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RADIO ACCESS MANAGEMENT USING MULTIPLE NUMEROLOGIES FOR MASSIVE MACHINE TYPE COMMUNICATIONS TOWARDS 6G

YAĞIZ CAN ÇAĞAN

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Yağız Can Çağan

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YAĞIZ CAN ÇAĞAN

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APPROVAL

This thesis titled RADIO ACCESS MANAGEMENT USING MULTIPLE NUMEROLOGIES FOR MASSIVE MACHINE TYPE COMMUNICATIONS TOWARDS 6G submitted by YAĞIZ CAN ÇAĞAN, in partial fulfillment of the requirements for the degree of Master of Science in Electronics Engineering is approved by

Asst. Prof. Yalçın Şadi (Advisor) ....
Kadir Has University

Assoc. Prof. Eylem Erdoğan ....
Istanbul Medeniyet University

Prof. Dr. Metin Şengül ....
Kadir Has University

I confirm that the signatures above belong to the aforementioned faculty members.

....
Prof. Dr. Mehmet Timur Aydemir
Dean of School of Graduate Studies
Date of Approval: 02.09.2022

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- that this Master of Science Thesis does not contain any material from any research submitted or accepted to obtain a degree or diploma at another educational institution;
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YAĞIZ CAN ÇAĞAN

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02.09.2022

To my dearest parents

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ABSTRACT

As 5G and beyond cellular systems aim at providing primary support for machine-type communications (MTC) under the domain of massive MTC (mMTC), 5G New Radio introduces many flexible physical layer features to enable massive connectivity while satisfying diverse service and traffic requirements of MTC services. In this thesis, optimal radio resource management for periodic MTC traffic towards 6G networks is investigated considering multiple numerologies supported by New Radio. An optimization framework to minimize the total bandwidth required while meeting the periodic data generation requirements of MTC services is presented. Two alternative optimization problem formulations are provided along with a comparative computational complexity analysis. For both optimization problems, semi-persistent radio resource allocation algorithms are proposed. The first phase of both algorithms provides optimal numerology selection and bandwidth partitioning for MTC services and the second phase performs periodic allocation of MTC services in each bandwidth part based on maximum utilization of each band. Simulations illustrate that the proposed algorithms outperform single numerology-based resource allocation algorithms in terms of spectral efficiency and use multiple numerologies effectively.

Keywords: Flexible physical layer, resource allocation, 5G and beyond, 6G, machine type communications

6G'YE YÖNELİK BÜYÜK MAKİNE TİPİ İLETİŞİM İÇİN ÇOKLU NUMEROLOJİ KULLANAN RADYO ERİŞİM YÖNETİMİ

ÖZET

5G ve ötesi hücresel sistemler, masif MTC alanı altında makine tipi iletişim için birincil destek sağlamayı amaçlarken, 5G Yeni Radyo, MTC servislerinin çeşitli servis ve trafik gereksinimlerini karşılarken masif bağlantılılığı sağlamak amacıyla birçok esnek fiziksel katman özelliği sunaktadır. Bu tezde, 6G ağlarına yönelik periyodik MTC trafiği için optimal radyo kaynak yönetimi, Yeni Radyo tarafından desteklenen çoklu numerolojiler dikkate alınarak araştırılmaktadır. MTC servislerinin periyodik veri üretim gereksinimlerini karşılarken gereken toplam bant genişliğini en aza indirecek bir optimizasyon çerçevesi sunulmaktadır. Karşılaştırmalı bir hesaplama karmaşıklığı analizi ile birlikte iki alternatif optimizasyon problemi formülasyonu sunulmaktadır. Her iki optimizasyon problemi için yarı kalıcı radyo kaynak tahsisi algoritmaları önerilmektedir. Her iki algoritmanın ilk aşaması, MTC hizmetleri için optimal numeroloji seçimi ve bant genişliği bölümleme sağlar ve ikinci aşama, her bir bantın maksimum kullanımına dayalı olarak her bant genişliği parçasında MTC hizmetlerinin periyodik olarak tahsisini gerçekleştirir. Simülasyonlar, önerilen algoritmaların, spektral verimlilik açısından tek numeroloji tabanlı kaynak tahsis algoritmalarından daha iyi performans gösterdiğini ve çoklu numerolojileri etkin bir şekilde kullandığını göstermektedir.

Anahtar Sözcükler: Esnek fiziksel katman, kaynak tahsisi, 5G ve ötesi, 6G, makine tipi iletişim.

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i	Resource element in the resource grid
Δ_f^{min}	The bandwidth indicator of the resource grid divided into resource elements (Hz).
Δ_t^{min}	Time duration indicator on the resource grid (seconds).
N_t	Time axis limit in resource grid
N_f	Frequency axis limit in resource grid
n	Each row of resource elements (band)
I_n	The set of elements in the n^{th} band
I	Set of all resource elements in the resource grid
b	Each element of block set B
$a_{b,i}$	Indicator whether block b includes element i
k	Indicator of each element of the $\mathcal{K}$ numerology set
$\mathcal{M}$	Set of MTC services
L_m	Time-triggered MTC devices
p_m	Packet generation period
B_k	The resource blocks whose leftmost element is in the I_k column
$(p_m)'$	The period in seconds
$x_{b,m}$	Indicator of MTC devices is assigned to a block b
z_n	Indicates whether the band n is used or not.
z_n	Indicates whether the band n is used or not.

LIST OF ACRONYMS AND ABBREVIATIONS

BS	Base Station
BWP	Bandwidth-Part
CA	Carrier Aggregation
CLI	Cross-link Interference
cMTC	Critical Machine Type Communication
CP	Cyclic Prefix
C-RNTI	Cell Radio Network Temporary Identifier
DBS	Dynamic Borrowing Scheduler
DC	Dual Connectivity
DRX	Discontinuous Reception
eMBB	Enhanced Mobile Broadband
FDD	Frequency Division Duplex
H-H	Human to Human
IGA	Iterative Greedy Algorithm
IoT	Internet of Things
ITU-R	International Telecommunication Union – Radiocommunication
KPI	Key Performance Indicators
LTE	Long-Term Evolution
MDP	Markov Decision Proces
MDRAP	Multi-Dimensional Resource Allocation Problem
MIMO	Multiple-Input Multiple-Output
M-M	Machine to Machine
M2M	Machine-to-machine communication
mMTC	Massive Machine Type Communication
MTC	Machine Type Communication
MTD	Machine Type Device
NOMA	Non-Orthogonal Multiple Access
NR	New Radio
OFDM	Orthogonal Frequency Division Multiplexing

PBCH	Physical Broadcast Channel
PDCCH	Physical Downlink Control Channel
PHY	Physical Layer
PRB	Physical Resource Block
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QoS	Quality of Service
RACH	Random Access Channel
RAN-1	Radio Layer1
RAR	Random Access Response
RB	Resource Block
RE	Resource Element
RIM	Remote Interference Management
RPA	Resource Partitioning-based Algorithm
SCS	Subcarrier Spacing
SS	Synchronization Signal
TDD	Time Division Duplex
TTI	Transmission Time Interval
UE	User Equipment
URLLC	Ultra-Reliable Low Latency Communications

1. INTRODUCTION

1.1 Driving Applications 5G and Beyond

Considering the extensive studies and projections conducted, billions of IoT devices will boost productivity and efficiency in various industries and societal domains towards 2030s. These IoT devices are also expected to make up the bulk of the world's data. Transmitting this data, preventing the transmission network from being overloaded and providing healthy access to many users reveal the importance of 5G networks. Much larger than 4G networks and helping this multi-device ecosystem with various solutions, 5G consists of different driving applications. Expressed in 3GPP Release 15, 5G has 3 basic working areas. Among these, eMBB includes capacity improvements. The URLLC area includes innovations on latency and reliability themes. mMTC explores an ecosystem that periodically connects multiple devices, considering traffic conditions.

eMBB, one of the innovations of 5G NR, has a structure that provides more bandwidth compared to 4G and stands out with its low latency. Examples of applications in this field are studies on augmented reality and virtual reality, 360-degree streaming and 3D virtual meetings. In addition to the innovations contained in eMBB, an example of a smart office can be given as a low latency and wide bandwidth, enabling an office worker to use cloud-based applications and all devices connecting to each other wirelessly. Also, eMBB will provide great convenience in real-time translations for people who speak different languages [1].

URLLC includes a structure that provides low latency and high reliability features that provide faster cloud access as mentioned in Release 15. These service features of URLLC enable innovations such as remote diagnosis and performing robotic surgery, industrial automation, smart electricty grid and intelligent transportation systems.

For example, with URLLC, various networks are created in production systems and the system is automated in order to facilitate industrial control in the processes in the factory. Robots take part in studies aimed at increasing production and safety here. URLLC ensures parts are not damaged by providing minimal delays during installation in car manufacturing plants [2].

mMTC, which is the most prominent area of 5G and offers innovations for IoT user scenarios, offers power efficiency, lower costs and more efficient communication, where many machine-type devices are interconnected. Smart areas where hundreds of smart sensors are connected to each other, smart logistics, thousands of traffic cameras and smart cities that will help reduce traffic congestion can be given as examples [3].

