UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

Escola Tècnica Superior d'Enginyeria
de Telecomunicació de Barcelona

MULTI-TENANT ADMISSION CONTROL FOR FUTURE NETWORKS

A Master's Thesis

Submitted to the Faculty of the

Escola Tècnica d'Enginyeria de Telecomunicació de Barcelona

Universitat Politècnica de Catalunya

by

Alexandro Vera Maraví

In partial fulfillment

of the requirements for the degree of

MASTER IN TELECOMMUNICATIONS ENGINEERING

Advisor: Jordi Pérez-Romero

Barcelona, January 2020

Title of the thesis: Multi-tenant Admission Control for future networks

Author: Alexandro Vera Maraví

Advisor: Jordi Pérez-Romero

Abstract

The global telecommunications landscape is going to shift considerably due to the impact of the new generation of future networks. It is estimated that by 2025, one-third of the global population will use 5G. Accordingly, all industry players are searching to develop new business cases.

One of the main capabilities of 5G to answer these new requirements is Network Slicing since it allows splitting a common infrastructure into several virtual networks, enabling Multi-tenancy. In this case, the admission control function plays a vital role in ensuring the correct operation of these virtual networks by providing the required QoS to the services by allocating radio resources to them.

Consequently, the purpose of this thesis is to study a new method to implement the admission control function, which allows optimizing the use of radio resources, to increase the available capacity of tenants, and offer flexibility under different traffic loads.

Several simulations are performed to evaluate the algorithm within a multi-tenant, multi-cell environment using MATLAB, where the simplicity and flexibility of our proposal are assessed in each cell and the whole scenario. We obtain a 127% improvement in the bit rate when compared with a baseline scheme, and a gain of 17% when compared to a reference scheme that allows using extra capacity left by other tenants.

Keywords: Multi-tenancy; Future networks; 5G; Network slicing; Slices; Admission Control; Tokens; QoS.

Dedication: To my family, parents, and especially my father.

Acknowledgments

I want to express my sincere gratitude to my supervisor, Prof. Jordi Perez-Romero, for his full support, guidance, and feedback. Without his mentoring, it would not have been possible for mi to complete this work.

I especially want to thank my girlfriend, Carmen, who gave me the strength to move on.

Additionally, I would like to thanks my classmates and friends, Andy, Mohammed, Efraín, and José, who supported and encouraged me all the time, even in the distance.

Last but not least, I could not have succeeded without the support of my lovely family.

Revision history and approval record

Revision	Date	Purpose
0	10/07/2019	Document creation
1	21/01/2020	Document revision

Written by:		Reviewed and approved by:	
Date	10/07/2019	Date	28/01/2020
Name	Alexandro Vera Maraví	Name	Jordi Pérez-Romero
Position	Project Author	Position	Project Supervisor

Table of contents

List of Figures

List of Tables

1. Introduction

The next generation of mobile communications has started its commercial deployment and opens the arrival of the long enunciated future networks. It is estimated that, by the year 2025, the number of customers subscribed to 5G networks will reach around one-third of the world's population. This is an example of the importance of technology and the impact that it is going to have on the industry [1].

Considering the changes to come, experts from industry, government, regulators, and research agreed to team up to deliver the 5G vision through multiple phases. Market partners like GSMA are working together with vertical industries like automotive, financial, or transport, to innovate and develop new business cases capable of taking advantage of 5G's full capabilities [1].

One of the tools expected to provide the efficiency and productivity needed in the new requirements associated with vertical industries is **Network Slicing**. Considered to be a leading capability in 5G networks since it offers customized network functionalities, Network Slicing captures our attention. It motivates its study, considering that we observe how it encourages business customers to become smart network operators. This upgrade derives into enhanced communications services.

The diversity of requirements from this new range of communication services may lead to an underperformance of the mobile network, considering the different needs from services, varying from massive broadband at ultrafast speed, to ultra-reliable communications with low latency and small capacity. Such a contrast in the network specifications drives to sub-optimal network usage. In [2], Network Slicing is proposed as the solution to this problem. Instead of building several physical networks to fit with the requirements of each service, the solution consists of configuring different logical systems, i.e., **network slices**, over shared physical infrastructure.

Therefore, by definition, Network Slicing is a technology that enables operators to create customized networks to provide optimized solutions for different market scenarios. As a consequence, tailored requirements are attainable, which translates into customizable network capabilities such as data speed, quality, latency, reliability, among others.

With Network Slicing, **mobile network operators** (MNO) can rent separate slices of network resources. The owner of the network can lease these slices to, e.g., different operators, known as tenants, allowing them to offer their services to end customers over an independent virtual network. In that sense, Network slicing emerges as one key enabler for Multi-tenancy services in 5G. By definition, **Multi-tenancy** is an agreement between operators where infrastructure is shared, including radio resources. There must be an infrastructure provider and participating MNOs or tenants, which leases a shared part from the network, to offer their services to end-users over a specific region that the infrastructure covers.

Radio Resource Management (RRM) techniques constitute a relevant driven force to develop Network Slicing at the **Radio Access Network** (RAN), knowing that an essential requirement for 5G is an efficient use of network resources. Among RRM, a critical feature in mobile networks is **Admission Control** (AC), a mechanism used to optimize radio resource usage while maintaining a high **quality of service** (QoS) among **end-users** (UE). The Admission Control definition considers both characteristics, framing AC as the validation process performed before the establishment of a user´s connection, where the request of a new bearer can be admitted or rejected. It takes into consideration the number of available radio resources, QoS of in-progress sessions, and the QoS requirement of the new radio bearer connection's request.

The concept of Admission control is studied in [3], where it mentions that RANs should support as many users as possible to increase revenue. However, the radio resources of the network limit the number of users. As a consequence, Admission Control manages the trade-off between the number of UEs in the system and network performance and quality experienced.

The focus of the present document is on Admission Control, a key feature for 5G. We are going to study the current AC algorithm reviewed in [4], and from that basis, develop a new scheme capable of providing higher radio resource usage.

The research in [4] presents an Admission Control for Multi-tenant Radio Access Networks. It starts from the 5G scenario, where places the analysis of a critical feature such as Small Cells over multi-tenancy. It also addresses the concept of multiple tenants sharing common infrastructure, considering the additional financial benefits for the operators. Furthermore, it emphasizes the usage of Small Cells as a critical component on 5G's deployment in highly densified scenarios. Nevertheless, it introduces an important question about where to perform the split of radio resources to be adequately distributed among tenants: either at the packet scheduler or the Admission Control function. The authors choose Admission Control since it ensures the quality of service provided to each tenant.

1.1. Statement of purpose

Our research focus on future networks, the evolution from network sharing towards network slicing, and the role of the Admission Control functionality over a multi-tenant RAN scenario, intending to study how to improve radio resource usage in mobile networks.

We found extensive literature about RAN slicing, but some aspects remain unclear. For instance, tenants do have the possibility to ask for customized slices with some desired capacity at a specific moment; but what happens when their offered load exceeds the fixed agreed value? Some demand may be left unattended, even when the serving cell has unused resources available.

Let us put it this way: when MNOs leases services from an Infrastructure Provider, they are limited by the fixed amount of assigned capacity, specified in a **service-level agreement** (SLA). Therefore, whenever a high-demand event occurs, this scenario cannot be attended, even though the involved base station has available capacity. Due to this, we have unproductive network resources on the part of the infrastructure provider and traffic demand without being attended by the MNOs.

Given this existing problem, the following question arises: Is it possible to optimize Admission Control's performance, in a way that would make it likely to increase radio resource usage over a multi-tenant RAN scenario?

1.2. Motivation

With the previously stated research question, the goal of this thesis project is to understand how future networks manage radio resources. At the same time, to study a novel method for implementing the Admission Control that will allow increasing potentially available capacity for MNOs, by optimizing the usage ratios of cell's radio resources.

We will review related literature to address the definition of future networks, its architecture, and functionalities. Then, Network Sharing and Network Slicing definitions, and finally, we will present current studies about resource management in 5G. After establishing the theoretical background, we set the simulation's environment, explaining first the rationale behind our algorithm proposal, followed by its translation into the simulation environment, and we will evaluate how it behaves under different traffic conditions.

Our motivation lies in finding an enhanced process capable of increasing the usage ratio of physical resources, which may lead to a higher available capacity for tenants. We propose a novel algorithm capable of achieving this goal. Such an algorithm will be designed as a software function, using a proprietary programming language, MATLAB. Our primary tool will be a simulation program developed in [4], which contains an outdoor urban micro scenario, in which we are going to test the performance of our new admission function algorithm. We use this Simulator as a starting point, and from here, we adapt the program to our scenario, to incorporate our proposal. This development involves designing, develop, and test an optimized Admission Control algorithm that successfully achieves the previously mentioned aspects.

1.3. Contributions

If we achieve our goals, the meaningful contributions of this master thesis can be summarized as follows:

C1: Proposal of a novel design for an AC algorithm capable of increasing the current radio resource usage.

C2: Measurements of the behavior of multiple operators sharing the same RAN.

C3: Thanks to the performance graphs, we determine how to properly configure the parameters of the AC algorithm to increase gains in the use of resources.

C4: Obtaining effective capacity improvements concerning previous works. Higher usage of resources translates into a higher amount of services attended and, as a consequence, higher revenue for the infrastructure provider and the MNOs as well.

C5: Evaluation of existing methods and algorithms for QoS management in fixed networks such as the internet, and its application in a heterogeneous mobile scenario, such as future networks.

1.4. Thesis organization

The organization of this master thesis has been established as follows:

- **Chapter 2** gives a theoretical background needed for the concepts used and presents the current situation of RAN sharing scenarios.
- **Chapter 3** describes the algorithm solution, along with the principles of operation for the proposed algorithm.
- **Chapter 4** describes the simulator used and the implementation of our algorithm on it.
- **Chapter 5** presents the performance evaluation and results.
- **Chapter 6** finalizes with the conclusions and future paths for this topic.

2. State of the art

The goal for this theoretical chapter is to present an extensive review of recent research about future networks, multi-tenancy, and how Admission Control works within this complex scenario. What we pursue is to understand how radio resources work in future systems, and at the same time, to find a way to optimize their use. As a consequence, we could optimize the AC function, and those optimizations should translate into higher operating revenue for MNOs.

This chapter organizes as follows: first, recent literature about network slicing and future networks is presented. Next, the concept of multi-tenancy is discussed, followed by a review of radio resource management, focusing on the AC function and its behavior in a multi-tenant RAN scenario.

2.1. Future Networks

The **International Telecommunications Union** (ITU) is known as the international entity specifically designated by the United Nations to be responsible for all the subjects related to the Telecommunications and Information technologies field. It is composed of three main sectors: **Radiocommunications** (ITU-R), **Telecommunication Standardization** (ITU-T), and **Telecommunication Development** (ITU-D); with the ITU-T as a permanent organ in charge of telecommunications standards coordination.

ITU-T has the task of guaranteeing an efficient production of standards related to all telecommunication fields and delivering them on time. Additional assigned goals are the correct definition of tariffs and to provide recommendations for the accounting of international services.

The ITU-T releases every standard that it produces under the designation of “Recommendations.” Each of those recommendations is the result of research parties called **Study Groups** (SG), which in turn are organized by **Focus groups** (FG) [5].

Back in the year 2009, ITU-T designated SG13 to be in charge of the “**Focus group on Future Networks**” (FG-FN) to lead the discussion on to develop a shared understanding of what does the concept of Future Networks means. It also has to identify global visions based on current technologies and to assess the interactions between Future Networks and future services [6].

The definition of a Future Network (FN) presented by the FG-FN, is a network that can provide revolutionary services, capabilities, and facilities that are difficult to produce using existing network technologies. A future network is either:

- A new component network or an enhanced version of an existing one.
- A federation of new component networks or an alliance of new and existing component networks.

Four main objectives summarize the new necessities that are emerging in nowadays society. Those requirements are currently not being accomplished in a fulfilling extent by current networks:

- **Environment Awareness**: where future networks should be environmental-friendly;
- **Service Awareness:** where FNs should provide services that are customized with the appropriate functions to meet the needs of applications and users;
- **Data Awareness:** where FNs should have architecture optimized to handling massive amounts of data in a distributed environment; and
- **Social-economic Awareness:** where FNs should have social-economic incentives to reduce barriers to entry for all the participants in the telecommunications sector.

As described in [7], FNs should support the following design goals, to achieve previous objectives:

1. Service Diversity → support for diversified services with a variety of traffic characteristics.
2. Functional Flexibility → supports services from future user demands.
3. Virtualization of resources → a single resource used by multiple virtual resources.
4. Data Access → mechanisms for retrieving data faster.
5. Energy Consumption → improvement in power efficiency.
6. Service Universalization → accelerates the provision of convergent facilities.
7. Economic Incentives → provide a sustainable competitive environment.
8. Network Management → operate, maintain, and provision of services.
9. Mobility → offers high levels of reliability, availability, and QoS.
10. Optimization → optimizing the capacity of network equipment.
11. Identification → of a new identification structure for mobility and data access.
12. Reliability and Security → extremely high-reliability services.

