used for the rest of

Table 5.5: Simulation Parameters for Multiple Numerologies

The number of users for NUM #1	E	5
The number of users for NUM #2	F	5
Reference value for Δf	Δf_{ref}	15 kHz
The scaling factor for Δf	k	1
Reference size of IFFT/FFT blocks	N_{ref}	4096
CP Ratio	CP_R	1/16

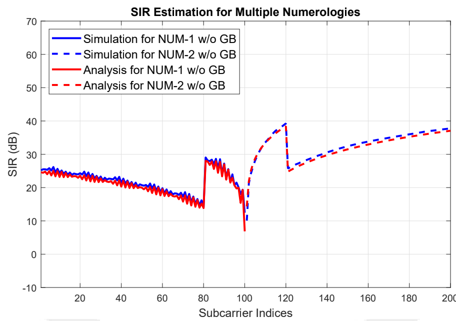
this section.

Theoretical analysis results in Section 5.1.4 show that inner parts of subblocks with different numerologies are on the safe side regarding INI effects. Besides, most of the INI is gathered in the edge subcarriers and users of each subblocks. All of the UEs have equal PLs and the same number of SCs in Section Section 5.1.4.

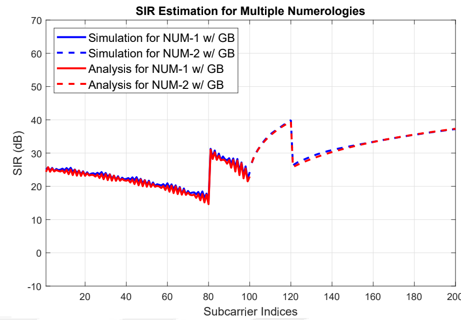
Here, POs of the UEs alternate between 0 dB and 7 dB. INI and SIR estimations are done for each of the used SCs separately. Monte Carlo method is applied to increase the statistics in performance results. The number of independent tests is 1000 and different set of random data is used in each of these tests. Thereafter, the average INI and SIR on the SCs are estimated. Estimations are done with a simulation based script and analytical equation based script separately under the same conditions. Simulation based SIR results are presented and compared with analytical SIR results in Fig. 5.8 with the below inferences:

1. If Case-1 and Case-3 are compared to each other, it can be seen that SIR results at the edge UE of NUM-1 decrease about 14 dB while SIR values at all UEs of NUM-2 increase between 9 dB and 11 dB in Case-3. Scheduling edge UEs with different PLs causes this unfairness. Reliability for edge UE is very low in Case-3 because of the PO.

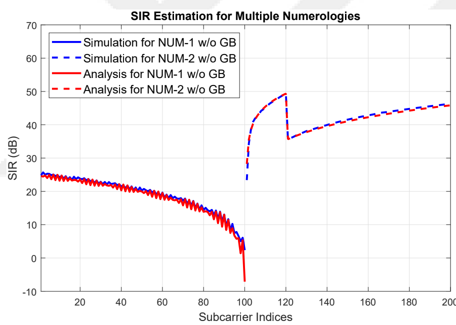
2. If Case-3 and Case-5 are compared to each other, high PL UE is shifted from edge to inner side in Case-5. Then, there is not any PO between the edge UEs. There are SIR increments of 6-14 dB at the edge UE and 1.5-6 dB at the non-edge UEs of NUM-1. SIR results of all UEs of NUM-2 stay



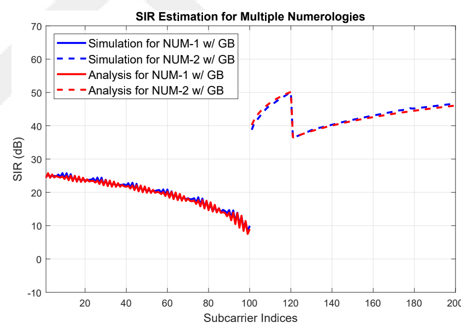
(a) Case 1: Edge UEs of NUM-1 and NUM-2 have higher PLs than the other UEs. There is not any POs between the edge UEs. There is not any GB between numerologies.



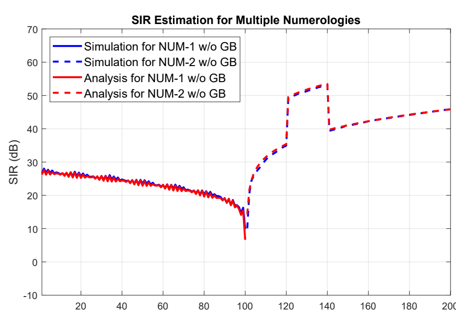
(b) Case 2: Edge UEs of NUM-1 and NUM-2 have higher PLs than the other UEs. There is not any POs between the edge UEs. There is a GB of six SCs between numerologies.