In mMTC scenarios, there are many and demanding devices (such as low power) called machine type devices (MTDs) in cellular networks. The factors causing the increase in the number of connected MTDs are smart grid, large scale environment and structure monitoring etc. example can be given. In MTC, these devices interact with little or no human interaction. Smart electrical measuring instruments, automats, smart traffic regulator devices are examples for MTC. MTC plays an important role in facilitating human life with the interconnectivity of devices [4]. We come across examples of this in our daily life. With smart parking and smart parking reservation, people can find a parking space and learn the distance to the parking lot easily [5]. Smart power meters arrange the energy use used in the home, can investigate our one day use, send it to a server and examine it [6]. Intelligent heating systems, designed to regulate the temperature in the house and save energy thanks to IoT technology, are examples of MTC we encounter in real life [7]. In Fig. 1.1 we see examples with smart cars, health monitoring devices, which are becoming increasingly popular today.

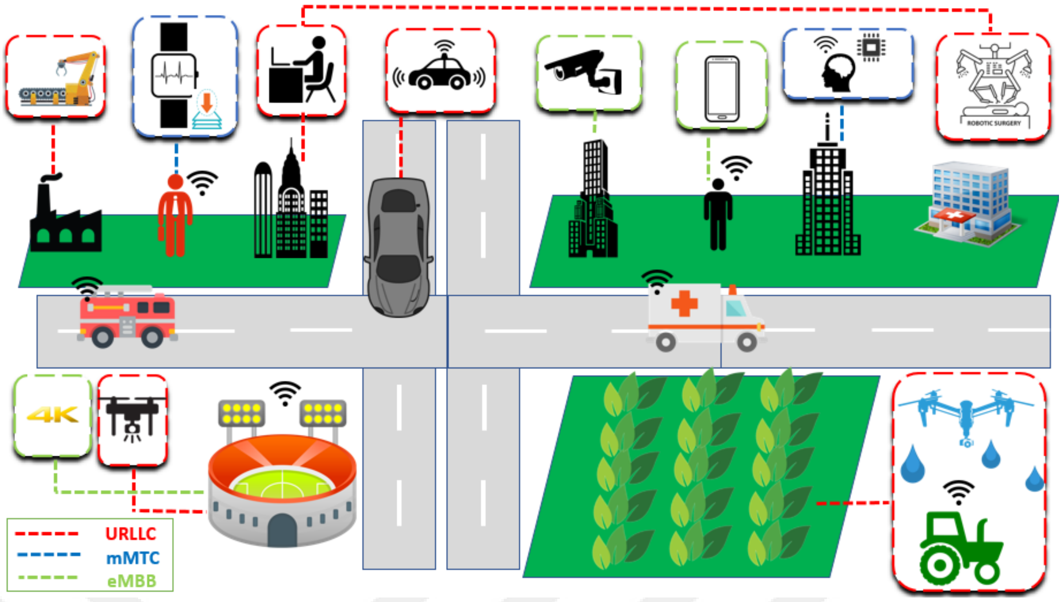

Figure 1.1 6G Application Scenario Towards 2030

1.2 Massive Machine Type Communication Towards 6G

Today, the network created by multiple, different, and interconnected machine-type devices, which is becoming more popular with the new generation of cellular networks, is known as the IoT. It is expected that the number of IoT-connected devices will triple in the next ten years and serve a variety of needs and uses. IoT enables different applications such as high data rates required for sensors and reliable real-time connection with its comprehensive features. For 5G and beyond systems, URLLC and mMTC are in the IoT service classes. As mentioned in Release 15, the new radio interface published by 3GPP and named NR has a configurable and scalable structure thanks to flexible numerology. To give an example of MTC key drivers for 6G communication towards 2030, an environment where autonomous mobility, connected living, human-machine industrial relations, digital reality, zero energy, and MTDs are essential data providers for industries in line with technological demands. Considering our world's economic, social, and technological developments in the 2030s, it is expected that MTC will serve various use cases with 6G technology [8]. These use cases include more agile and adaptable mobile connectivity systems of factories with artificial intelligence that emerged with Industry 5.0, technologies such as autonomous vehicles and unmanned aerial vehicles which we can call swarm networking, skin-patches and bio-implants where MTDs have become a part of people in the 6G era. Internet of Senses technology, where human senses will communicate with MTDs, are important examples. These various use cases will cause the key performance indicators (KPIs) in 6G to be varied and challenging. It will also cause new metrics to be added to the metrics evaluated in 5G. The International Telecommunication Union – Radiocommunication Sector (ITU-R) has offered KPIs such as reliability, latency, connection density, and energy efficiency for minimum technical performance [9]. These KPIs will play an important role for 6G MTC. In addition, thanks to the heterogeneous nature of wired and wireless access technologies, 6G technologies are expected to ease seamless harmony and the ability of work together. We observe 6G MTC classes in Fig. 1.2.

As mentioned above, 6G is expected to serve various service classes. In the white paper [10], the service classes for 6G MTC are classified as dependable critical machine type communication (cMTC), broadband cMTC, scalable cMTC, globally-scalable mMTC, zero-energy mMTC. Dependable cMTC stands for supporting reliability and low latency. Broadband cMTC refers to ensuring broadband information that requires high reliability and low latency, such as robotic surgery. Scalable cMTC represents support for services with massive device numbers such as factory automation. Here again, the connection with high reliability and low latency comes to the fore. Globally-scalable mMTC stands for supporting very large system coverage even in very large areas without a space constraint. Zero-energy mMTC covers situations where long battery life is required, such as agricultural activities.

In addition to the various technological developments that 6G offers, it has also brought challenges that need to be resolved [11]. The most challenging task to realize massive MTC for 6G is to develop grant-free access methods with limited radio resources, which is also mentioned in the 6G White Paper [10]. In this thesis, we study resource management with minimum bandwidth by making use of multiple numerologies for massive MTC.

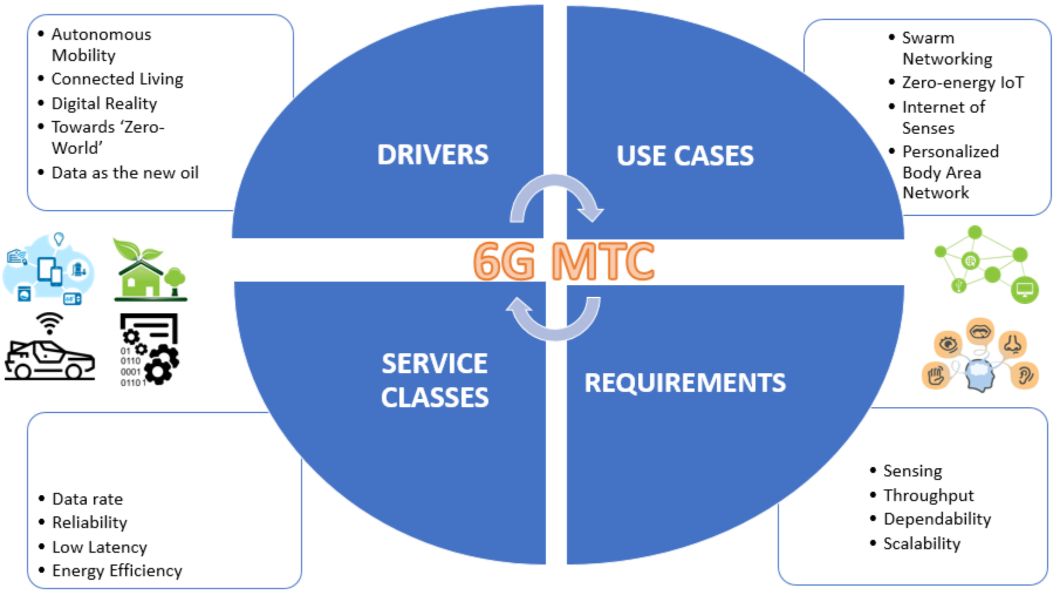

Figure 1.2 6G MTC Towards 2030

1.3 Flexible Physical Layer Architecture in 5G and Beyond

As New Radio, 5G aims to provide various services while delivering waveform parameters to the user with a flexible structure. We see the limited support and service observed in Long-Term Evolution (LTE) while supporting rich service and different user needs in 5G NR. The multiple numerology structure and frame structure that provides flexibility with this new radio interface, and the NR-related innovations in Release 15 and 16 offered by 3GPP are described in this section.

1.3.1 Multiple numerologies and frame structures

The flexibility feature of the 5G structure emerges with the combination of the parameters included in the multiple numerologies. Both LTE and NR use a waveform called orthogonal frequency division multiplexing (OFDM). OFDM is a multi-carrier structure where the transmission of information signals takes place. A digital modulation plan in which knowledge is divide between multiple orthogonal carriers and transmitted in parallel. Although the same waveform is used in both communication generations, multiple numerologies are used in NR, and single numerology is used in the LTE structure. Using the OFDM waveform, the 5G NR numerology

Table 1.1 Numerology Features of Blocks in The Resource Grid

Parameters	Numerologies		
	Num-1	***Num-2***	***Num-3***
Subcarrier Spacing (kHz)	15	30	60
Transmission Time Interval Duration (ms)	0.5	0.25	0.125
Symbol Duration (μs)	66.7	33.3	16.7
Cyclic Prefix (μs)	4.7	2.3	1.2

set includes subcarriers, subcarrier spacing (Δf), slot duration, and CP duration (T_{CP}) [12]. These different parameters shown allow the use of various numerology scenarios.