At present, many of the previously listed goals have become valuable 5G's tools that are already available. That is why MNOs are making their way into monetizing those new opportunities. If they aim to account for these benefits, they will need to perform an economic enhancement on their networks. The deployment of innovative technologies and the development of new commercial agreements can make such improvements [8].

Future Networks can be a game-changer for organizations or Operators that aim to perform a transition to the All-IP world and migrate towards 5G. Two critical enablers for this transition are IP technologies and Virtualization. Both options allow optimized services, which give users the expected flexibility from the OTTs, but with a broader range of service [9].

2.1.1. IP technologies

All-IP technology is changing the way people experience mobile networks. Operators, OEMs, vendors, and partners have the opportunity to increase revenues by using these technologies presented in [10]:

- **RCS**: Rich Communication Services. For sharing media without downloading additional apps.
- **5G**: The next generation of mobile networks, after LTE.
- **VoWifi**: Stands for Voice over Wi-Fi. A parallel technology for VoLTE, which provides seamlessly calls using IP voice from WIFI towards mobile networks.
- **ViLTE**: Video over LTE, is an extension of VoLTE. Enables a conversational video service that works on IP packets and used through the mobile network.
- **VoLTE**: Delivers Digital Voice over an LTE Network. It is the evolution of voice since VoLTE allows us to operate voice as IP packets, unifying voice, and data networks.
- **HD Voice**: High definition voice, provides more natural sounds during calls, which brings full experience, higher clarity, and reduced background noise.
- **Roaming**: Keep devices connected to a network while traveling abroad, without losing connection.
- **Interconnection**: Physical link of an IP network with the IP equipment or resources from another operator´s network.

Voice and messaging have evolved, and now this new technology RCS is replacing SMS. It works to connect and interact with anyone naturally and effortlessly. It does not require to have a pre-installed over the top application, since it comes integrated with the network's system, just like SMS.

The way that RCS is present everywhere opens new business possibilities thanks to the crossover between messaging and shopping, creating new personalized conversations, without the need for any external applications [11].

RCS initiative has accomplished to reunite operators, vendors, and service providers to allow them to participate in the development of applications and their deployment.

One of the benefits of being part of this project is working with some of the leading software and equipment developers, as it is contributing to shaping the future of messaging communications.

At present, RCS has been launched by 76 MNOs worldwide, and it is forecasted to increase the number up to 125 Operators, by 2020 [12].

2.1.2. 5G Networks

5G is the **fifth generation of mobile network technology**, developed and presented by the **Third Generation Partnership Project** (3GPP) entity. Group collaborations form this organization from regional telecommunication associations, formerly known as “organizational partners.” The 3GPP is in charge of providing a stable environment for the production of technical reports and specifications that will define new 3GPP technologies. This standardization project conveys radio access, core networks, and service architectures [13].

The 3GPP introduced 5G technology on release 15, and it is known as “the 5G system” (**5GS**), which is composed of the User Equipment, the 5G access network (**NG-RAN**), and the core network (**5GC** or **5GCN**) [14].

3GPP has defined two deployment options: “Non-Stand Alone,” as a previous step towards a full 5G network, and “Stand Alone,” where are deployed both the NR and the 5GC, being connected for a complete 5GS. Similar to its predecessor, 5G-NR uses spectral modulation based on the **Orthogonal Frequency-Division Multiplexing coding scheme** (OFDM), only this time in both Downlink as well as Uplink.

An additional feature related to Spectrum is the extended use of a wide range of frequencies, working from shallow bands: 0.4 GHz, to very high: 100 GHz. The amount of bandwidth designated is up to 100 MHz for bands below 6 GHz and up to 400 MHz for bands above 6 GHz [13].

5G Key enablers and Features

One of the biggest reasons that have led to the evolution of mobile network technologies has been the increasing demand for data traffic. As a consequence, three main features define future networks:

- ***Ubiquitous connectivity***: End users should be able to connect to the network everywhere, all the time. The aim is to achieve enhanced and uninterrupted experiences.
- ***Very low latency***: To reduce transmission times for real-time applications, or life-critical systems.
- ***High-Speed, Gigabit connections***: to minimize download times and improve overall navigation experience.

This unique set of capabilities allows 5G to become a key enabler for technologies like the **Internet of Things** (IoT) and **Machine to Machine** (M2M) communications [15].

Fig. 2-1 illustrates the way 5G is going to affect our cities, by connecting everything with its three main service types: Enhanced Mobile Broadband (**eMBB**), Ultra-reliable Low-latency Communications (**URLLC**), and Massive Machine Type Communications (**mMTC**):

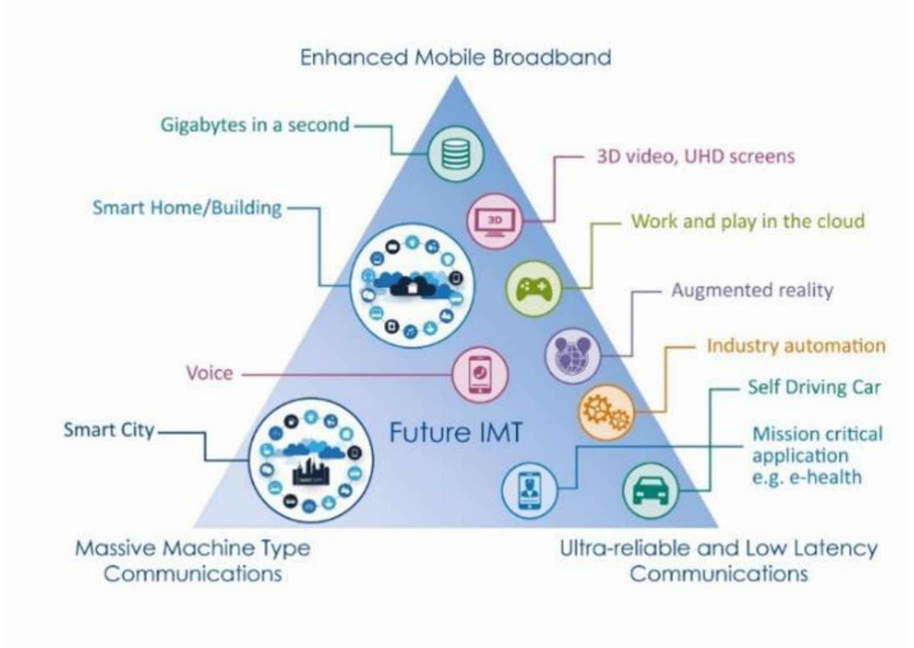

Enhanced Mobile Broadband
Gigabytes in a second
3D video, UHD screens
Smart Home/Building
Work and play in the cloud
Augmented reality
Industry automation
Voice
Self Driving Car
Smart City
Future IMT
Mission critical application e.g. e-health
Massive Machine Type Communications
Ultra-reliable and Low Latency Communications

Fig. 2-1: 5G service types and use cases. [13]

Those three service types are covering a wide range of necessities from users, but at the same time from smart cities and verticals.

With the exponential growth in the number of transmissions carried by the network, “always-on” communications become relevant. For this reason, 5G implements an “ultra-lean design” aiming to minimize these excessive signaling, enabling higher network energy performance and higher achievable data rates [16].

Spectrum landscape

About designated radio spectrum for 5G, large new portions of the spectrum have been released, with the target of fulfilling throughput requirements. ITU has specified several frequency ranges, split into two main groups: Frequency Range 1 (**FR1**) below 6GHz, including bands like 600 - 700 MHz, 3.1 - 4.2 GHz, and 4.4 - 4.9 GHz; and Frequency Range 2 (**FR2**) for frequencies above 6GHz, including the range bands of 26-28 GHz and 28-42 GHz [13].

The use of high-frequency ranges provides wide transmission bandwidths and extreme data rates but at the cost of radio-channel attenuations. Those losses are why 5G includes spectrum flexibility, which uses simultaneously low and high-frequency bands. This feature provides the benefit of using high-frequency bands with a large amount of spectrum to serve a large portion of users, while low frequencies attend users with coverage problems [16].

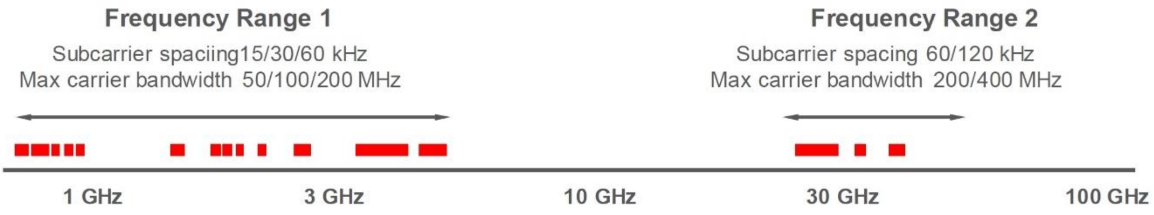

Frequency Range 1
Subcarrier spaciing15/30/60 kHz
Max carrier bandwidth 50/100/200 MHz
Frequency Range 2
Subcarrier spacing 60/120 kHz
Max carrier bandwidth 200/400 MHz
1 GHz
3 GHz
10 GHz
30 GHz
100 GHz

Fig. 2-2: 5G Spectrum. [16]

5G Architecture

The 5G system comprises the Radio Access Network, named NG-RAN, and the Core Network, as 5GC.

NG-RAN nodes can be **gNB** or **ng-eNB** nodes. gNB is the “5G base station”, providing NR access towards the UE, and ng-eNB is an “enhanced 4G base station”, or eNB, providing E-UTRA access towards UEs. NR is the radio interface technology defined for gNBs. Both gNBs and ng-eNBs interconnect with each other via the **X**$_n$ interface. They also connect with the 5GC via the **NG** interfaces through the AMF [17].

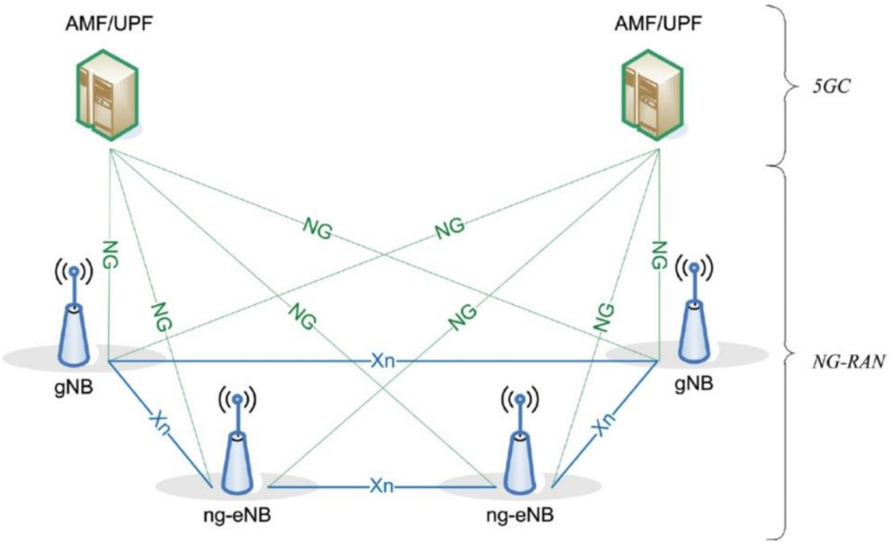


Fig. 2-3: NG-RAN Architecture and division between NG-RAN and 5GC. [17]

The principal elements of the NG-RAN appear in Fig. 2-3. In this graphic, we can see both gNB and ng-eNB nodes, which communicate via Xn Interface, and to the core network via NG Interfaces. Several network functions form the 5GC, where the three main entities are: the Access and Mobility Function (**AMF**), the User Plane Function (**UPF**), and the Session Management Function (**SMF**). Fig. 2-4 presents the functional split between elements, showing the logical parts and the network functions that the system sets to administrate.

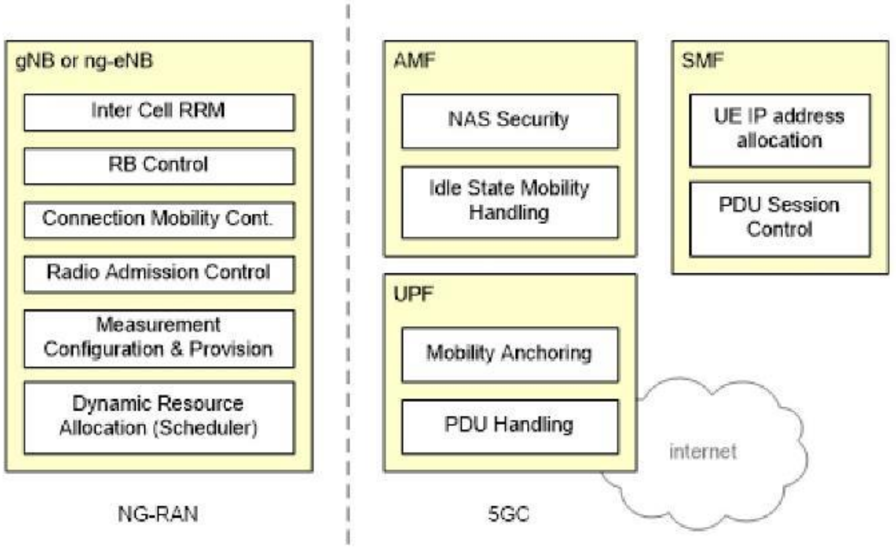


Fig. 2-4: Functions served by each 5G element. [17]

Deployment options

There are two deployment architectures: Stand-Alone (**SA**) and Non-Stand-Alone (**NSA**).