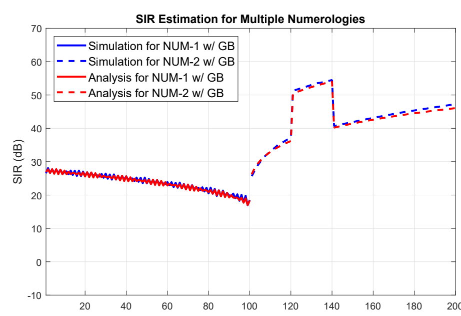
(c) Case 3: Edge UE of NUM-2 has higher PL than the other UEs. There is not any GB between numerologies.



(d) Case 4: Edge UE of NUM-2 has higher PL than the other UEs. There is a GB of six SCs between numerologies.



(e) Case 5: Non-edge UE of NUM-2 has higher PL than the other UEs. There is not any GB between numerologies.



(f) Case 6: Non-edge UE of NUM-2 has higher PL than the other UEs. There is a GB of six SCs between numerologies.

Figure 5.8: Performance analysis results for different cases. NUM-1 has narrow SCs with 15 kHz Δf and NUM-2 has wide SCs with 30 kHz Δf. If there is a PO, it is 7 dB. There are 5 UEs for NUM-1 and 5 UEs for NUM-2 with equal number of SCs.

above 14 dB in Case-5.

3. If there is a GB of six SCs between the numerologies (Case-2, Case-4, and Case-6), SIR values for the edge UEs increase between 1 dB (non-edge side) and 17 dB (edge side). GB usage enhances the SIR in exchange for some spectrum resources but it does not change the truth that numerology edges always have more INI.

All of these results and inferences show that inner parts of the numerology subblocks are better against INI effects. Then, they also show that FND scheduling is meaningful mechanism to provide an extra protection for some of the users. On the other side, PDB scheduling algorithms are also useful for different cases. As an example, the proposed algorithms try to make a resource allocation based scheduling similar to Case-1 and Case-5.

Chapter 6

Conclusion and Future Directions

6.1 Concluding Remarks

Until 5G systems, there was not too much flexibility on the lattice, pulse shape (filter structure), and frame. Therefore, waveform components were almost fixed and RRM algorithms were mainly related with the resource allocation between users. The relationship between MAC layer and waveform was limited. However, 5G systems use flexible lattice and pulse shape for OFDM waveform. Hence, frame structures are more flexible than the previous generations. This flexibility increases the importance of RRM mechanisms.

Waveform parameter assignment is one of the key topics that are related with the RRM mechanisms. Assignment of waveform parameters in 5G and beyond will be an important and promising research topic. There is a great flexibility to be exploited. This dissertation constitutes a basis for all different types of waveform parameter assignment techniques that employ ML and conventional methods; alone or together. Probably, the future techniques for waveform parameter assignment will be compatible with the proposed inclusive framework.

For 5G NR, 3GPP standards give freedom to implement any additional algorithms that BS and UE manufacturers desire as long as it is transparent to the receiver. Additionally, multi-numerology waveform structure in 5G NR provides more flexibility compared to LTE. The proposed RRM algorithms can be applied in 5G and beyond technologies.

NR flexibility can be exploited by finding optimal and practical solutions for implementation dependent parts of the 5G standardization. The flexibility of NR brings too many open-ended research opportunities compared to the previous cellular communications generations. Most probably, these opportunities will increase with 5G beyond technologies.

For ML applications, feasibility of them should be analyzed before applying them into cellular communications systems to see whether ML provides beneficial solutions together with the practical and effective conventional techniques. ML systems will play an important role when classical methods cannot be designed for different scenarios easily. Combination of ML and conventional methods may result with optimal solutions for the RRM techniques.

6.2 Challenges and Future Research Directions

Standards give freedom to vendors for RRM related system designs. At that point, analysis of the necessary amount of flexibility and complexity in RRM mechanisms of 5G is an important promising research area. Additionally, the role of ML will increase in the next generation cellular networks especially if there are more waveform parameter options. Moreover, the future communications systems can use multi-waveform and multi-numerology structures together in the same frame. There may be different parameter options for different waveforms. Hence, the number of total waveform-related parameter options will be numerous. As it can be seen, waveform parameter assignment subject will be one of the most important topics for RRM and resource allocation in communications systems.

Different RRM techniques can be designed considering different goal functions and KPIs. For example, waveform parameter assignment topic can be studied to enhance several other performance metrics. Moreover, resource allocation and RAN slicing subjects can be investigated like the waveform parameter assignment in this dissertation. Additionally, different feedbacks can be employed to design new RRM techniques.

As a future work for the ML applications, the proposed dataset generation methodology in Chapter 4 can be used to develop large datasets for better ML models for 6G. Many different information can feed the feature extractor to obtain useful 6G datasets related with waveform parameters. New numerology options, CP utilization methods and different lattice domains may be integrated to waveform parameters considering the possible 6G requirements. Multiple waveforms can be implemented and then different work distributions in the proposed framework can be compared.

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