LTE only supports 15 kHz subcarrier spacing, while 5G NR supports 30, 60, 120, and 240 kHz higher subcarrier spacing. As we can see in Table 1.1 NR structure, numerology values have a scalable characteristic with $2^n \times 15$ kHz SCS where n=0,1,2,3,...,n. A 240 kHz subcarrier spacing is used only for Synchronization Signal (SS) / Physical Broadcast Channel (PBCH) blocks. (Also, the SS/PBCH block does not show assists at subcarrier spacing of 60kHz.). A sync signal is a physical signal that enables the mobile station to detect cell frequency, reception timing, and cell identity to initiate communication while powered up. PBCH is the control channel and a channel for broadcasting the wireless parameters necessary to receive the associated shared channel.

In Fig. 1.3 shows multiple OFDM symbols create slots, subframes, and frames. A slot includes of 14 OFDM symbols for subcarrier spacing; a subframe is described 1 ms interval, and a frame is ten subframes. The OFDM symbol is a transmission data unit consisting of multiple subcarriers. A Cyclic Prefix (CP) is added in front of each symbol. The slot has a structure consisting of multiple OFDM symbols. A subframe is a radio resource unit consisting of many slots in the time domain. A resource block consists of 12 subcarriers for specific subcarrier spacing in the frequency axis on recource grid.

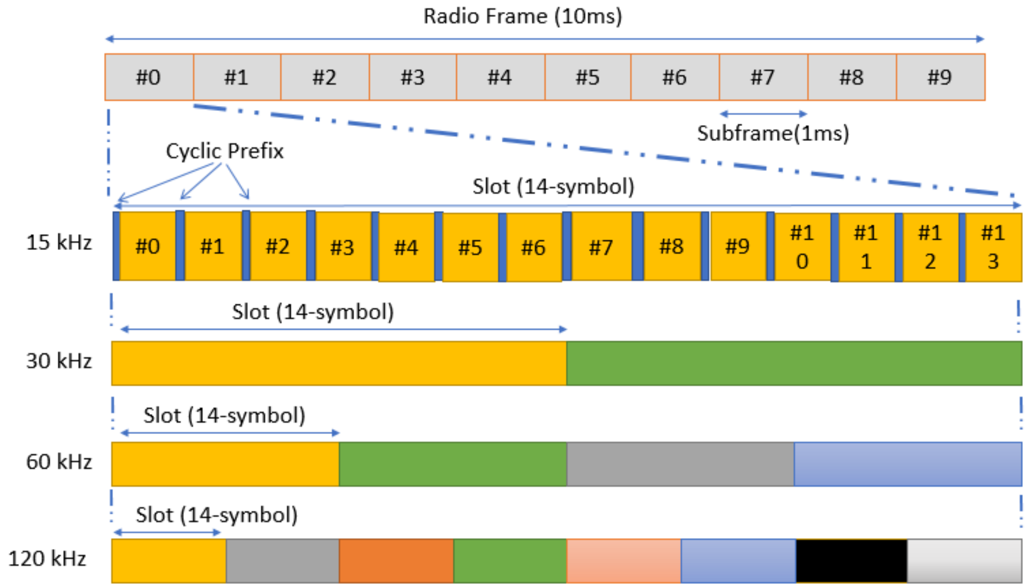

Figure 1.3 NR Frame Structure

In NR, the frame structure does not depend on the duplex. That is, the frame structure use joint frame design. Duplex mode is in which transfer can be performed at the same time on the uplink and the downlink. It is usually implemented as Frequency Division Duplex (FDD) or Time Division Duplex (TDD). NR provides much more flexible solutions in the uplink and downlink models of Time Division Duplex (TDD) than LTE. TDD is a functioning in two directions send/receive system. This system provides communication in two directions by partitioning different time slots to uplink and downlink transfers on the same frequency.

Unlike LTE, the presence of multiple subcarrier spacing values in 5G NR provides various flexibility. It is capable of supporting a wide range of scenarios from 1GHz to mm wavelengths. Larger subcarrier spacing values are favorable for smaller cell sizes. In addition, wide subcarrier spacing values also provide convenience for supporting low latency services. The latency that occur in NR are determined by the slot time, so a lower slot time or a wider subcarrier spacing means a lower latency. A wider subcarrier spacing is used to ensure the system advantageous against phase noise. Because the phase noise decreases with the lower subcarrier spacing. Studies in high frequency ranges can be performed with wider subcarrier spacing values. This makes it easy to reduce phase noise.

1.3.2 Rel-15 new radio features

In Release 15 offered by 3GPP, initial studies on the 5G NR structure have been presented, and solution scenarios and methods for various problems have been described. These studies on the NR structure are described in this section.

To solve the demanding requirements of future radio access systems, Rel-15 describes studies on the non-orthogonal multiple access (NOMA) method. In the old generation communication technologies, orthogonal frequency division multiple access (OFDMA) was used in which information is assigned to a sub-carrier subset for each user, but in NOMA, all subcarriers can be used by each user. This is an important factor for massive connectivity, enabling common resources to be used by MTC devices. Bandwidth-Part (BWP) is a recent term that refers to the structure in which the identical numerology is used in certain bandwidth parts. It is a connection between numerology and resource management. BWP's are a structure that is controlled at the base station according to the requirements in the system. BWPs authorise UEs to handle just a portion of the band, decreasing power consumption and ensuring longer cell life. This is especially important for mMTC. New Radio enables overlapping of BWPs by using diverse numerologies on the resource grid [13]. To provide productive use of resources while ensuring information to noncritical services, BWPs can overlap to simplify low-latency services. 5G NR enables the implementation of semi-persistent scheduling solutions for uplink transmissions. This is especially true for MTC devices, periodicity of the time-triggered traffic allows designing semi persistent schemes eliminating both the need for dynamic allocation of the resources on a transmission time interval basis and the excessive control signaling burden on the access point.

1.3.3 New radio-related release-16 features

Release 16, just like its predecessor Release 15, describes various work towards NR. Also, various methods and scenarios are explained in communication for 6G. We can classify these developments in two different categories. The first of these covers the improvement and development of long time ago available structures. The other offers the new deployment situations [14]. If we examine the developments in the first category, cross-link interference (CLI) mitigation and remote interference management (RIM) can be given as an example. These two situations are interference scenarios in TDD systems. CLI mitigation can find CLI with the new metrics it provides. RIM focuses on large area TDD transmissions. These deployments can create atmospheric channels that cause interference from very distant base stations (BSs). Thanks to RIM, interference situations can be managed automatically [15]. Apart from that, multiple-input multiple-output (MIMO) related developments are presented in Release-16. MIMO-related innovations contribute to increasing efficiency and reducing overhead. [16]. Also, for the purpose of user euipment (UE) power saving, innovations are presented in control signaling and scheduling operations [17]. Another improvement includes dual connectivity (DC) and carrier aggregation (CA) cases. These improvements include lower latency and better system capacity for the setup and activation of the CA/DC.

In Release 16, a new 2-step model was introduced instead of the 4-step random access channel (RACH). RACH refers to the first message from user to base. RACH design is an important step for radio access network implantation. RACH currently consists of a 4-step process, the 2-step process expressed in Release 16 will reduce latency and optimize signaling. In Release 15, the contention based random access procedure has 4 steps. Contention based procedure preambles are randomly selected for available preambles. As a result, various UEs can transfer the same preamble simultaneously. Transmits msg3 containing an ID in response to random access response (RAR) for UE contention resolution. Cell radio network temporary identifier (C-RNTI) uses a connected UE in the cell to distinguish between a particular radio channel and the transmitted system information for all UEs. It also includes physical uplink shared channel (PUSCH) transmission, also known as msg3. After the msg3 is transmitted, the contention resulotion message is transmitted along with the contention resuliotion ID, also known as msg4. The UE receives msg4 and sends an acknowledgment via physical uplink control channel (PUCCH) if it finds the contention resolution ID. In this way, the 4-step random access procedure is completed. The 4-step random access procedure has some issues. It requires two round trips and two return loops between the UE and the base station. This increases latency and causes control signaling overhead. In 2-step RACH, there is a one-turn loop between the UE and the base. This reduces latency and control signaling overhead. In 2-step RACH, msg1 and msg3 are transmitted from the UE as msgA as a single message. msg2 and msg4 are transmitted from the base to the UE as a whole as msgB.

Another NR focused work in Release 16 is UE Power Saving. Radio Layer-1 (RAN-1) studies of power saving in Rel-16 have resulted in significant power saving gains compared to Rel-15 NR features. The RAN-1 is liable for the physical layer features of the radio interface for the UE. The areas where UE has shown power savings in Release 16 are: discontinuous reception (DRX) operation with UE adaptation in frequency domain, time domain and antenna domain. In addition, tight control of DRX processes provides power savings. In case of DRX, the user continues to listen to the network even if there is no traffic situation the network and the user. So at least it should be ready to decode the physical downlink control channel (PDCCH). This means that the user must always be on, even when there is no traffic, and this negatively affects the battery. The DRX situation comes into play in this case and produces a solution.