- In a SA scheme, mobile phones connect to a fully deployed 5G network, where gNBs are installed and combined with a 5GC.
- In an NSA scheme, there are several variations in the configuration, since NG-RAN nodes can be gNBs or ng-eNBs connected to the same core network; either an EPC network or a 5GC network.

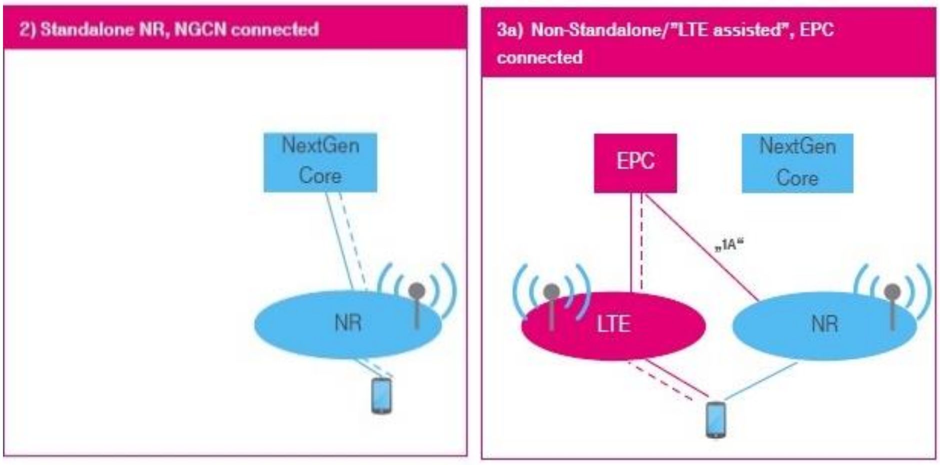

2) Standalone NR, NGCN connected
NextGen Core
NR
3a) Non-Standalone/"LTE assisted", EPC connected
EPC
NextGen Core
„1A"
LTE
NR

Fig. 2-5: 5G SA and NSA. [13]

Numerology

A new concept that is considered vital for radio resource management on 5G is Numerology. This new scheme is defined as the codification of relations between channels and carrier frequencies in different spectral bands.

Considering that the design of 5G is to serve different services operating over various spectral bands with different subcarrier spacing or transmission interval lengths, the purpose for this concept is to group time or frequency resources with the same Numerology into the same **Resource Block Group** (RBG). As a result, we can count on a scalable OFDM numerology, with the scaling of subcarrier spacing between different frequency bands [13].

Numerology offers sub-carrier spacings from 15, 30, 60, and 120 KHz, with a proportional change in the cyclic-prefix duration. Smaller spacings allow a longer cyclic-prefix, and larger spacings handle phase noise. A carrier consists of up to 3300 sub-carriers, which may result in bandwidths of 50/100/200/400 MHz, for subcarriers spacings of 15/30/60/120 KHz [16].

Not all numerologies are used in every frequency band since each of them presents radio requirements and defines a sub-set of bandwidths. Fig. 2-2 shows the numerologies for each frequency band: for FR1, NR considers spacings of 15/30/60 KHz, while FR2 considers 60/120 KHz sub-carrier spacings. Having these subsets, not every equipment needs to support the maximum carrier bandwidth. Therefore NR allows bandwidth adaptation to decide in which bandwidth receives regular traffic or high data rates [16].

NG-RAN functionalities

There are some aspects to be considered while deploying 5G-NR. For instance, we have to take into account that implementing this technology is going to enable improvements in network performance, but at the cost of higher base station density. As a consequence, Small Cells are gaining in interest to be the main element capable of delivering 5G requirements.

Another aspect appears when we evaluate new frequency bands usage since it has become a reality the utilization of millimeter waves, even when they present several propagation issues, like high-penetration loss, increased scattering, or reflection. With NR now is possible to overcome these problems by using antenna arrays known as massive Multiple Input Multiple Output (**massive-MIMO**). This configuration enables dynamic Beamforming, a wave propagation technique used to combine signals constructively. Due to this, it is possible to use low radio frequency power output.

Another aspect that improves 5G connectivity is Dual Connectivity (**DC**), a feature that enables users near handover time to be connected to two Base Stations at the same time.

Coordinated multi-point connectivity (**CoMP**) is a feature that improves signal reception near a cell edge since it allows simultaneous connections to more than one base station at the same time.

Front-Haul, **Back-Haul**, **Relay**, and **Side-Haul** are additional features for enabling new network configurations, with the target of extending coverage [13].

2.2. Multi-tenancy

2.2.1. Network sharing

When the Global System for Mobile Communications (**GSM**) networks started operating for the first time, there was no need for sharing infrastructure, since it was the first mobile network technology deployed. Only when the following generation of mobile technology arrived with Universal Mobile Telecommunications System (**UMTS**), it became necessary to set up a new infrastructure capable of providing UMTS requirements. Under that context, the idea of sharing existing infrastructure between providers emerged.

In [19], the 3GPP working group SA1 is in charge of define service and user requirements needed, and to standardize how networks should be shared, so it describes five business scenarios:

- ***Multiple core networks sharing a common RAN:*** Different tenants share a single common RAN, but not the spectrum. Each tenant uses its core network.
- ***Operator collaboration to enhance coverage:*** Two tenants with independent RANs covering different areas come together to serve a larger area.
- ***Sharing coverage on specific regions:*** A tenant can share its RAN coverage over one particular area where another tenant does not have a presence.
- ***Common spectrum sharing:*** A tenant shares its spectrum, or it may be several tenants putting their frequency together in order to increase their bandwidth.
- ***Multiple RANs sharing a common core network:*** Each tenant have its RAN and its spectrum.

Within any of these cases, a network operator should be able to differentiate its services from other MNOs, as well as be able to ensure service continuity to its end users.

Passive and Active Sharing

The first attempt at sharing the network was with **Passive Sharing**. It is defined as passive because it shares elements which do not require active coordination between sharing participants. These elements can be site locations, shelters, power supply, air conditioning, and even masts.

Active Sharing took the next step and moved on sharing base stations, antennas, and in some cases, the core network also, allowing to share spectrum resources, under contractual agreements.

3GPP working group SA2 defines two types of Active Sharing architectures in [20], as it follows:

- ***Multi-Operator Core Network (MOCN):*** Under this scheme, each tenant shares a single common RAN and the spectrum, while maintaining a separated Evolved Packet Core (EPC).
- ***Gateway Core Network (GWCN):*** In this scheme, tenants share a common RAN, while also sharing the Mobility Management Entity (**MME**). This distribution allows them to reduce costs, but it also reduces flexibility.

Network Sharing Management

3GPP working group SA1 studies in [21], four use case scenarios:

- ***RAN sharing monitoring:*** This case considers measurements shared with participating tenants, requested information by participating tenants to manage allocated resources, and quality information from RAN coverage.
- ***Flexibility in capacity allocation:*** This use case considers revenue, asymmetric resource allocation, load balancing in shared RAN, and automated capacity brokering for participating tenants upon request.
- ***RAN Sharing charging:*** This use case involves an event triggering charging records, or charging restoration where it is allowed to verify data usage over the RAN.
- ***RAN sharing broadcast capability:*** Scenario where users can select their home Public Land Mobile Network (**PLMN**), and also public warnings regarded public safety are allowed.

Management of shared networks takes into account two entities. It considers the Master Operator (**MOP**), a body in charge of infrastructure deployment, and it offers network management services to the Participating Operators (**POP**).

MOP uses an enhanced management system called MOP-Network Manager (**MOP-NM**), which provides notifications and signaling to POPs, using their POP-Network Manager (**POP-NM**). Communication uses Type 5 Interface [22].

2.2.2. Network slicing

Network Slicing is the result of theoretical concepts that exist from many years ago. The idea of virtualization initiated in the early 60s, with the first operating system developed by IBM and spread during the 70s and 80s with the use of Datacenters. During the 80s also appeared the idea of overlay networks, where logic nodes and links share a common physical infrastructure to create virtual networks. Those developments offer a previous version of Network Slicing.

The alliance of mobile operators, known as **Next Generation Mobile Networks** (NGMN), defines Network Slicing under the context of 5G, as a group of several logical networks, self-contained and built over a shared physical infrastructure, which allows the existence of a flexible stakeholder's environment. 3GPP defines Network Slicing as a technology that enables operators to create customized networks capable of providing enhanced solutions for different market scenarios, each of them with different requirements [22].

Network slicing basis is on seven fundamental principles: Automation, Isolation, Customization, Elasticity, Programmability, End to End, and Hierarchical Abstraction.

Enabling technologies

Virtualization technologies are the foundation for Network Slicing. In [22], is presented a review of the most critical technologies for the contribution they make:

a. Hypervisor

The concept of virtualization consists of creating an additional layer between the physical infrastructure and the Operating Systems running at the top. This layer is called Virtual Machine Monitor (VMM), also known as **Hypervisor**. It is a virtual platform for hosting guest operating systems that contain services and allows the sharing of hardware resources.

b. Virtual Machines and containers

A virtual machine (VM) is a software platform that creates the illusion of being a physical resource with its Operating System. The hardware virtualization is performed by the Host, while the guest machine is the VM. Each VM shares computational storage and network resources. Containers are a light-weight option instead of VMs, mostly to virtualize physical servers.

c. Software-Defined Networking

Software-defined Networking (SDN), enables programmability and open network access, by splitting control and data planes using centralized network intelligence. An SDN controller allows third parties to have an abstracted vision of the network, which leads to enabling multi-tenancy, using an agent.

d. Network Function Virtualization (NFV)

NFV enables the deployment of hardware-based network functions, but by software means over a virtualized environment. **Virtual Network Functions** (VNF) are the software instantiation of existing network functions, implemented over VMs.

NFV Infrastructure (NFVI), is defined as the construction blocks where the VNFs are stored. It comprises storage, networking, computational hardware elements.

Management and orchestration (**MANO**) are in charge of manage VNFs and NFVI. It is composed of the NFV Orchestrator (**NFVO**), VNF Manager (**VNFM**), and the Virtualized Infrastructure Manager (**VIM**).

e. Cloud and Edge computing

Cloud and edge computing are infrastructure services that provide storage, computing and networking resources over a single platform, to enable Network Slicing. Edge computing makes it possible to put processes and analysis closer to the user, enabling edge-centric networking. A widespread use case is Multi-access Edge computing (**MEC**).

Network slicing management

Network Slicing lies on a closed-loop process in charge of check service requirements to assure a certain performance level. It achieves such a level of performance thanks to a service management layer, where it executes the creation and operation of services, and to a control layer, which enables resource abstraction to service management and handles control operation and resources administration [23].

- **Network Slicing orchestration architecture**

Fig. 2-6 presents an example of a network slice orchestration architecture:

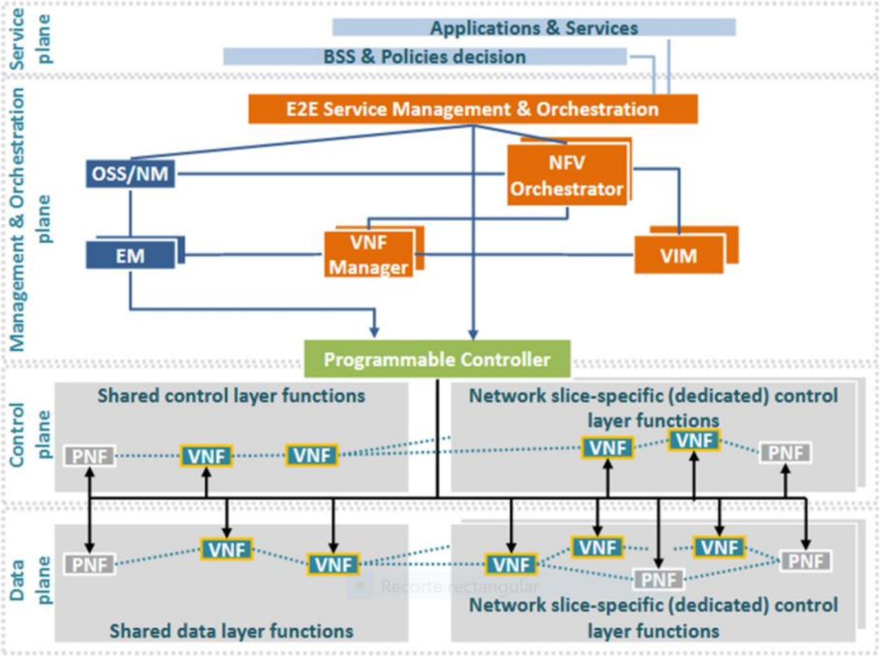

Service plane
Applications & Services
BSS & Policies decision
Management & Orchestration plane
E2E Service Management & Orchestration
OSS/NM
NFV Orchestrator
EM
VNF Manager
VIM
Programmable Controller
Control plane
Shared control layer functions
Network slice-specific (dedicated) control layer functions
PNF
VNF
Data plane
Shared data layer functions
Network slice-specific (dedicated) control layer functions
Recorte rectangular

Fig. 2-6: Network orchestration architecture. [23]

- ***End to End Service Management & Orchestration:*** takes incoming Network Slice requests, and fabricates the slice performing slice brokering, Admission Control, policy provisioning, and resource mapping, taking into consideration SLAs and Slice Templates.
- ***Virtual resource orchestration:*** Is in charge of the insertion and instantiation of VNFs, and to perform MANO´s operations upon virtual resources.