1.4 Related Work

5G and beyond wireless communication has contributed to the emergence of various studies by serving many heterogeneous services. MTC and URLLC services benefit from innovations such as flexible transmission time interval (TTI) scheduling and mixed numerology to ensure low latency and high reliability. Many studies have researched mixed numerology frame structures for scheduling different services such as MTC, URLLC, and eMBB. You. *et al.* [13] focused on maximizing throughput by defining two different services and utilizing a flexible numerology structure. They have generated their sub-optimal and low complexity algorithms with Lagrangian duality and Linear programming. They expressed the bit rate and latency tolerances of different subcarrier spacings (SCSs) with their optimal results. Nguyen *et al.* [18] considered solving the scheduling problem through two different algorithms, Resource Partitioning-based Algorithm (RPA) and Iterative Greedy Algorithm (IGA). In this study, unallocated resources enabled the formation of new blocks by defragmentation. Marijanovic *et al.* [19] showed how resource management depends on channel properties such as doppler and channel spread and explained how to allocate bandwidth to have the same QoS properties among users. Marijanovic *et al.* [20], in their other studies on this subject, compared 3GPP's studies on physical layer (PHY), such as mixed numerology and mini slot, as two different categories. They used these two approaches as a tool to provide low latency communication and developed optimization problems that maximize the achievable rate of best effort users. Tang *et al.* [21] present a Markov Decision Process (MDP) based optimization problem to meet the requirements of URLLC services and increase the efficiency of eMBB services. They propose a mixed numerology and Deep Q-learning based scheduling algorithm for optimal scheduling. Boujelben [22] proposed in his study to minimize the number of scheduled-but-not-served QoS flows. In his work, he defines the block classes by creating two different databases. One of these databases is for block configurations, and the other is for different packaging layouts within the frame. In his study, he reduced the complexity of the block packaging and resource allocation problem to a simple solution and discussed the allocation for heterogeneous flows in 5G in terms of both formulation and resolution.

In the literature, besides the multiple numerology method, solutions to various resource allocation-based problems are also presented due to the explosive growth of the number of MTDs. Such as, efficiency maximization, energy efficiency and new random accesses. Studies on these subjects are as follows. Saddoud *et al.* [23] presented two different schedular as a solution to the scheduling problem in 5G systems. These are for multi-traffic systems in 5G. They named these two systems as

Static Scheduler and Dynamic Borrowing Scheduler (DBS). Static Schedular offers a resource allocation that provides demand balance for human to human (H–H) and machine to machine (M–M) flows. On the other hand, dynamic Borrowing Scheduler (DBS) is like a version of the first schedules and uses a borrowing system to increase bandwidth utilization and allocate resource blocks. Wu *et al.* [24] presented a dynamic resource allocation with quality of services (QoS) guarantees for clustered M2M Communications. In this study, they present an analytical formula that maximizes overall efficiency for 4 different resource allocation scenarios. Here, the situation with the maximum total efficiency is selected as the optimal resource allocation scheme. In this study, two different services are proposed and the throughpout is tried to be maximized. According to Tefek *et al.* [25] describe their proposed relaying scheme for mMTC. These relaying schemes are two as signal-to-interference ratio-based relaying and location based relaying. Unlike similar studies, they used stochastic geometry to characterize the received signal and interference powers and presented the optimum solution. In another study on resource allocation for M2M, Zhang *et al.* [26] proposes new random access with the goal of collision-free resource allocation. They present the scheduling protocol for the uplink channel in the study. Zhan *et al.* [27], showed solutions on how to efficiently manage massive connections with MTDs. For this, they offer a solution that optimizes signaling overhead and access delay for 5G mMTC networks.

Unlike the mixed numerology approach related to resource management in following generation communication systems, studies have been carried out on the non-orthogonal multiple access (NOMA) structure that allows multiple users with channel states to share the same radio resources. Wang *et al.* [28] have worked in this field and proposed a new optimization problem called Multi-Dimensional Resource Allocation Problem (MDRAP). They aimed to maximize the weighted sum rate. They changed the positions of the physical resource blocks (PRBs) with the method they named zone displacement and zone allocation in their algorithms and changed the location of the zones for allocation in each layer.

All these studies reveal various solutions by using the mixed numerology flexibility feature in the NR frame structure. None of these studies aimed at frequency minimization. However, solutions for different objectives are solved with mixed numerology. Therefore, these solutions in the literature cannot be used for bandwidth minimization. In addition, periodic traffic was not taken into account in these studies. To the best of our knowledge, scheduling periodic MTC traffic using multiple numerologies while minimizing the required bandwidth has yet been addressed in the literature.

1.5 Original Contributions

The goal of this thesis is to investigate radio resource management for periodic MTC traffic using multiple numerologies towards 6G cellular networks. The original contributions of the thesis are listed as follows:

1. We characterize an optimization framework for minimum bandwidth resource allocation problem for periodic MTC traffic and define two alternative realizations of the problem, Partitioned Bandwidth Minimization Problem $\mathcal{P}-\mathcal{BMP}$ and Non-partitioned Bandwidth Minimization Problem $\mathcal{NP}-\mathcal{BMP}$.
2. We mathematically formulate $\mathcal{P}-\mathcal{BMP}$ and $\mathcal{NP}-\mathcal{BMP}$ problems as Integer Programming problems and illustrate that both problems are NP-hard. We also provide a computational complexity comparison between the two problems.
3. We propose Maximum Utility Resource Allocation and Resource Fragment Utilization algorithms for $\mathcal{P}-\mathcal{BMP}$ and $\mathcal{NP}-\mathcal{BMP}$, respectively. Algorithms incorporate mechanisms to select optimal numerologies for different MTC services and resource allocation policies to utilize each band maximally.
4. We present simulation results illustrating the spectral efficiency of the proposed algorithms.

1.6 Organization

The rest of the thesis is organized as follows. Chapter 2 presents the system model and the assumptions used throughout the thesis. Then, in Chapter 3, two alternative realizations of the minimum bandwidth resource allocation problem are formulated along with a comparative computational complexity analysis. Next, Chapter 4 presents the resource allocation algorithms proposed for each optimization problem. Simulations are presented in Chapter 5. Finally, concluding remarks and future work are given in Chapter 6.

2. SYSTEM MODEL AND ASSUMPTIONS

System model and assumptions used throughout the study are detailed in the following sections.

2.1 Resource Grid, Resource Blocks and Flexible Numerology

5G NR is an essential technology for next-generation cellular communication with its advanced features. This technology, which handles various communication service classes such as mMTC, URLLC, eMBB, requires considerable flexibility in wireless systems. An example of this flexibility is the necessity of obtaining smaller symbol times with large subcarrier spacing in URLLC services. One of the most critical systems that will create solutions to various difficulties of communication towards 6G is the flexible numerology defined in 3GPP Release 15.

5G NR structure offers us an ecosystem where flexible numerology structure can be used in the time frequency axis. This numerology set consists of number of subcarriers, subcarrier spacing, slot duration and CP duration. The concept called numerology generally represents the SCS in the frequency domain and also includes parameters such as cyclic prefix and symbol length. New Radio technology supports 15, 30, 60, 120, 240, and 480 kHz SCS. SCS values of 120 and above support the higher frequency bands in the spectrum.

In order to model resource management on the axis of time and frequency, the resource grid is handled in two dimensions, and the system model and developed solutions are created on this grid. Three different numerologies are used on this grid. The SCS values of these numerologies are 15, 30 and 60 kHz. Each piece in the resource grid is expressed as a resource element. By combining resource elements, physical resource blocks representing various numerologies are formed.

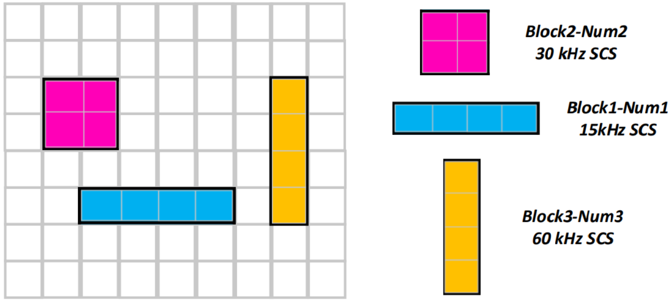

Figure 2.1 Resource allocation with three types of blocks with mixed numerology. Each squares in the resource grid represent basic units i.

We refer to each resource element in the resource grid as i. The available time-frequency resource is divided into resource elements (REs) with a bandwidth of Δ_f^{min} Hz and a time duration of Δ_t^{min} seconds. 5G NR uses a flexible physical layer architecture supporting multiple numerologies where each numerology is defined by subcarrier spacing and cyclic prefix overhead. The physical layer grid consist of N_t successive resource elements in time domain and N_f resource elements in frequency domain. We call each row of resource elements a band. For non-partitioned bandwidth minimization, the set of elements in the n^{th} band is denoted by I_n ($n \in [1, N_f]$). I is the set of all resource elements in the resource grid such that $|I| = N_t \times \mathrm{N}_f$. I^k ($k \in [1, N_t]$) is the set of elements in the k^{th} columns.

Resource Blocks (RBs) is defined as a collection of continous resource elements in time and frequency domain which is referred as $b = 1,2,...,B$. Then, $a_{b,i}$ is a indicator whether block b includes element i. We assume that each resource block consist of four resource elements. In the Fig. 2.1 of size $N_t \times \mathrm{N}_f$, as an element of set B, a 15 kHz SCS block representing 4×1 *Numerology 1.* for $b = 1$, a 30 kHz SCS representing 2×2 *Numerology 2* for $b = 2$, and $b = 3$ for a 60 kHz SCS resource block representing *Numerology 3* in size 1×4 is used. It is possible to obtain (N_t-1)$\times$(N$_f$-1) configurations for Block 2, (N_t-3)$\times$N$_f$ configurations for Block 1, and $N_t \times$(N$_f$-3) configurations for Block 3. As shown in Fig. 2.1, the dimension value of resource blocks changes according to the numerology used.

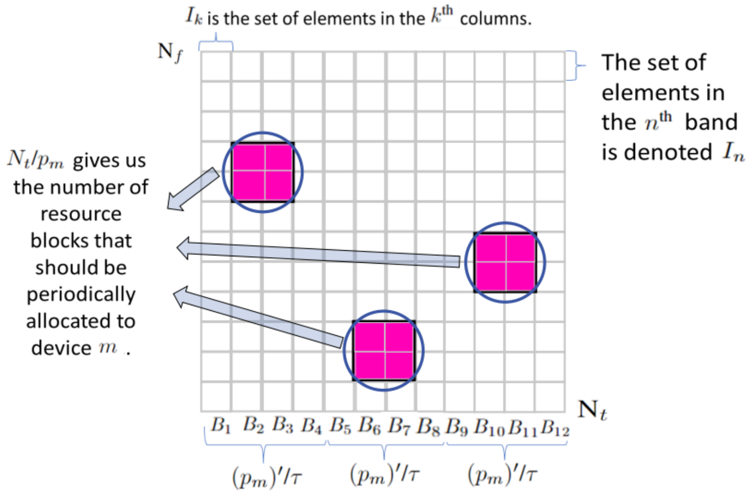

Figure 2.2 Figüre illustrated a feasible periodic resource allocation for device m whose packet generation $(p_m)'$ is equal to 4 then this device should be allocated a resource block within these sets: [B_1,B_4],[B_5,B_8],[B_9,B_{12}]

2.2 QoS Characterization: Periodicity

In uplink transmission scenarios, periodic transmission based on the repetition of resource allocation can be realized. This allows MTC devices to generate data packets periodically and also allows grant-free transmission. In our optimization problem, periodicity comes to the fore as a QoS characteristic. We consider a 5G and beyond cellular system where a base station supports a set of MTC services $\mathcal{M}$ each having L_m number of time-triggered MTC devices with packet generation period p_m. Then, p_m/τ gives the packet generation period in terms of the number of resource elements. N_t/p_m gives us the number of resource blocks that should be periodically allocated to device m then a device m should be given one resource block in each successive p_m resource columns corresponding to the sets $p_m(j\text{-}1)+1$ to $p_m j$. Also, we assume that N_t/p_m is an integer. For non-partitioned bandwidth minimization B_k ($k\in[1,\ N_t]$) refers to the resource blocks whose leftmost element is in the I_k column. For example, suppose $p_m = 4$ for $m = 1$, then this device m should be given one resource block in union of B_1, B_2, B_3, B_4 then another resource block in B_5, B_6, B_7, B_8 and other recource block in B_9, B_{10}, B_{11}, B_{12} for $N_t = 12$. Fig. 2.2 illustrated a feasible periodic resource allocation for device $m = 1$. As can be seen, this example explains the periodic scenario.

$(p_m)'$ represents the period in seconds. Then, p_m equals $(p_m)'/\tau$ gives the period in resource block length and we assume that this value is an integer. $(p_m)'$ values are at least milliseconds in any application. The width of the elements in the grid is much less. Therefore, this assumption is practical.

3. OPTIMIZATION PROBLEMS

In this chapter, we investigate two alternative realizations of the Bandwidth Minimization Problem considering the complexity of the optimization problems and corresponding solution frameworks. The first optimization problem is called Non-Partitioned Bandwidth Minimization in which a particular band can incorporate resource blocks of different numerologies. The second optimization problem is called Partitioned Bandwidth Minimization in which different numerologies are used in different parts of the available bandwidth hence creating Bandwidth Parts at the end of resource allocation. In the following, we propose mathematical formulations for both problems and investigate their complexities along with a comparative discussion.

3.1 Non-Partitioned Bandwidth Minimization

Non-Partitioned Bandwidth Minimization Problem, denoted by $\mathcal{NP}-\mathcal{BMP}$, is mathematically formulated as follows.

NP-BMP:

$$\textbf{min} \quad \sum_{n=1}^{N_f} z_n \tag{3.1a}$$

$$\textbf{s.t.} \quad \sum_{b \in \mathcal{B}_m^j} x_{b,m} = 1, \forall m, \forall j \in [1, N_t/p_m] \tag{3.1b}$$

$$\sum_{m \in \mathcal{M}} \sum_{b \in \mathcal{B}} a_{b,i} x_{b,m} \leq 1, \forall i \tag{3.1c}$$

$$\sum_{m \in \mathcal{M}} x_{b,m} \leq 1, \forall b \tag{3.1d}$$

$$[\sum_{i \in \mathcal{I}_n} \sum_{m \in \mathcal{M}} \sum_{b \in \mathcal{B}} a_{b,i} x_{b,m}]/N_t \leq z_n, \forall n \tag{3.1e}$$

$$\textbf{vars} \quad z_n \in \{0,1\}, \; x_{b,m} \in \{0,1\}. \tag{3.1f}$$

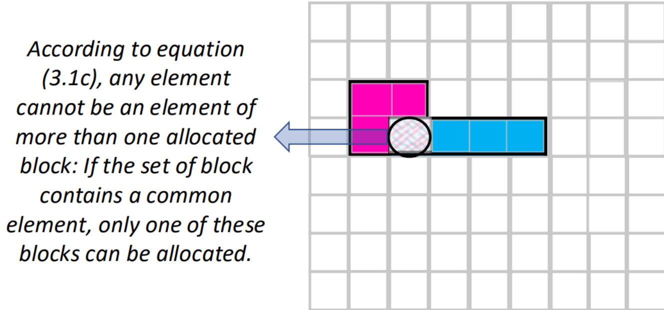

Figure 3.1 Overlapping part of Block 1 and Block 2 is shown in the shaded part. So, in here $a_{1,i}$ and $a_{2,i}$ is equal to 1. Eq.(3.1c) prevents this situation.

The objective of the $\mathcal{NP} - \mathcal{BMP}$ is to minimize the number of unit element bands as given in Eq. (3.1a). The variables of the optimization problem are z_n, binary variable indicating the allocation of each band $n \in \mathcal{N}$; and $x_{b,m}$, binary variable indicating the allocation of resource block b for device m, as given in Eq. (3.1f). Eq. (3.1b) represents the periodic data generation requirement of the MTC devices. Eq. (3.1c) states that each resource element i can be included in at most one resource block allocated to a certain MTC device. The element-wise orthogonality of resource allocation is illustrated in Fig. 3.1. Eq. (3.1d) states that each resource block can be allocated to at most one MTC device. Finally, Eq. (3.1e) specifies a band n is considered to be used if at least one resource element on that band is included in a resource block allocated to MTC devices. Note that this constraint is required to build the forced dependence between variables z_n and $x_{b,m}$. The left side of the equation expresses how many elements are used in that band, and by dividing it by the N_t value (number of elements in the band), we force the z_n value to be 1 if the obtained value is not zero. For example, if the value obtained on the left side of the equation is 0.2, the inequality forces the value of z_n to be 1 indicating the use of the associated band.

3.2 Partitioned Bandwidth Minimization

Partitioned Bandwidth Minimization Problem, denoted by $\mathcal{P} - \mathcal{BMP}$, is mathematically formulated as follows:

P-BMP:

$$\begin{aligned}
\textbf{min} \quad & \sum_{k \in \mathcal{K}} \sum_{n \in N_k} z_n && \text{(3.2a)} \\
\textbf{s.t.} \quad & \sum_{b \in \mathcal{B}^j_{k(m)}} x_{b,m} = 1, \forall m, \forall j \in [1, N_t/p_m] && \text{(3.2b)} \\
& \sum_{m \in \mathcal{M}} x_{b,m} \leq 1, \forall b && \text{(3.2c)} \\
& [\sum_{m \in \mathcal{M}} \sum_{b \in B} a_{b,n} x_{b,m}]/N_t \leq z_n, \forall n && \text{(3.2d)} \\
\textbf{vars} \quad & z_n \in \{0,1\},\ x_{b,m} \in \{0,1\}. && \text{(3.2e)}
\end{aligned}$$

The objective of the $\mathcal{P}-\mathcal{BMP}$ is to minimize the sum width of the bandwidth parts used with each numerology as given in Eq. (3.1a). The variables of the optimization problem are z_n, binary variable indicating the allocation of each band $n \in \mathcal{N}$; and $x_{b,m}$, binary variable indicating the allocation of resource block b for device m, as given in Eq. (3.2e). Eq. (3.2b) represents the periodic data generation requirement of the MTC devices. Eq. (3.2c) states that each resource block can be allocated to at most one MTC device. Note that element-wise orthogonality constraint used in $\mathcal{NP}-\mathcal{BMP}$ is discarded. Finally, Eq. (3.2d) specifies a band n is considered to be used if at least one MTC device is assigned a resource block on that band. This constraint is required to build the forced dependence between variables z_n and $x_{b,m}$.