  - ***Network resource programmable controller:*** enables VNFs chaining, QoE control, and resource programmability, decoupling Control/Data planes.
  - ***Life cycle management:*** performs legacy management and policy provisioning,

- **Network Slice broker**

  Network Slicing uses an element called **Network Slice Broker** (NSB) to guarantee high performance and cost-efficiency since it enables on-demand resource allocation utilizing the Admission Control, resource negotiation, and charging. NSB uses a global network view, achieved through network monitoring and traffic forecasting, to secure resource availability, latency, and resiliency.

  To create **Network Slice Instances** (NSI), Network Slice Blueprints and Templates are needed. **Blueprints** are complete descriptions of structure, configuration, and workflow, while **Templates** are logical representations of NFs and resources required to habilitate the requested Network Slice.

- **Life-cycle management**

  The 3GPP has separated the life-cycle management of an NSI from the service instance that uses it. The management of an NSI needs four procedures: Fault management, Performance management, Configuration management, and Policy management.

  The life-cycle management phases of an NSI are 1) Preparation, 2) Instantiation, configuration, and activation, 3) Runtime, and 4) Decommissioning [22].

RAN Slicing

It is declared in [23], that a network slice is an end-to-end concept that involves all network segments, including the radio network, wire access, core, transport, and edge network. In general, this research defines network slices as a RAN-slice component and a core-network slice component.

The core component consists of a set of network functions and network applications, bundled over cloud infrastructure, using the previously mentioned virtualization technologies. A collection of RAN functions shapes the RAN component that serves a specific use case, and RRM functions define its behavior. The focus during the development of this work is on the RAN-slice component, and each slice mention will refer to the RAN component.

Understanding the relevance of Network Slicing, market partners and vertical industries are working together to describe a generic slice template (**GST**), to define a set of slice characteristics that the industry can use to set the description of a network slice type. The idea is to use this template as a reference to understand SLAs signed with operators and to define the attributes of their products [24].

As the number of RAN slices grows, the concept of slice queuing arises. It is identified in [25], that the inter-slice control, or brokering process, need a deeper understanding of slices and the slice request queuing method. This process may consider slice duration, frequency of the application, or others. Slicing opens a new business possibility for the infrastructure provider, defined as **slice as a service** (SlaaS). In SlaaS, the offered services, which are slices, can be highly heterogeneous, varying from each other due to different requirements from their services. Consequently, management and orchestration need advanced policies to decide which slices can be accepted or declined [26].

We find some methods for improving RAN performance. [3] presents a cell load measurement method, and predictions on load increase as well. The research evaluates both approaches under simulated environments, which had determined that it is possible to achieve a trade-off between blocking probability and QoS of UE bearers. Finally, the study suggests that these upgrades can be enhanced if it considers an adaptive Admission Control threshold of the cell's capacity. In [27], an optimization method is discussed. It analyzes the Admission Control scheme for multiclass services in the LTE scenario, where the issue stands on the maximization of admitted UEs using multiclass services. The solution lies in the resource allocation model used. This study shows a different approach to the problem of resource optimization for the Admission Control function. The conclusion is that by adjusting the allocation of resources for the available services, it is possible to achieve optimal use of the system capacity.

There are some questions about the operation of RAN slicing. In [28], the motivation is to identify possible options for implementing the slicing concept at the RAN level, but the first question that tries to answer is about slice granularity options. It states that there is still no agreement on the level of granularity that a slice should have, and it may depend on the infrastructure provider. With that affirmation, it presents different slice implementations, where each slice attends different service requirements while sharing the same radio and processing resources. However, some problems still are pending, like the scheduling mechanism used, or the Monitoring and orchestration of slices.

- ***RAN slicing requirements***

  RAN slices need dynamic resource management, using advanced MAC scheduling functions and different **Key Performance Indicators** (KPI) for each slice.

  Resource isolation is essential, considering that each slice manages its own rigorous set of requirements and security.

  Finally, a RAN slice also has functional requirements, where each slice utilizes different sets of VNFs, with a separate control plane/user plane functional split [22].

- ***Slice resource management and Isolation***

  Different resource management models can vary according to the level of isolation needed. Those can go from the dedicated resource model to the shared resource model.

  The dedicated resource model handles a specific number of dedicated resources. In contrast, the shared resource model is managed by a universal scheduler that allocates resources according to specified policies and criteria. The latter allows resource elasticity while lacking the support of strict QoS guarantees and isolation. [29] studies both models.

  The management of slice resources utilizes resource sharing by doing modifications into the MAC scheduler, using the Hypervisor or the NVS.

- ***RAN Programmability***

  It is also known as **Software-Defined RAN** (SD-RAN). An important function is to abstract RAN resources and to enable open APIs using a service orchestrator entity. There are already several use cases, where some of the best known are **SoftRAN** and **FlexRAN**. The first is a project working on the idea of abstracting the whole base station. The latter is FlexRAN protocol, which performs RAN abstraction, providing open APIs and RAN programmability for Open Air Interface eNBs [22].

2.3. Admission Control

2.3.1. Radio Resource Management

Radio Resource Management (RRM) appears in [30] as a set of strategies and algorithms deployed with the aim of handle existing co-channel interference in the air interface by controlling radio resources and radio access network infrastructure efficiently.

RRM functionalities are responsible for giving the most appropriate use of air interface resources. It has three primary goals: to assure the end-to-end QoS of existing connections, to maintain the planned coverage area, and to enable high capacity.

The group of RRM functionalities considers several tasks such as Power Control, Handover Control, Admission Control, Load Control, and Packet Scheduling. These functions manage an actual amount of hardware inside the network or existing resources over the air interface. It is known as **Hard-blocking** when hardware limitations restrict potential capacity. **Soft-blocking** occurs when the current load overcomes the existing air interface capacity. When any deployment considers planning RRM, it is advisable to opt for a Soft blocking design, since it allows higher capacity [30].

2.3.2. Admission control principle

The AC function is required when a radio bearer is created or modified, and it has to decide to accept or reject the request for establishing a new **Radio Access Bearer** (RAB) into the RAN. To take that decision, the AC estimates the projected load increase that the incoming bearer would produce, both in the Uplink and the downlink directions. Once the decision is made, and the RAB is accepted, it is the RAN's job to provide the RAB into the mobile core network, carrying user's data delivery services. LTE designates its bearers as **evolved-RABs** (E-RAB), an element that represents the conjunction of an S1 bearer with the corresponding Data Radio bearer, and its purpose is to transport IP-packets over the air interface [31].

The creation of new RABs requires radio resource allocation. As a consequence, there must be an AC algorithm at each cell that is part of the RAN. AC is responsible for whether a RAB is accepted or rejected. It takes into account overall resource utilization in the cell, meeting QoS from active RAB connections, and QoS requirements from the incoming RAB request [4].

Another concept needed to understand resource allocation into RABs is the **Resource Block** (RB), a basic physical radio resource unit used for capacity allocation. In LTE access, resource allocation takes place over a time-frequency grid, with 1 RB as a base unit, which is formed by seven subcarriers with 15 KHz subcarrier separation each, allocated during a slot of 0.5 ms. For instance, 25 RBs compose a carrier of 5 MHz. In 5G, the concept is very similar since an RB is composed of 12 subcarriers of the same numerology. The 5G scenario addresses different services, using different spacing and even different **Transmission Time Interval** (TTI) lengths. Applying the Numerology concept, it groups time-frequency resources labeled with the same Numerology number into an **RB Group** (RBG), also known as Tile. Such a feature allows reducing processing load from scheduling and allocation problems at the borders of RBGs [28].

AC fulfills a fundamental function of ensuring agreed QoS levels in all current connections, which is a decisive part of a multi-tenant scenario, considering that it has an impact on shared resources allocation. Consequently, it also affects performance from existing network slices of the shared RAN.

An infrastructure provider delivering the physical platform to tenants should be able to guarantee specific QoS values to each leased RAN slice. It is stated in [32], that an accorded SLA must detail those values, between the Infrastructure provider and each tenant. Over this document are specified technical and operational aspects for implementing the requested slice. SLA values may include Data Rate speeds and maximum delay times, which may combine with a period for guaranteeing the agreed conditions, a percentage like 99.9% of the time as an example. Also, it must take into account that every data flow may arrive with specific QoS requirements.

2.3.3. Multi-tenant Admission Control

A multi-tenant Admission control scheme is presented in [4], with the target of ensuring efficient use of radio resources. The primary aim of the study is on the spatial distribution of radio resources over the RAN. The algorithm that grants access to a connection request has to validate two different aspects: If there are enough resources in the cell. At the same time, it also must ensure that the tenant who is making the request should have enough capacity available from the one specified in the SLA agreed.

This double validation, although it does perform a precise control of resource usage, may not be simple enough to cope with the speed that is required for the attendance of large amounts of connection requests, as it will happen in 5G. Extensive analysis for the calculation of resources distribution over the whole scenario may not be necessary all the time, especially when the saturation of resources inside the cell is still not reached.

This section develops the algorithmic solution for the AC scheme deployed in [4]. This research is the starting point of our work, where we start from this theoretical background, and from here, we develop a new AC model for RAN slicing in 5G.

Under this purpose, we need three consideration:

- The Admission/Rejection decision depends on the amount of capacity assigned to the corresponding tenant, defined in the SLA, and specified through the Scenario Aggregated Guaranteed Bit Rate (SAGBR). This value represents the aggregated Bit Rate from all the active RABs of a tenant across all the RAN.

- The Admission/Rejection decision has to accounts for the current usage of RBs necessary to accomplish the Bit Rate from the RAB requests due to the random behavior from radio channels and the environment. Such factors do not allow us to assign a predetermined number, and it has to be statistically calculated.

- The AC function should allow that a tenant could reach the agreed SAGBR in each cell of the scenario, but with flexibility enough to handle fluctuations in traffic distribution, between all the cells and inside any particular cell but between different tenants [4].

Algorithm definition

After presenting the principle of operation for the AC function, we are going to review the algorithmic solution. To do so, we assume a scenario consisting of N cells numbered as $n = 1, \dots, N$; Shared by $s = 1, \dots, S$ tenants. The amount of available RBs at the n-th cell is $\rho(n)$.

- The n-th cell executes the AC algorithm every time that a RAB setup request arrives, which also indicates its required QoS, expressed as the Bit Rate $\boldsymbol{R_{req}}$.
- The AC algorithm must assure two things:
  1. That the amount of RBs necessary for the new RAB and the already accepted RABs must not exceed the total amount of available RBs $\rho(n)$.
  2. That distributes the available RBs among all the active tenants.

The multi-tenant AC function accepts the RAB request if the following two conditions hold:

1. **Capacity check at cell-level**

This check guarantees that the n-th cell has enough physical resources after accepting the new RAB request. The requests pass the condition if:

$$\sum_{s'=1}^{S} \rho(s', n) + \Delta\rho \ \leq \ \rho(n) * \alpha_{th}(n) \tag{2.1}$$

Where:

- $\rho(s, n)$ is the average number of RBs assigned to the RABs of the s-th tenant.
- $\rho(n) * \alpha_{th}(n)$ is the cell-level AC threshold.
- $\Delta\rho$ is the estimated number of RBs needed by the new RAB, based on the required R_{req}:

$$\Delta\rho = \frac{R_{req}}{\hat{r}(n)} \tag{2.2}$$

$\hat{r}(n)$ is an estimation of the bit rate per RB, based on actual measurements from the cell:

$$\hat{r}(n) = \frac{\sum_{t=1}^{Te} R_{meas}(n,t)}{\sum_{t=1}^{Te} N_{RB}(n,t)} \tag{2.3}$$

2. Per-tenant capacity share check

The previous check guarantees that it exists enough radio resources within each cell. As a second validation, this check makes sure to allocate the correct amount of resources to the tenant, according to the SAGBR specified in the SLA.