3.3 Computational Complexity

Single numerology variant of $\mathcal{P}-\mathcal{BMP}$; i.e., $|\mathcal{K}| = 1$, is proven to be *NP-hard* [29]. Furthermore, since $\mathcal{NP}-\mathcal{BMP}$ and $\mathcal{P}-\mathcal{BMP}$ are equivalent for single numerology scenario, both optimization problems are *NP-hard*. Hence providing an optimal resource allocation requires exponential-time algorithms which would be intractable considering the massive connectivity envisioned for next-generation cellular systems. Massive MTC requires computationally efficient resource allocation schemes while fully grant-free schemes are the ultimate goal. Periodicity of the time-triggered traffic allows designing semi-persistent schemes eliminating both the need for dynamic allocation of the resources on a transmission time interval basis and the excessive control signaling burden on the access point.

3.4 Complexity Comparison of the Problem Formulations

The set of all possible RBs on the time-frequency resource grid is denoted by $\mathcal{B}$. In any feasible solution of $\mathcal{P}-\mathcal{BMP}$, for each numerology $k \in \mathcal{K}$, a bandwidth part is formed with bandwidth $N_f^k \Delta_f^{min}$ such that $N_f = \sum_{k\in\mathcal{K}} N_f^k$. The set of possible resource blocks in the bandwidth part with numerology k is denoted by $\mathcal{B}_k$. Then, $|\mathcal{B}| \approx |\mathcal{K}| \sum_{k\in\mathcal{K}} \mathcal{B}_k$. Hence, the complexity of $\mathcal{NP}-\mathcal{BMP}$ is greater than $\mathcal{P}-\mathcal{BMP}$ from a combinatorial point of view considering $\mathcal{NP}-\mathcal{BMP}$ has $|\mathcal{K}|$ times more variables. Note that both are integer programming (IP) problems.

4. SOLUTION FRAMEWORK

In this chapter, we present the solution frameworks proposed for both $\mathcal{P}-\mathcal{BMP}$ and $\mathcal{NP}-\mathcal{BMP}$ optimization problems presented in Chapter 3.

Since $\mathcal{P}-\mathcal{BMP}$ has lower complexity suggesting more practicality for algorithm design and adapts to the envisioned physical layer grid in New Radio, we first investigate and algorithm for $\mathcal{P}-\mathcal{BMP}$ and then introduce a variant of the former one for $\mathcal{NP}-\mathcal{BMP}$.

4.1 Maximum Utility Resource Allocation Algorithm

Maximum Utility Resource Allocation Algorithm ($\mathcal{MU}-\mathcal{RAA}$) is proposed for $\mathcal{P}-\mathcal{BMP}$. The algorithm consists of two phases. In first phase, the optimal numerology for the devices in each MTC service class is determined and thus the available bandwidth is partitioned into *bandwidth part*s over which the communication is maintained with the same numerology as defined in Release-15 of 3GPP. This phase both will decrease the complexity of the solution as suggested by the problem definition of $\mathcal{P}-\mathcal{BMP}$ and will allow low-power battery-operated MTC devices save power since they will not need to monitor the entire bandwidth as in LTE. In second phase, each bandwidth part is allocated with the associated MTC services using a semi-persistent resource allocation scheme aiming at maximum utilization of each band while meeting the heterogeneous periodicity requirement of the MTC services.

4.1.1 Phase I numerology selection

Optimal numerology for an MTC service can be determined by considering how suitable a particular numerology is for maximum utilization of a band since the objective of $\mathcal{P}-\mathcal{BMP}$ is to minimize the total bandwidth. The numerology selection section contains the phase 1 part. Let u_m^k denote the *utilization* of a band by an MTC service m with packet generation period p_m (in REs) if assigned a particular numerology $k \in \mathcal{K}$. $u_m^k = \beta_k/p_m$ for a single device from MTC service m when allocated one resource block of numerology k with β_k resource elements in time. Note that numerologies are sorted in increasing order of β_k. Then, $L_m^k = \lfloor \frac{1}{u_m^k} \rfloor$ is the maximum number of devices that can be allocated from MTC service m using numerology k on a band. Selecting a numerology with an RB wider in the time domain; i.e., greater β_k may decrease the number of users to be allocated within the same band due to the periodicity of the resource allocation. On the other hand, selecting a numerology with ann RB wider in the frequency domain may decrease the overall utilization of the allocated band depending on the number of devices to be allocated. For each MTC service m, numerology should be selected to yield use of minimum bandwidth. Let L_m be the number of devices to be allocated for an MTC service m. Then, using numerology k, the number of bands required for the allocation of all devices in MTC service m is proportional to

$$N_m^k = \lceil \frac{L_m}{L_m^k} \rceil \frac{1}{\beta_k} \tag{4.1}$$

Consequently, considering the allocation of a single MTC service m on a band, the optimal numerology selection can be determined by

$$k_m^* = \text{argmin}_{k \in \mathcal{K}_m} N_m^k = \text{argmin}_{k \in \mathcal{K}_m} \lceil \frac{L_m}{L_m^k} \rceil \frac{1}{\beta_k} \tag{4.2}$$

where $\mathcal{K}_m$ is the set of feasible set of numerologies for MTC service m defined by the channel and traffic requirements.

Note that k_m^* is the numerology that will yield minimum number of unallocated elements on a band for a certain MTC service m and thus result in minimum bandwidth use for the given number of devices in MTC service m. In first phase of the algorithm, the optimal numerology for each MTC service m will be determined using Eq. 4.2.

4.1.2 Phase II maximum utility allocation

The optimal numerology selection in Phase I allows maximum utilization of a certain band if there are large enough number of unallocated devices from a certain MTC service m. For example, if there are at least $L_m^{k^*} = \lfloor \frac{1}{u_m^{k^*}} \rfloor$ devices from MTC service m, then at least one band can be allocated with maximum utilization $E_m^{k^*} = L_m^{k^*} u_m^{k^*}$ where E_m^k as the total utilization of a band by MTC service m using numerology k. Hence, if the number of devices $L_m \geq L_m^{k^*}$, then $N_m^* = \lfloor \frac{L_m}{L_m^{k^*}} \rfloor$ bands can be allocated with maximum utility using only devices from MTC service m. These bands are defined to be *maximally allocated bands* since no further devices from other MTC services can be allocated. However, if L_m is not an integer multiple of $L_m^{k^*}$, then upon allocation of N_m^* maximally allocated bands, there remains $L_m^{'=L_m - N_m^* L_m^{k^*}}$ unallocated devices from MTC service m. While at most one fully empty band is sufficient for allocating these remaining unallocated devices, this band may be utilized further via allocation of devices from other MTC services since it will not be maximally allocated by the remaining devices from MTC service m. This type of bands are defined to be as *residual bands* in the following discussion. Considering M different MTC services for allocation, at most M residual bands exist for resource allocation. In the second phase, $\mathcal{MU} - \mathcal{RAA}$ incorporates an additional mechanism to allocate devices from different services on residual bands to maximize utilization of the entire bandwidth.

$\mathcal{MU} - \mathcal{RAA}$ is given by Algorithm 1 and described as follows. The algorithm performs Numerology Selection (Lines $2-4$) and Maximum Utility Allocation Allocation (Lines 5-11) phases sequentially for each MTC service (Line 1). For MTC service m, first, the set of feasible numerologies $\mathcal{K}_m$ is determined based on channel and application requirements (Line 2). The optimal numerology among the feasible ones k_m^* is then calculated considering Eq. 4.2 (Line 3). The number of maximally

Algorithm 1 Maximum Utility Resource Allocation Algorithm

Input: a set of MTC services $\mathcal{M}$, a set of numerologies $\mathcal{K}$

Output: allocation of MTC services to bands

1: **for** $m = 1 : M$ **do**

Phase-I: Numerology Selection

2: determine feasible numerology set $\mathcal{K}_m$

3: calculate optimal numerology $k^*_m = \text{argmin}_{k \in \mathcal{K}_m} \lceil \frac{L_m}{L^k_m} \rceil \frac{1}{\beta_k}$

4: calculate the number of maximally allocated bands $N^*_m = \lfloor \frac{L_m}{L^{k^*_m}_m} \rfloor$

Phase-II: Maximum Utility Allocation

5: **for** $n = 1 : N^*_m$ **do**

6: allocate $L^{k^*_m}_m$ devices from MTC service m to band n periodically with p_m

7: **end for**

8: allocate unallocated devices from MTC service m to the residual band

9: calculate residual utilization for band n

10: utilize residual band with devices from MTC services in the order

11: update the number of devices L_m for MTC services

12: **end for**

allocated bands based on the optimal numerology is determined consequently (Line 4). Following the numerology selection phase, $L^{k^*_m}_m$ devices are allocated to each and every maximally allocated band for MTC service m (Lines $5-7$). Note that these maximally allocated bands constitute a bandwidth part allocated by devices of a single MTC service using common numerology. As we will discuss in the next section, the empty resource fragments in these bandwidth parts can be further utilized with resource blocks of other numerologies. Then, the unallocated devices from MTC service m are allocated to the residual band contiguous to the maximally allocated bands (Line 8). Since this band is not fully utilized by the devices in MTC service m, first the residual utilization is calculated (Line 9). Then, this residual band is further allocated with devices from MTC services in the order until the band is maximally allocated without violating the periodicity of traffic (Line 10). For this utilization, QoS provisioning technique in [29] is used to determine the residual utilization of the band and the number of devices that can be allocated from a particular MTC

Algorithm 2 Resource Fragment Utilization Algorithm

Input: a set of MTC services $\mathcal{M}$, a set of numerologies $\mathcal{K}$

Output: allocation of MTC services $\mathcal{M}$ to bands

for $m = 1 : M$ **do**

  perform Phase-I of $\mathcal{MU} - \mathcal{RAA}$ for optimal numerology selection

  perform Lines 5-7 of Phase-II of $\mathcal{MU} - \mathcal{RAA}$ for the allocation of maximally allocated bands to create a bandwidth part BWP_m with N_m^* bands

  determine the size of periodic unallocated resource fragment in BWP_m

  determine the numerology $k_m^{'}$ to be used for utilization of the unallocated resource fragment

  allocate unallocated devices from MTC service m to the unallocated resource fragment

  perform Lines 8-11 of Phase-II of $\mathcal{MU} - \mathcal{RAA}$ for residual band allocation

end for

service. Finally, the number of unallocated devices for each remaining MTC service is updated (Line 11). Then, the resource allocation of the next MTC service begins (Line 1) until all MTC services are completed and the algorithm terminates (Line 12).

4.2 Resource Fragment Utilization for $\mathcal{MU} - \mathcal{RAA}$

While $\mathcal{MU} - \mathcal{RAA}$ creates maximally utilized bandwidth parts incorporating single common numerology for all allocated devices, this creates a suboptimality in terms of spectrum efficiency since the empty resource fragments can be further utilized with allocation resource blocks of other numerologies which would otherwise be infeasible using the same numerology. Algorithm II gives a variant of $\mathcal{MU} - \mathcal{RAA}$, called Resource Fragment Utilization ($\mathcal{RFU}$) that can provide an effective resource allocation solution for $\mathcal{NP} - \mathcal{BMP}$ in which use of multiple numerologies in the same band is allowed despite the computational complexity introduced. The details in this section are summarized as follows.

Resource Fragment Utilization algorithm performs identically to $\mathcal{MU} - \mathcal{RAA}$ except Lines $4-6$. In Lines $4-6$, the unallocated resource fragment within the bandwidth part formed for MTC service m is further utilized. First, the time-frequency size of the resource fragment is determined (Line 4). Then, the numerology $k_m^{'}$ used in this fragment is calculated (Line 5). Note that this numerology is necessarily a numerology with an RB narrower in time domain compared to the optimal numerology k_m^* initially selected for MTC service m; i.e., $\beta_{k_m^{'}}$¡$\beta_{k_m^*}$. This numerology is used to allocate other devices from MTC service m to the resource fragment (Line 6).

5. PERFORMANCE EVALUATION

This chapter illustrates the performance of the proposed resource allocation algorithms compared to previously proposed algorithms for periodic radio resource allocation.

Simulations are performed in MATLAB on a computer with 3.2GHz CPU and 16GB memory. For better illustration, the simulation results are averaged over 100 independent runs for each data point presented in the figures.

Table 5.1 Simulation Setup

Parameter	**Value**
# of MTC services	5
# of devices in each MTC services	[10:50]
packet generation periods, p_m, in REs	[5, 7, 10, 20, 40]
# of numerologies	3
resource element width	180 KHz
resource element duration	0.125 ms
system effective bandwidth	18 MHz

Table 5.1 lists the parameters used in the simulations. Further parameters about the numerologies are listed in Table 1.1. 5 MTC services are considered in the simulations unless otherwise stated. Each MTC service consists of a uniformly randomly picked number of MTC devices distributed in the $[10, 50]$ range. Packet generation periods of MTC services are $p_m \in \{5, 7, 10, 20, 40\}$ REs, $\forall m \in \{1, ..., 5\}$, respectively. The bandwidth reserved for MTC services is assumed to be 18 MHz and thus $N_f = 100$ bands each with a RE width of 180 KHz are considered for

resource allocation. 3 numerologies are used with sizes of 4×1, 2×2, and 1×4 REs.

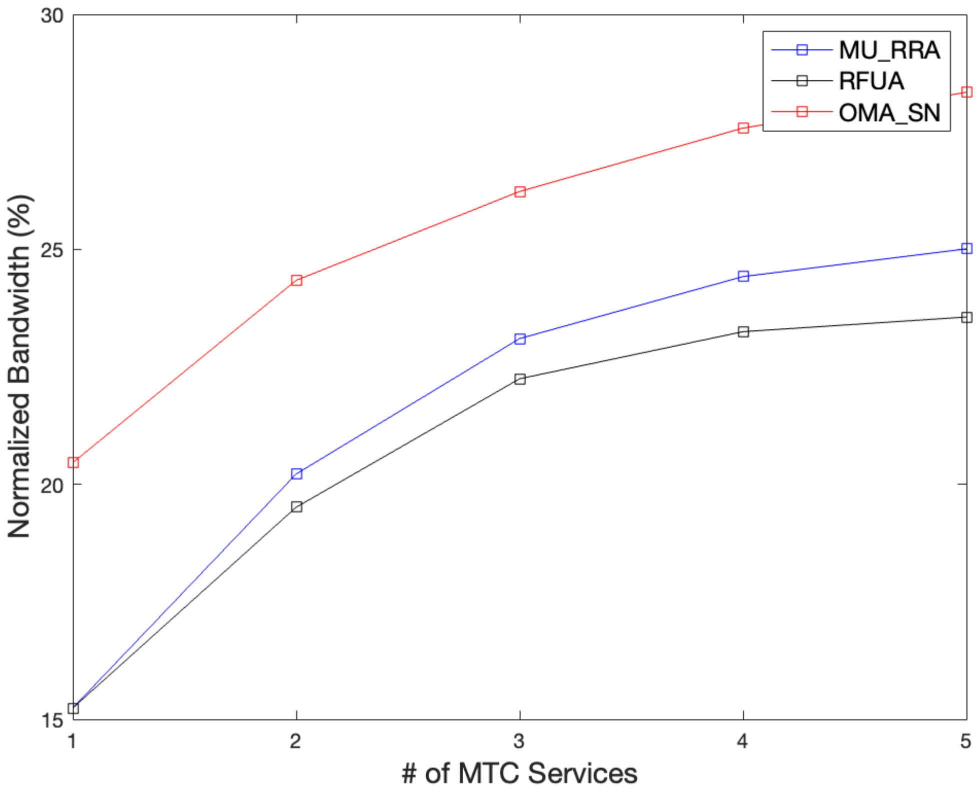

Figure 5.1 Spectral efficiency performance of MU_RAA and RFUA algorithms for different number of MTC services.

In Fig. 5.1, the performance MU_RAA and RFU algorithms proposed for $\mathcal{P}-\mathcal{BMP}$ and $\mathcal{NP}-\mathcal{BMP}$ optimization problems respectively, are illustrated in comparison to OMA_SN algorithm [30] proposed for periodic MTC traffic for a single numerology physical layer architecture. Performance comparison is shown for different number of MTC services considering MTC service parameters listed in Table 5.1. Normalized bandwidth is used as the performance metric which is the ratio of the bandwidth required by the investigated solution to the bandwidth needed for AGTI-based algorithms used for LTE systems. OMA_SN algorithm schedules different MTC services on a band considering a periodicity-based priority order without violating the QoS requirements of each MTC service with the aim of minimizing the overall bandwidth. It uses a common numerology for all MTC services without considering the flexible PHY layer architecture and multiple numerologies defined by New Radio. There-