In this regard, the nominal capacity share of a tenant s is defined as $C(n)$:

$$C(s) \ = \frac{SAGBR(s)}{\sum_{s'=1}^{S} SAGBR(s)} \tag{2.4}$$

Moreover, the RABs pass the per-tenant capacity share check if:

$$\rho_G(s,n) \ + \ \Delta\rho \ \leq \ \rho(n) * \alpha_{th}(n) * (\ C(s) + \Delta C(s,n)\ ) \tag{2.5}$$

In the upper bound of the condition, we find that according to $C(s)$, the AC allocates a share of the resources to the tenant s, with an extra capacity $\Delta C(s,n)$. The condition considers additional capacity available due to unused resources inside the cell or due to traffic distribution from the tenant across the scenario.

The algorithm defines $\Delta C(s,n)$ as:

$$\Delta C(s,n) = \begin{cases} \beta \cdot \Delta C_e(s,n); & if \Delta C_e(s,n) \geq 0 \\ \gamma \cdot \Delta C_b(s,n); & if \Delta C_e(s,n) = 0 \end{cases} \tag{2.6}$$

- γ and β are configuration parameters in the range of [0,1].
- $\Delta C_e(s,n)$ is the potential capacity available due to unused RBs by other tenants:

$$\Delta C_e(s,n) = max\left(\sum_{s' \neq s}\left(C(s') \cdot \theta - \frac{\rho_G(s',n)}{\rho(n)}\right), 0\right) \tag{2.7}$$

- $\Delta C_b(s,n)$ is the capacity share shift of the s-th tenant across all the cells. It measures the increase in the capacity that should be applied to ensure an overall capacity of C(s) across the scenario:

$$\Delta C_b(s,n) = (n-1)C(s) - \sum_{\substack{n'=1 \\ n' \neq n}}^{N} \frac{\rho_G(s,n')}{\rho(n')} \tag{2.8}$$

3. Algorithm description

In this chapter, a novel token-based, multi-tenant Admission Control algorithm for future networks is proposed, to increase current AC performance. The main objective focuses on optimizing resource utilization, which finally translates into an increase of available capacity for tenants. We introduce the algorithm solution along with some traffic policing concepts that support the rationale of the selection. After that, we explain a general description of how the algorithm operates.

3.1. Preamble

The AC function is in charge of accepting or rejecting new connection requests, so it is a fundamental piece in the multi-tenant scenario since it guarantees the required QoS levels. The importance of implementing a specific QoS in each network slice motivates us to analyze the concepts of QoS in networks. In this section, we present a new admission control algorithm based on the token's concept, intending to optimize the access function by applying a faster, more straightforward policy in resources administration, so in that way, improve the provided QoS in the slices leased by the operators.

The proposed method corresponds to the **token-bucket concept**, which has applications in other areas of the literature, such as QoS management, for traffic shaping and traffic policing. We base our motivation on finding an analogy in the use of the token-bucket algorithm applied to manage the QoS in heterogeneous computer networks and to transfer its application to the access of mobile networks, where we manage the QoS of the RAN slices.

There are two established architectures for providing QoS in heterogeneous networks: Integrated Services (***IntServ***) and Differentiated Services (***DiffServ***). Although the orientation of IntServ is towards individual streams, DiffServ focuses on classes of services, applying QoS to service groups that share similar requirements. This feature allows it to be a scalable architecture that offers flexibility. DiffServ classifies and manages network traffic, allocating each data packet into its corresponding traffic class, and providing different treatment to each class. We observe a similarity between this behavior and the multi-tenant AC policy, where it controls the admission requests of packets from multiple tenants with different traffic requirements [33].

Providing end-to-end QoS in heterogeneous networks is complicated since bandwidth, jitter, or delay can vary dramatically, and demand can exceed the available computing resources. To offer QoS in networks, we need a specialized infrastructure, one that complies with the main concepts, mechanisms, and algorithms necessary to provide QoS. Among the most important ones we have: Traffic description, SLAs, Packet classification, resource reservation, admission control, and traffic policing.

For the traffic description, a quantitative description of generated traffic is necessary. In this regard, there are two types of traffic sources: constant bit rate (**CBR**), like coded voice, and variable bit rate (**VBR**), as coded video. We are interested in VBR sources since they represent the behavior of typical users within a mobile network. Three traffic parameters can describe VBR sources: peak rate, average rate, and burst size [34].

For traffic policing, the Leaky Bucket algorithm is a policy mostly for controlling CBR sources. Token Bucket algorithm controls the **average rate** (r) and **burst size** (b), so it is better suited for policing VBR sources. This algorithm also operates in real-time without causing any additional delay, since it does not need additional buffering.

Token Bucket algorithm

The algorithm works as an analogy of a bucket filled with tokens, which represents units of bytes, or single packets of a predetermined size. Every time a packet arrives at the network, the algorithm checks the bucket to see if there are enough tokens.

- The algorithm does not require a buffer, only a counter.
- The counter sets to a maximum value of the burst size.
- The counter is reduced by one each time the AC scheme accepts a packet into the network. If a burst of packets arrives, the counter is reduced by that amount.
- If the bucket does not have enough tokens to accept more packets, it discards them.

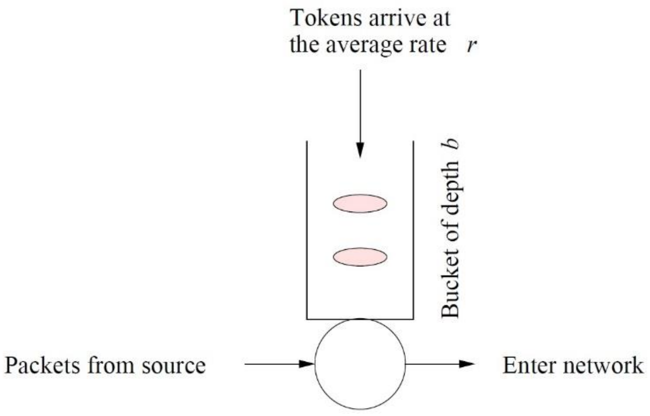


Fig. 3-1: Token bucket algorithm. [34]

We extend the concept of tokens towards multi-tenant admission control as follows:

- We have multiple tenants requesting different network slices to offer specific services through every segment. We consider each slice as a service class with specific parameters.
- Connection requests are heterogeneous, and the generated traffic is arbitrary in the same way as a VBR source, where the token-bucket operates for policing traffic.
- The token-bucket algorithm works with two parameters: burst size, which is the number of packets of a stream or collection of data packets, and the average rate, the speed at which it establishes new packets. Both parameters can model incoming traffic of a heterogeneous mobile network.
- Each token uses the size of the incoming packets. The bucket depth is the maximum number of packets a tenant could send, which we established would be equal to the Tenant´s cell capacity. If the user´s arrival rate is higher than r, the radio resources could not be available, and the token counter would decrease. If there are no more tokens available, the algorithm drops the packet.
- We consider tokens as a report of the system´s debt, so in our implementation, tokens start at zero and increase with every request rejection until it reaches a threshold limit.

3.2. Algorithmic solution

The AC scheme that we propose operates in the 5G scenario at the multi-tenant RAN every time a new RAB request arrives at any cell from the core network and tries to establish a connection. When a petition arrives at the RAN, the AC function evaluates the RAB request, measures the QoS needed to provide, and executes the logic. Fig. 3-2 depicts the procedure followed by the AC when a RAB request arrives:

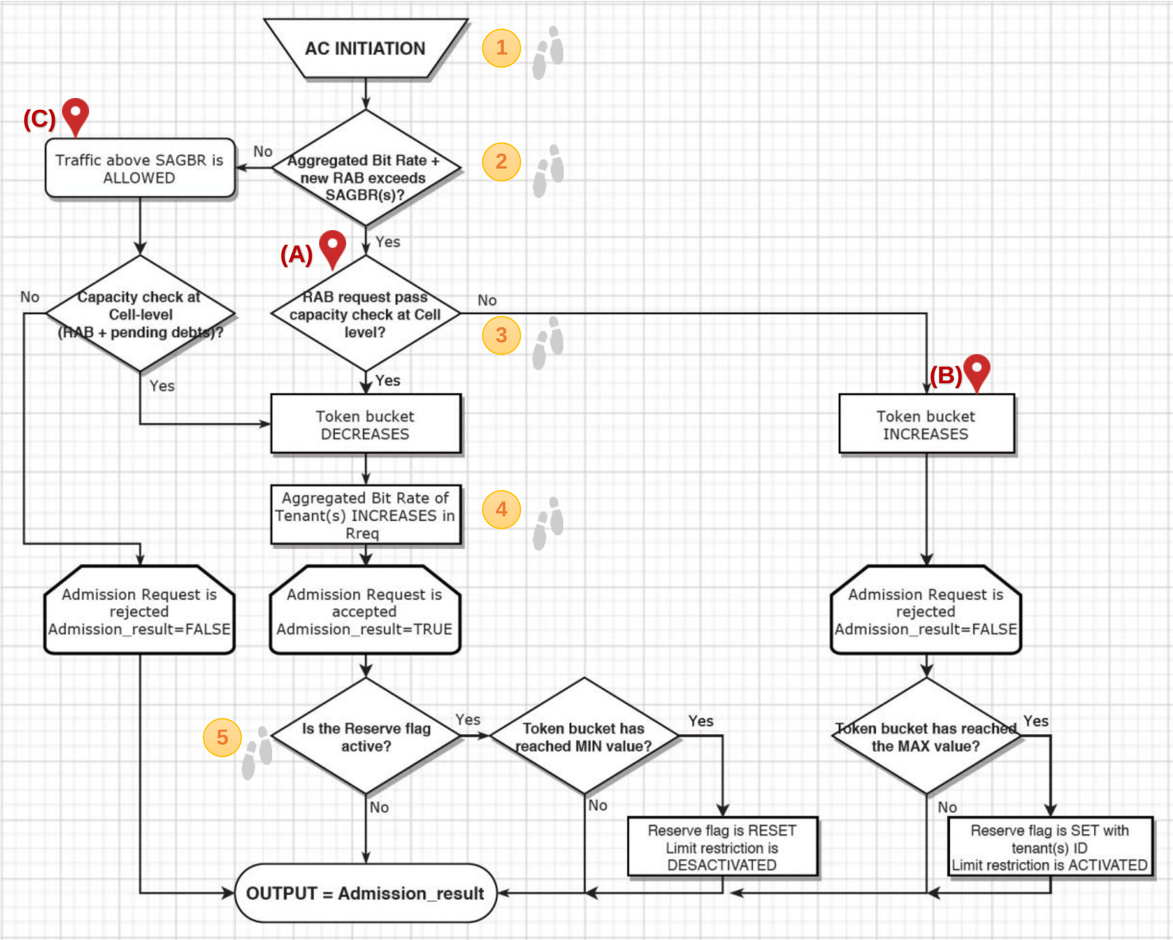

AC INITIATION
1
(C)
Traffic above SAGBR is ALLOWED
No
Aggregated Bit Rate + new RAB exceeds SAGBR(s)?
2
Yes
(A)
No
Capacity check at Cell-level (RAB + pending debts)?
RAB request pass capacity check at Cell level?
No
3
Yes
Yes
(B)
Token bucket DECREASES
Token bucket INCREASES
Aggregated Bit Rate of Tenant(s) INCREASES in Rreq
4
Admission Request is rejected Admission_result=FALSE
Admission Request is accepted Admission_result=TRUE
Admission Request is rejected Admission_result=FALSE
5
Is the Reserve flag active?
Yes
Token bucket has reached MIN value?
Yes
Token bucket has reached the MAX value?
Yes
No
No
No
Reserve flag is RESET Limit restriction is DESACTIVATED
Reserve flag is SET with tenant(s) ID Limit restriction is ACTIVATED
OUTPUT = Admission_result

Fig. 3-2: Diagram flow for the AC algorithm.

We are considering an NG-RAN scenario with N cells, going from $n = 1,2, \dots, N$, and S tenants sharing the scenario $s = 1, 2, \dots, S$. The number of RBs in each cell is $\rho(n)$. The incoming RAB request includes the QoS required, defined by the required bit rate of the bearer, R_{req}. The SAGBR indicates the aggregated bit rate that the NG-RAN should provide to each tenant across all the cells, according to the agreed SLA.

When a new RAB request arrives, our AC scheme executes a few steps to decide whether to accept/decline the application. This scheme considers three different cases, which we point out in Fig. 3-2 as A, B, and C. Case **(A)** considers the flow of a petition when it meets the contractual SAGBR values; case **(B)** details what happens when the algorithm rejects the RAB request, and case **(C)** recognizes a possible situation where the involved tenant exceeds its contracted SAGBR.

As a **first step**, the algorithm begins by taking the input parameters that it needs to estimate the required capacity from the incoming RAB $\Delta\rho$, which is the required bit rate divided by the measurement of the bit rate per RB: $\Delta\rho = \frac{R_{req}}{\hat{r}(n)}$.