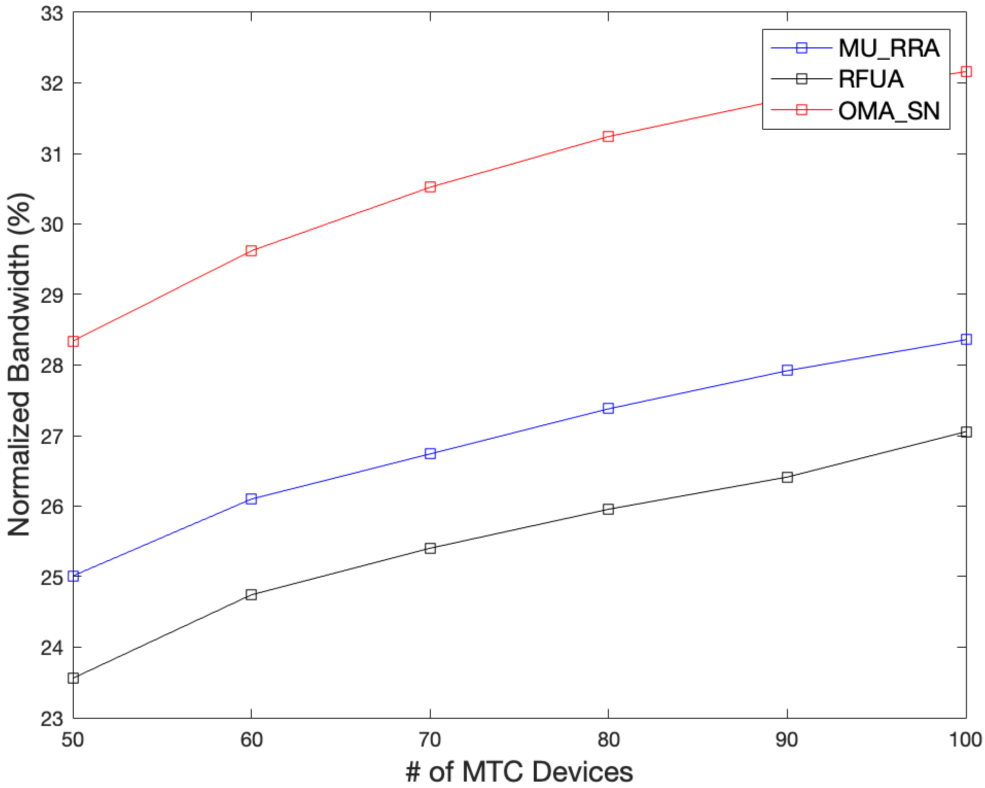

Figure 5.2 Spectral efficiency performance of MU_RAA and RFUA algorithms for different number of MTC devices per each MTC service.

fore, the performance improvement of the proposed MU_RRA and RFU algorithms over OMA_SN illustrates how efficient the former ones are in terms of getting use of multiple numerologies. As the figure suggests both MU_RAA and RFU algorithms improve the spectral efficiency considerably exploiting multiple numerologies compared to OMA_SN algorithm. They decrease the required bandwidth by around 20% on the average for different number of MTC services. Both algorithms perform robust for increasing heterogeneity in the network since the performance improvements are close for 1 to 5 MTC services with different with a slight decrease as the number of services increases. Overall efficiency of the algorithms shows that the numerology selection phase of the algorithms work efficiently while selecting optimal numerology for each MTC service. MU_RAA and RFU algorithms perform identical for 1 MTC service scenario while RFU algorithm outperforms the former one by utilizing the empty resource fragments within the bandwidth parts created by MU_RRA algorithm.

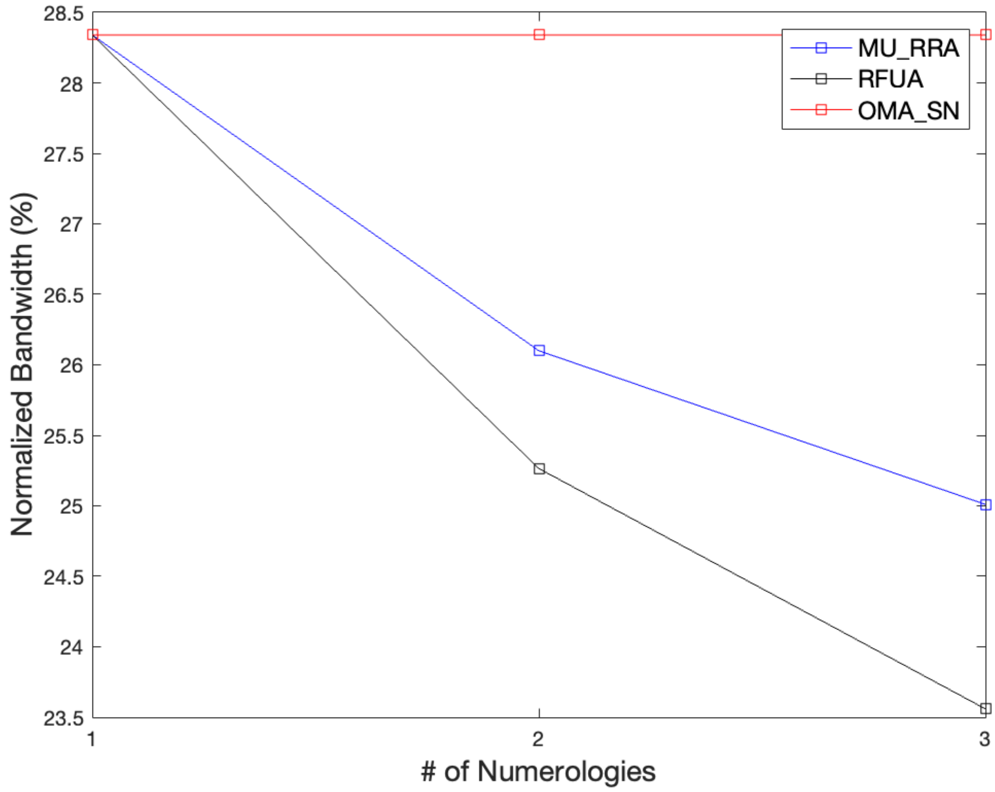

Figure 5.3 Spectral efficiency performance of MU_RRA and RFUA algorithms for different number of PHY layer numerologies.

Fig. 5.2 illustrates the performance of MU_RAA and RFU algorithms in comparison to OMA_SN algorithm for increasing number of devices in MTC services. All 5 MTC services listed in Table 5.1 are considered. Similar to Fig. 5.2, MU_RAA and RFU algorithms outperform OMA_SN algorithm by a performance improvement of around 10% on the average. Performance of both algorithms slightly increases compared to OMA_SN as the number of MTC devices in each service increases. Moreover, RFU algorithm improves the spectral efficiency by around 5% compared to MU_RAA and performs robust for increasing number of devices.

Fig. 5.3 illustrates the performance of MU_RAA and RFU algorithms in comparison to OMA_SN algorithm for different number of numerologies for 5 MTC services with 10 to 50 devices. As the figure suggests, the performance of OMA_SN is stable since it uses single numerology for all MTC services. Similarly, MU_RAA and RFU algorithms perform identically to OMA_SN for 1 numerology since they all utilize the resource blocks on each band until no further devices can be allocated. However, for 2 and 3 numerologies specified in Chap. 2, MU_RAA and RFU algorithms perform significantly better than OMA_SN by optimally selecting numerology for different MTC services. As the number of numerologies increases from 2 to 3, spectral efficiency performance of the algorithms increases compared to OMA_SN due to the availability of more numerology options for each service. The figure clearly illustrates that using multiple numerologies is spectrally efficient when properly exploited in resource allocation. Further improvements can be obtained for more numerologies as suggested by New Radio.

6. CONCLUSION AND FUTURE WORK

Machine type communications is one of the major domains addressed by 5G and beyond networks. It is of paramount importance to support MTC applications towards 6G systems. However, massive connectivity envisioned for next-generation systems introduces a major challenge in radio resource allocation also considering the spectrum scarcity problem. On the other hand, the flexible PHY layer architecture introduced by New Radio brings opportunities to overcome this challenge.

This thesis investigates minimum bandwidth resource allocation problem for periodic MTC traffic considering flexible PHY layer architecture, specifically multiple numerologies. First, we discuss the flexible physical layer architecture as introduced in 3GPP Releases 15 and 16. We then introduce and mathematically formulate the Non-Partitioned Bandwidth Minimization Problem ($\mathcal{NP} - \mathcal{BMP}$) and Partitioned Bandwidth Minimization Problem ($\mathcal{P} - \mathcal{BMP}$) as two alternative realizations of the minimum bandwidth resource allocation problem. We illustrate the NP-hardness of both problems and discuss the complexity comparison between the two. We then propose the Maximum Utility Resource Allocation Algorithm (MU_RAA) and Resource Fragment Utilization Algorithm (RFUA) for $\mathcal{P} - \mathcal{BMP}$ and $\mathcal{NP} - \mathcal{BMP}$ problems, respectively. Both algorithms incorporate an optimal numerology selection and maximum utility resource allocation phases along with different mechanisms to utilize the unallocated resource elements after initial allocation. Through simulations, the performance of both algorithms is presented for various scenarios illustrating their spectral efficiency. They both outperform previously proposed single numerology-based resource allocation algorithms.

As part of future work, QoS characterization of the MTC applications will be reconsidered incorporating jitter requirements and packet error loss tolerance. Optimization problems and the proposed solution framework will be revisited for the extended QoS characterization. Moreover, other New Radio features beyond multiple numerologies will be utilized to improve the spectral efficiency of the algorithms such as mini-slot and sub-PRB allocation.

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CURRICULUM VITAE

Personal Information
Name and Surname : Yağız Can Çağan

Academic Background
Bachelor's Degree Education : Kadir Has University 03.08.2015-10.07.2020
Post Graduate Education : Kadir Has University 17.09.2020-02.09.2022
Foreign Languages : English(C1)

Work Experience
ETA Mühendislik 25.06.2019 – 01.08.2019
VIP Grup Asansör 01.11.2019 – 01.02.2020
Kadir Has University – Tübitak Project Assistant 01.10.2020 – 30.08.2022