After it calculates the number of resources that are necessary to fulfill the QoS of the RAB, the scheme moves forward the **second step**, where it evaluates the aggregated bit rate $R(s)$ of the corresponding tenant s over the global scenario in the condition:

$$R(s) + R_{req} \ \leq SAGBR(s) \qquad (3.1)$$

If the capacity already admitted by the tenant is below the global contracted capacity, the algorithm proceeds to evaluate the request regularly and moves forward with case (A). However, when it exceeds the contracted SAGBR, it continues to the case (C).

Once the RAB request meets the overall contracted capacity condition, it continues with the **third step**, where it checks the algorithm checks the capacity at cell-level, with the condition:

$$\sum_{s'=1}^{S} \rho(s', n) + \Delta\rho \ \leq \ \rho(n) * \alpha_{th}(n) \qquad (3.2)$$

Where it validates that the amount of required RBs by the new RAB $\Delta\rho$, plus the ones used by the RABs already admitted $\sum_{s'=1}^{S} \rho(s', n)$ should not exceed the total available RBs in the cell. If the required resources are available, the RAB passes the condition, and the admission of the new RAB is accepted.

At **step four**, every time a request gets approved the algorithm updates three algorithm parameters: Token bucket decreases, aggregated bit rate increases by R_{req}, and it sets the logical output to true. This token bucket represents a “debt” that the system holds with the tenant, expressed in bit rate units Kb/s. For the case in which a RAB gets accepted, the associated bit rate is decreased of the token´s pile, reducing the system debt:

$$\text{Token(s, n)} = \max\left(\text{Token(s, n)} - R_{req}; 0\right) \qquad (3.3)$$

The rationale for using tokens is, that if a RAB request gets rejected when the corresponding tenant has available capacity, the token’s pile increases to register that required bit rate, for keeping track of the potentially attended capacity that the network assumes as debt.

When no request rejections occur, the value of the token bucket will be zero, and for the case when RAB requests do not pass the capacity check at cell-level, the token value is progressively increased by each rejection until reaching a maximum threshold, $MaxToken$, which cannot exceed the amount of reserved capacity for the tenant, at that specific cell. After a request is accepted and the tokens pile updates, the global bit rate assigned to the tenant s within the network increases, by adding the bit rate of the RAB:

$$R(s) \ = R(s) + R_{req} \qquad (3.4)$$

Case **(B)** in the fig.3-2 considers what happens when the RAB request does not pass the capacity check at cell-level in (3.2). For this case, tenant s still have the available contracted capacity, but the cell does not have available resources, so the AC function rejects the request. This rejection increases the token pile:

$$\text{Token(s, n)} = \min\left(\text{Token(s, n)} + R_{req}; MaxToken\right) \tag{3.5}$$

When Token(s, n) reaches its maximum, it activates a mechanism that puts the tenant in a priority state, to prevent further rejections of RABs, by enabling a restriction called "**Limit**" that reduces the number of available RBs for all other tenants. Its value is a ratio between their current token value and the token threshold from the tenant that activated the mechanism.

Having $Limit$ active decreases the number of available resources for other tenants, which translates into a reduction of accepted RABs until the RABs from tenant s are accepted again, and its debt decreases back to zero. The flag that triggers this scenario is "**Reserve**" and stores the ID of the tenant that reached the debt limit.

There is the possibility of having more than one tenant reaching the maximum system debt when $Reserve$ is active. On that event, the new tenant reaching the token's threshold already had a $Limit$ applied, so the algorithm removes the restriction, but only for this tenant and not for others, as a way to prioritize service for tenants with higher system debt. Next, the scheme applies a new $Limit$ restriction for tenants that still have not reached the token limit.

Going back to the case (A), we move forward to **step five,** where after accepting the RAB, the algorithm checks if tenant s have $Reserve$ active. In that case, it reviews if the tokens are decreasing. When tokens decrease until zero, the tenant no longer needs special attention from the AC, so in that case, the algorithm resets the $Reserve$ flag and deactivates the $Limit$ restriction. Both actions only apply for the specific tenant s, considering that if the function removes the $Limit$ from all the remaining tenants, the ones with $Reserve$ active and tokens pending from being decreased would be harmed.

To confirm that the tenant who has reduced its tokens is also the last one to do so, the algorithm checks the $Reserve$ flag to see if it has been turned off by all other tenants. If that is the case, it resets both the flag and the restriction to its initial values. The final step is the end of the function, where it returns the admission result as an output.

Case (**C**) occurs when the tenant s exceeds the contracted global capacity in (3.1). In this case, the rationale is similar to case (A). First, it evaluates whether the cell has available resources. However, this time, it also needs to ensure that there is enough capacity to first attend pending debts from other tenants who have not exceeded their capacity, and only then the additional requested capacity. This way, the system performs equitably with all the involved tenants, while fulfilling the contracted SLAs with all operators. Consequently, if the algorithm rejects the request, the scheme only informs that the result is negative. Still, the token debt does not increase because the tenant is already using all its contracted capacity.

4. Simulation environment

This chapter describes the simulator used and the implementation of our algorithm on it. The first section provides an overview of the steps and tools used in the MATLAB simulation, explaining the components that are part of the simulator. The last section explains in detail the concrete implementation of the proposed algorithm within the MATLAB simulator.

4.1. Simulator description

We use Matlab to work on a simulator program that represents the behavior of a radio access network provided by an Infrastructure Provider, which operates on a specific geographical scenario, and multiple tenants as MNOs that leases the RAN.

The purpose of the simulator is to establish the main parameters that describe the RAN, such as propagation model parameters, spectral efficiency parameters, traffic parameters, admission parameters, and capacity share parameters. Using these values, it simulates the operation of a shared RAN between multiple tenants, operating within a wide range of offered loads for each tenant, and asses how they behave under RAN slicing.

The simulator collects statistics from the main parameters of the access network, which we analyze to measure performance from tenants and our algorithm proposal.

The simulator consists of a collection of Matlab classes and functions that describe the scenario, where the most relevant actions happen in *sim_AC_v3.m*, *base.m*, and *UE.m*:

- ***sim_AC_v3.m***: It is the class that contains the main program, inside a loop that is executed several times depending on the number of simulations, and it changes the session generation rate for each run. Every simulation executes a system performing as a shared RAN network, working through a simulation duration time to emulate a day of work for the network. The system checks for session finalizations, session starts, and reviews if any changes had occurred. Following those actions, it collects an array of statistics called **results**.
- ***Base.m***: It is a Matlab class that contains an NG_RAN cell. It contains parameters and functions for initiating each BS, initiating the radio channels, and the admission function that performs the selected AC policy.
- ***UE.m***: Matlab class for the parameters and functions of a UE. It stores information for the user, such as the tenant ID, which it belongs to, or the serving BS.

The first action is to configure the input parameters that the simulation scenario requires inside *sim_AC_v3.m*. We set the number of cells, number of tenants, simulation duration, and amount of RBs. After that, it is necessary to fix all the traffic parameters, propagation model parameters, and capacity share parameters. The next action is to distribute and initialize cells over the space. After that, to initiate all the tenants over the cells. Each tenant has active users, who gradually request to start a session into the base stations. During each simulation, the system runs through a for-loop that increases by steps of 0.1 seconds. During each step, it checks whether it has occurred any session finalization or session starts for each tenant, and in that case, the AC function executes the selected admission policy. It is possible to simulate the admission control without Network Slicing, with Network Slicing but no delta capacity allowed, or the proposed AC algorithm with the tokens policy incorporated.

Concerning the available offered loads for each tenant, the simulation program changes the session arrival rate of UEs within each cell, for each simulation to recreate different traffic scenarios that could challenge the algorithm. After running a complete simulation, it stores the output results in a file with all the statistics obtained from the RAN after performing a simulation, and stores the data into a results matrix. The last activity is to analyze the data and evaluate the behavior of the AC function.

4.2. Algorithm implementation

To assess the proposed AC algorithm, we carry out the simulations in a simplified version of an Urban Micro scenario that considers a neutral infrastructure provider that deploys N=2 cells: BS(1) and BS(2). Those nodes use one frequency carrier of 10 MHz each, enabling a total of $\rho(n)$ = 50 RBs. The scenario considers two tenants sharing the RAN: T1 and T2. $SAGBR(1)$ and $SAGBR(2)$ denotes the global capacity contracted by each tenant, and $cellSAGBR(1)$ and $cellSAGBR(2)$ corresponds to the nominal capacity share in each cell for each tenant. We assume that the token's threshold $MaxToken$ must be $cellSAGBR(s)$.

We implement our proposal for a novel Admission Control based on tokens, as a function that is part of the **base.m** class. This function is called ***Admission()***, and the system invokes it every time a new RAB request arrives. When a petition comes into the cell, *Admission()* selects the previously defined algorithm in the main program and executes the logic. The variable ***Admit,*** stores the logic value from the output of *Admission()* and determines whether the request is accepted or rejected.

If the AC function admits the request, the cell accepts the new UE, aggregates it to the corresponding tenant, compute the admission statistics, and updates the global $SAGBR(s)$. For the case where the algorithm rejects the request, the systems measure the blocking statistics.

The implementation of our proposed algorithm into the simulator follows the structure of the algebraic flow diagram presented in Fig. 4-1:

```
$\boldsymbol{if}\ (R(s) + R_{req}) \leq SAGBR(s)$
    $\boldsymbol{if}\ (\sum_{s'=1}^{S} \rho(s',n) + \Delta\rho) \leq \rho(n) * \alpha_{th}(n) * limit$
        Admission_result = 1;
        Token(s, n) = max(Token(s, n) $- R_{req}$; 0);
        $R(s) += R_{req}$;

        $\boldsymbol{if}(\ reserve(s,n) \neq 0\ )$
            $\boldsymbol{if}(\ Token(reserve,n) \leq min(Token))$
                reserve(s, n) = 0;
                limit(s) = 1;
                $\boldsymbol{if}(\ \boldsymbol{sum}(reserve) == 0\ )$
                    reserve = 0; limit = 1;
                $\boldsymbol{end}$
            $\boldsymbol{end}$
        $\boldsymbol{end}$
    $\boldsymbol{else}$
        Admission_result = 0;
        Token(s, n) = min$\big($Token(s, n) $+ R_{req}; MaxToken\big)$ ;

        $\boldsymbol{if}(\ Token(s,n) == MaxToken(s,n)\ )$
          $\boldsymbol{if}(\ \boldsymbol{sum}(reserve) ==\ 0\ )$
            reserve(s, n) = s;
            $\boldsymbol{for}(all\ the\ tenants\ s' \neq s)$
                $limit(s') = Token(s',n)/Token(s,n);$
          $\boldsymbol{else}$
             limit(s) = 1; reserve(s) = s;

            $\boldsymbol{for}(all\ the\ tenants\ with\ reserve(s')\ ==\ 0)$
              $limit(s') = Token(s',n)/Token(s,n);$
          $\boldsymbol{end}$
        $\boldsymbol{end}$
     $\boldsymbol{end}$
$\boldsymbol{else}$
    $\boldsymbol{if}\ \big(\sum_{s'=1}^{S} \rho(s',n)\ +\ \Delta\rho + \sum_{s'\neq s} token(s,n)\ \big)\ \leq\ \rho(n) * \alpha_{th}(n) * limit$
        Admission_result = 1;
        Token(s, n) = max$\big($Token(s, n) $- R_{req}; 0\big)$;
        $R(s)+= R_{req};$
    $\boldsymbol{else}$
        Admission_result = 0;
    $\boldsymbol{end}$
$\boldsymbol{end}$
```

Fig. 4-1: Algebraic representation form of the algorithm.

Each time that there is a new session arrival in a given cell, the main program executes *Admission()* in the cell by sending the tenant ID, the required bit rate R_{req}, and the system configuration as input parameters. First, the algorithm checks the condition for the global contracted capacity, according to SLA. If the current aggregated bit rate $R(s)$ and the required bit rate R_{req} does not exceed $SAGBR(s)$, it moves forward to evaluate the capacity check at the cell-level next.

If this second condition is met, the request is accepted, and the scheme changes the value of the logical output variable **Admission_result** to 1, reduces the system debt by the amount of R_{req} from **Token(s)**, and increases the current aggregated bit rate of the tenant by R_{req}:

```
aggregate_avg_Rb_multi_cell(s)=aggregate_avg_Rb_multi_cell(s)+Rbreq;
```

Following, it checks the $Reserve$ condition. If active, it means that the scheme is prioritizing the tenant due to having reached too many rejections. If its tokens are reducing, another If-condition evaluates when $token(s)$ reach to its minimum. At this point, the algorithm resets $Reserve$ and restores the $Limit$ restriction to its original value of 1.

At last, we check if it is the last tenant to reduce its debt. If so, it resets the complete $Reserve$ flag and $Limit$ restriction vectors, to assure that we are back to initial values.

If the RAB request does not pass the capacity check at cell-level condition, the algorithm rejects the request, so it sets *admission_result* to 0, and $token(s)$ increases by the amount of R_{req}.

Following the rejection, the algorithm evaluates if the token bucket of tenant s has reached $MaxToken$. In that case, it activates $Reserve$ for tenant s. If it is the first tenant to activate it, the $Limit$ restriction is applied to all other tenants. The limits are calculated within a for-loop, as a proportion of the differences between the tokens from tenants s' different than s, and the token from the corresponding tenant s:

```
limit(s_aux)=token(s_aux)./token(s);
```

For the condition where more than one tenant has reached its corresponding $MaxToken$ threshold, the scheme activates $Reserve$ and applies the $Limit$ restriction, but only to those tenants with $Reserve$ equals to 0.

The second part of the scheme evaluates the admission request when the corresponding tenant exceeds its contracted SAGBR. Admission to the network at this point is possible, but the algorithm needs to calculate first the actual debt that the system holds with other tenants. Next, it evaluates the capacity check at cell-level, but in this case, the request passes the condition only if the aggregated number of RBs used by all tenants **rho_aggr**, plus the RBs required for the new RAB **delta_rho** and the actual debt from other tenants **token_agg** does not exceed the amount of available RBs at the cell. *Token_agg* must be expressed in RB units:

```
token_agg=(sum(token)-token(s))./Rb_estimate_per_RB;
```

If the request passes the condition, the algorithm sets *admission_result* to 1, $token(s)$ decreases by the amount of R_{req}, and the overall aggregated bit rate of tenant s increases by R_{req}. For the opposite scenario, the scheme sets *admission_result* to 0; but there is no increment of the system's debt since the tenant already has all its capacity used.

5. Results

This chapter presents and analyses the simulation results obtained from using our proposal for a multi-tenant AC function for future networks. The first part of this section describes the simulation setup used for all the executed simulations using our algorithm. It then compares its performance with a baseline scheme and with the scheme presented in 2.3.3. We use aggregated bit rate, blocking probability, bit rate increase, and system RB occupation as the performance metrics to evaluate our algorithm.

5.1. Scenario description

The first step is setting the parameters that frame the scenario on which we perform the simulation. Next, we define values that translate those parameters into the simulation. The situation where we evaluate our new scheme considers an outdoor Urban Micro scenario, where an infrastructure provider deploys a multi-tenant RAN, conformed by gNB nodes. To simplify the analysis without losing generality, we consider N=2 cells, operating with one frequency carrier of 10 MHz each, which corresponds to 50 RBs per site. Considering the propagation parameters listed in Table 5.1, the infrastructure provider configures each cell with an effective capacity of 31 Mbps, considering an empirical correction of 0.7757 (θ).

Two tenants lease the deployed NG-RAN, identified as T1 and T2. Both operators have signed SLAs with the provider; therefore, the agreed capacity for T1 is SAGBR(1) = 25 Mbps, and for T2 is SAGBR(2) = 37 Mbps. With these SAGBR values, the capacity share for T1 is C(1) = 0.4, and C(2) = 0.6 for T2.

Parameter	Value
Inter-Site distance (ISD)	200 m
Path loss model	Urban micro-cell model with a hexagonal layout
Shadowing standard deviation	3 dB in LOS and 4 dB in NLOS
BS antenna gain	5 dB
Frequency	2.6 GHz
Tx power per RB	24 dBm
RBs per cell $\rho(n)$	50 RBs
Bandwidth per RB	180 KHz
UE noise figure	9 dB
Spectral efficiency model to map SINR	4.4 b/s/Hz
R_{req}	1024 Kbps
Session duration	Exponential model: 30 s
Session arrival rate	Values from [0.2, 1.2], following a Poisson model
$\alpha_{th}(n)$	1
γ, β, θ	(1.0, 1.0, 0.7757)

vector_variation	[0.2, 0.4, 0.6, 0.8, 1.0, 1.2]
simulation_duration	50000.0 s
time_step	0.1 s
num_cells	2
num_tenants	2
C(1)	0.4
C(2)	0.6
traffic_params.Rbreq	1024 Kbps
traffic_params.duration	30 s
MaxToken(s)	[12.287, 18.430] Mb/s
limit	[1, 1]
reserve	[0, 0]

Table 5-1: Simulation Parameters. [4]

For practical purposes, we are going to focus on the Downlink direction of the channel. The NG-RAN receives RAB requests from UEs, which arrive following a Poisson arrival model that simulates a random behavior. The session duration for these RABs follows an exponential model.

To test the algorithm under different conditions, we can change the offered loads for each tenant by varying the session arrival rate λ in each cell.

The objective is to see if we can increase the available capacity for the participating tenants by optimizing the usage of resources. We seek to achieve that by reducing the complexity of the policy processing, while at the same time trying to maintain fairness with the cell capacity distribution stated in the SLAs. Due to this, we focus on analyzing any bit rate increase for each tenant and the flexibility of our proposal under different traffic distributions. We can reach both purposes through the *Token(s)* concept from (3.3), (3.5).

Consequently, the performance assessment will consider as references two cases. The case where the same scenario utilizes an AC algorithm denoted as “NoDelta,” that contemplates network slicing with fixed values for the capacity shares but does not allow flexibility to re-use unused capacity left by other tenants.

After that, we compare our scheme with the “Delta_C” algorithm presented in 2.3.3, as a second benchmark for evaluating the bit rate increase and the blocking probability.

5.2. Results presentation with the baseline scheme

First, we evaluate our algorithm operating under a range of offered loads for each tenant, extending from 0 to 80 Mb/s. Upon this matrix of offered loads, we evaluate the aggregated bit rate obtained by our proposal, and the bit rate obtained by the "NoDelta" algorithm as a reference. From this comparison, we collect the gain achieved by our algorithm in terms of the bit rate increase percentage, as a function of the different offered loads for T1 and T2.

The analysis considers the total offered loads on the scenario, as well as the total bit rates, evenly distributed through all cells.

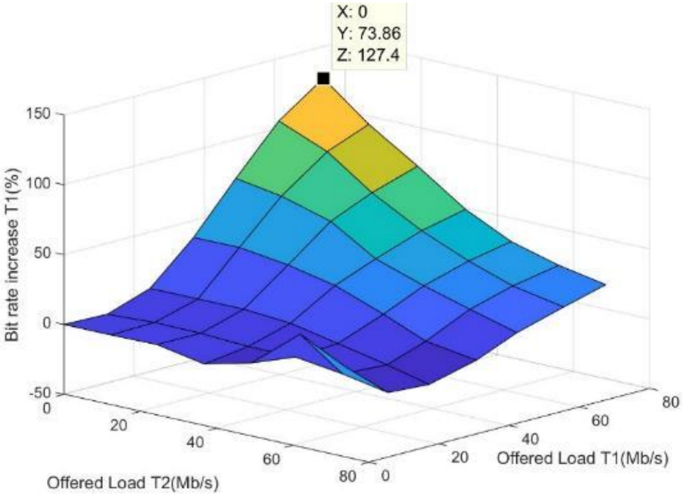


Fig. 5-1: Bit Rate increase obtained by T1 concerning "NoDelta."

Fig. 5-1 shows the aggregated bit rate increase obtained by T1 with the proposed scheme, in comparison to the "NoDelta" benchmark. The X-axis is the offered loads for T2, the Y-axis is the offered loads for T1, and the Z-axis represents the bit rate increase (%). We can see that, when T2 is using all its capacity (offered loads of around 60, 80 Mb/s), the improvements for T1 are small, from 24%, 30%. Nevertheless, we can see a peak, when the offered load of T2 is zero, and the amount of T1 is 73.8 Mb/s, T1 can increase its bit rate up to 127%, when the proposed scheme reaches a bit rate of 67 Mb/s, compared to the 29.4 Mb/s achieved with the "NoDelta" scheme.

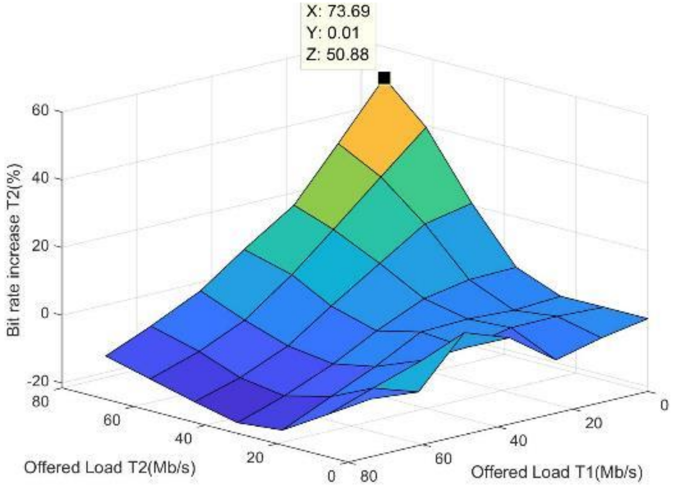


Fig. 5-2: Bit Rate increase obtained by T2 concerning "NoDelta."

For the case of T2, we also have a bit rate increase in terms of the offered loads, as seen in Fig. 5-2. Even though we see small decreases of bit rate, this happens for offered loads of zero or close to zero, so we can neglect these differences since they belong to minimal values. What we do appreciate is the peak for the bit rate increase, of around 51%, when the offered load of T1 is zero, and T2 can use all the available capacity. T2 reaches 66.9 Mb/s with the proposed algorithm and 44.3 Mb/s with the “NoDelta” scheme. We can see these improvements thanks to the re-use of resources, which allows increasing the available capacity for tenants. T1 obtains a more significant benefit since T2 can leave more unused resources.

Next, we want to see how our scheme performs when handling different traffic distributions for each tenant. In this way, we can evaluate the flexibility of the algorithm. Considering this, we assume two different traffic distributions: **Traffic A** and **Traffic B**. When the offered load of a tenant is equal to the contracted value in the SLA, it is marked as planned (P); when traffic is less than expected it is marked as low (L), and if it is above, is marked high (H). With this notation, we establish table 5.3:

Traffic Distribution	Tenant	Load BS(1)	Not.	Load BS(2)	Not.	Load Total	Not.
Traffic A	T1	24.6	(H)	24.6	(H)	49.2	(H)
	T2	12.3	(L)	12.3	(L)	24.6	(L)
Traffic B	T1	19	(H)	6	(L)	25	(P)
	T2	12	(L)	25	(H)	37	(P)

Table 5-2: Traffic distributions.

We first consider the scenario where T1 is receiving a heavy load of traffic, but T2 is not using all its capacity. The traffic distribution A tests how the proposed algorithm responds to these different traffic distributions and the available resources.

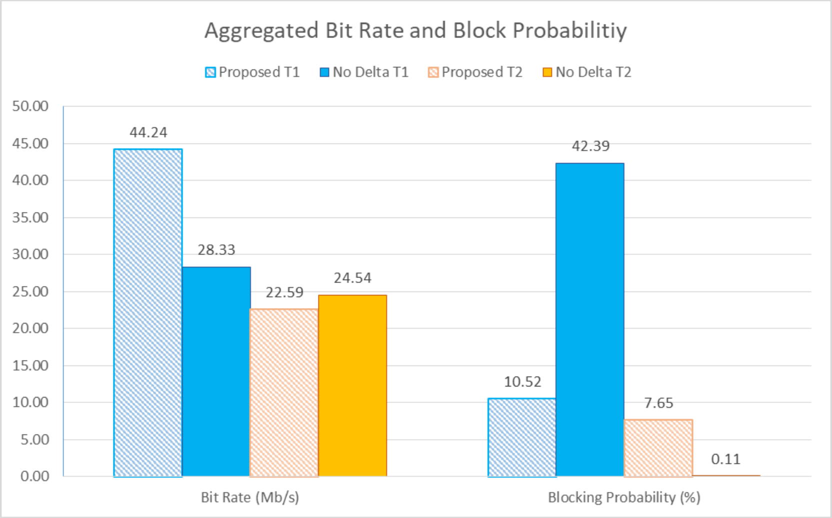


Fig. 5-3: Aggregated bit rate and blocking probability by each tenant in the whole scenario; Traffic A.

Fig. 5-3 shows the results for the total aggregated bit rate and total blocking probability experienced by each tenant by using our algorithm and compared with the “NoDelta” reference. We observe that the aggregated bit rate for T1 is 44.2 Mb/s, versus the 28 Mb/s obtained with NoDelta, which shows an increase of 56% in the bit rate of T1. Notice that T1 is making use of the available capacity from T2, which suffers a small decrease of around 7% in its bit rate. These results agree with the observed reduction in the blocking probability from T1, which reduces from 42% to 10%, but the blocking probability of T2 suffers a small increase, to 7%.

We next, consider the scenario where the distribution of traffic varies in each cell. In **traffic distribution B**, the offered load of T1 is high while T2 is low in the first cell, but in the second cell, the offered load of T2 is high, and T1 is low. Although the total offered load of both tenants corresponds to the planned one, this asymmetry in the traffic tests the flexibility of the algorithm.

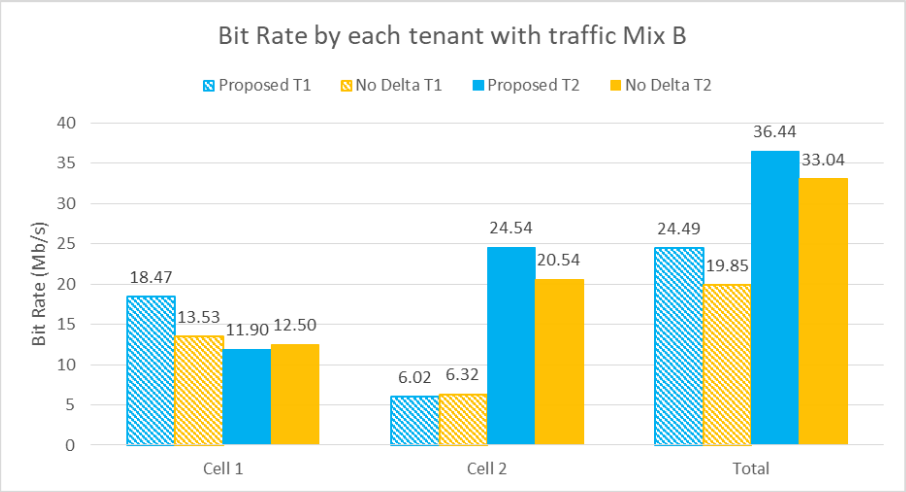


Fig. 5-4: Bit Rate by each tenant in each cell and the total scenario; Traffic B

Fig. 5-4 shows the bit rate obtained by each tenant in each cell and the entire scenario, using traffic distribution B. We can see that in cell 1, T1 improves its bit rate from 13.5 Mb/s to 18.5 Mb/s, while T2 remains almost the same. In cell 2, it is T1 that maintains the same bit rate, and T2 improves from 20 Mb/s to 24.5 Mb/s. These results translate into an improvement of 23% for T1 and 10% for T2, compared with the “NoDelta” reference.

Next, we review Fig. 5-5, where we depict the blocking probability in each cell and the whole scenario, also with the traffic distribution B. T1 achieves a significant reduction in cell 1, from 29% to 3%, at the cost of a small increase in T2, from 0.2% to 3%. In cell 2, it is T2 who uses the available capacity of T1, reducing its blocking probability from 18% to 3%, with a slight increase in T1, from 0.1% to 3%. These reductions represent a global gain for both tenants since the total blocking probability of T1 reduces by 84%, and that for T2 reduces by 74%.

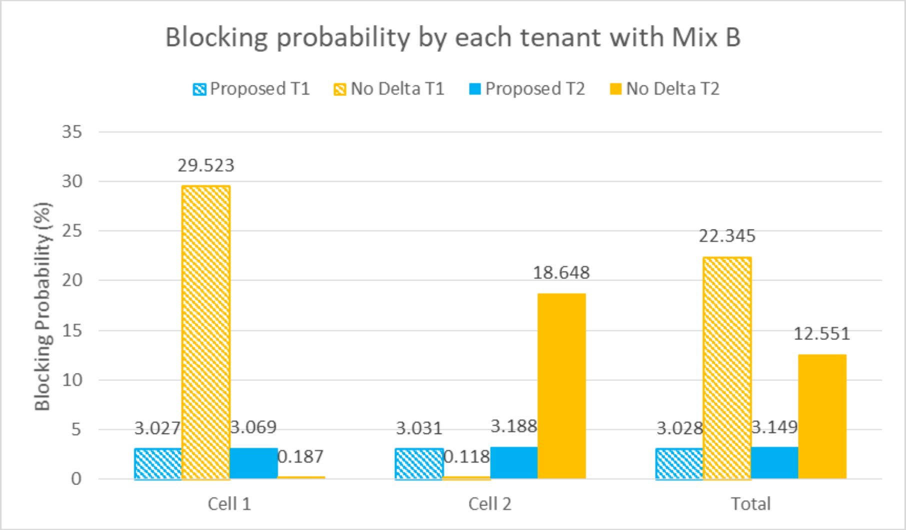


Fig. 5-5: Blocking probability by each tenant in each cell and the total scenario; Traffic B

5.3. Comparative versus the Delta_C algorithm

After studying the achieved bit rate increases concerning the case of a shared NG-RAN that does not take advantage of unused capacity left by other tenants, we now examine the performance of the *Tokens(s)* term. We check if it enhances the operation of the AC function concerning the $\Delta C(s,n)$ term from the scheme presented in section 2.3.3.

First, we evaluate the results obtained for the absolute values of bit rate and blocking probability, and then we analyze the flexibility of the schemes with the traffic distribution B.

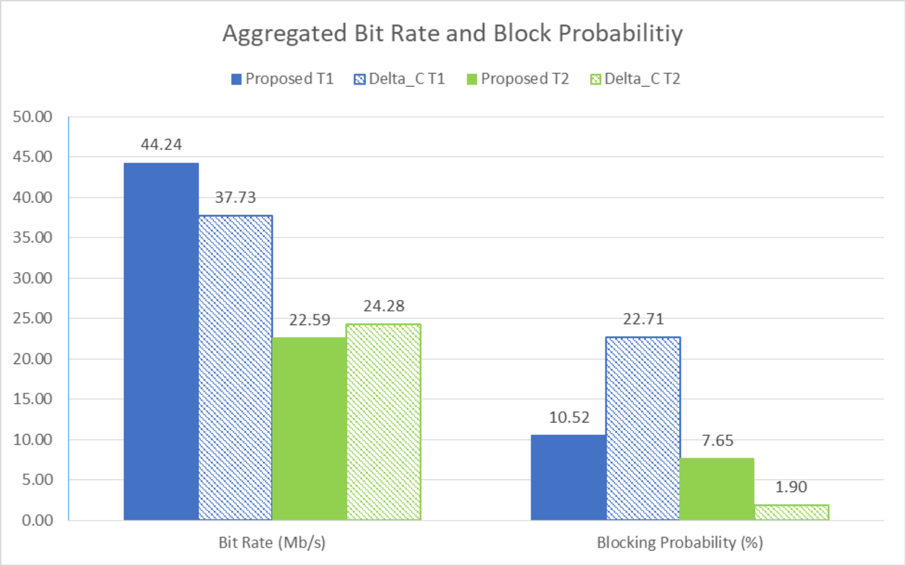


Fig. 5-6: Bit rate and blocking probability obtained with the proposed algorithm and with the Delta_C reference; Traffic A

In this case, fig. 5-6 shows a comparison in the gains of bit rate and blocking probability, between our proposal and the AC algorithm of section 2.3.3. Both schemes improve the bit rate concerning the “NoDelta” reference. Still, in this case, we see that by having fewer parameters and conditions to analyze, our proposal achieves an improvement in the use of resources, and at the same time, maintain fairness with the distribution of capacity for tenants. Using traffic distribution A, T1 achieves a total bit rate of 44 Mb/s with the proposed scheme, compared to the 37 Mb/s obtained with the "Delta_C" scheme, but with a slight degradation in the bit rate of T2, from 24.2 Mb/s to 22.6 Mb/s. The proposed algorithm obtains a total improvement of 17% in the bit rate compared to the reference, and only a small reduction in the bit rate of T2. T1 also achieves a significant decrease in its blocking probability, of 53%, due to a higher amount of spare capacity left by T2, at the cost of a small increase in the blocking probability of T2.

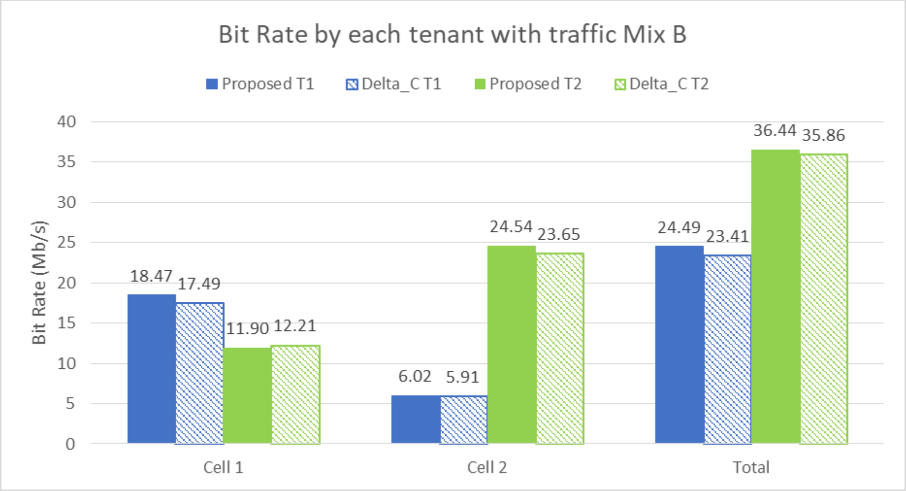


Fig. 5-7: Bit Rate in each cell and the total scenario with the proposed algorithm and with the Delta_C reference; Traffic B

With traffic distribution B, we want to measure the flexibility of the algorithms under different offered loads. Fig. 5-7 depicts the bit rates achieved by both schemes, in each cell and the entire scenario. The proposed algorithm makes an improvement for T1 in cell 1, although it suffers a reduction for T2. In cell 2, the opposite occurs since the distribution of offered loads is (L) for T1 and (H) for T2. Finally, we observe an increase in the global scenario of 4.6% in the bit rate of T1 and 2% in the bit rate of T2, respect to the "Delta_C" reference.

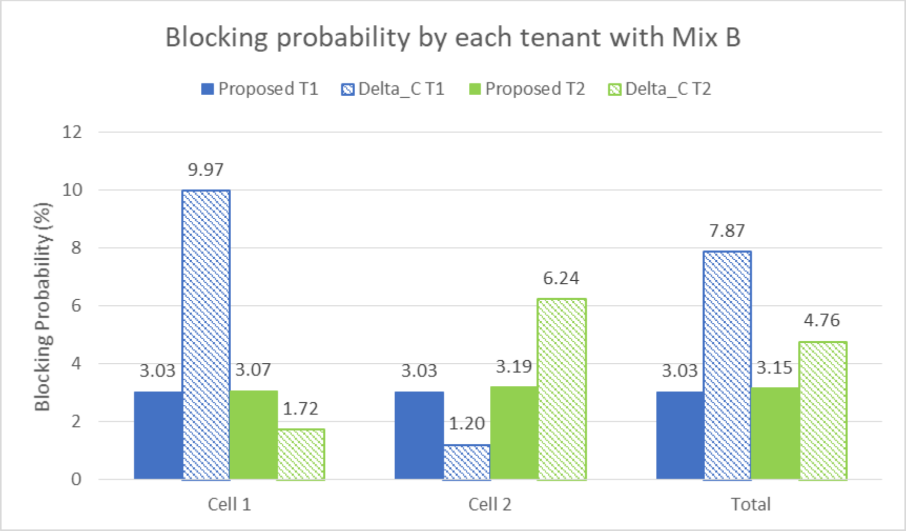


Fig. 5-8: Blocking probability in each cell and the total scenario with the proposed algorithm and with the Delta_C reference; Traffic B

Finally, we assess the flexibility of the schemes by analyzing the blocking probabilities obtained in each cell and the whole scenario. In fig. 5-8, we notice that the proposed algorithm has higher flexibility when managing the unused resources that each tenant leaves since in cell 1, where traffic load is (H) for T1 and (L) for T2, we see that T1 achieves a significant reduction in its blocking probability when using the proposed scheme. In cell 2, where traffic load is (L) for T1 and (H) for T2, we observe that T2 is who has a higher reduction when it also uses the proposed scheme. We conclude that our algorithm handles the available resources more efficiently, allowing a reduction in the total scenario of 61% for T1, and 33% for T2.

5.4. Impact of algorithm parameters

In this section, we are focused on the effect of the algorithm parameters on its performance under different traffic loads. To accomplish this, we will carry out the study only with results from this algorithm, considering some values of selected traffic loads. First, we study the dynamic evolution of the *Tokens(s)* term throughout a simulation. We examine the effect of the minimum and maximum values assigned to the *Tokens(s)* term and its impact on the operation of the AC function. Finally, we assess the importance of the $Reserve$ flag and its relation to the $MaxToken$ value.

Dynamic Token evolution

We have already expressed in section 3.2 that the *Tokens(s)* term represents the system's debt to the tenant. When the tenant RABs are accepted, the amount of tokens reduces, and the tenant increases its aggregated bit rate $R(s)$. When the AC function rejects the required bit rate R_{req}, only the amount of tokens increases.

Based on this definition, we find two characteristics in the behavior of the tokens:

1. When the tokens increase, it does not mean that the tenant's $R(s)$ decreases.
2. When the tokens decrease, it is because the system accepts RABs of the tenant again. So as a consequence, the aggregated bit rate $R(s)$ has to increase.

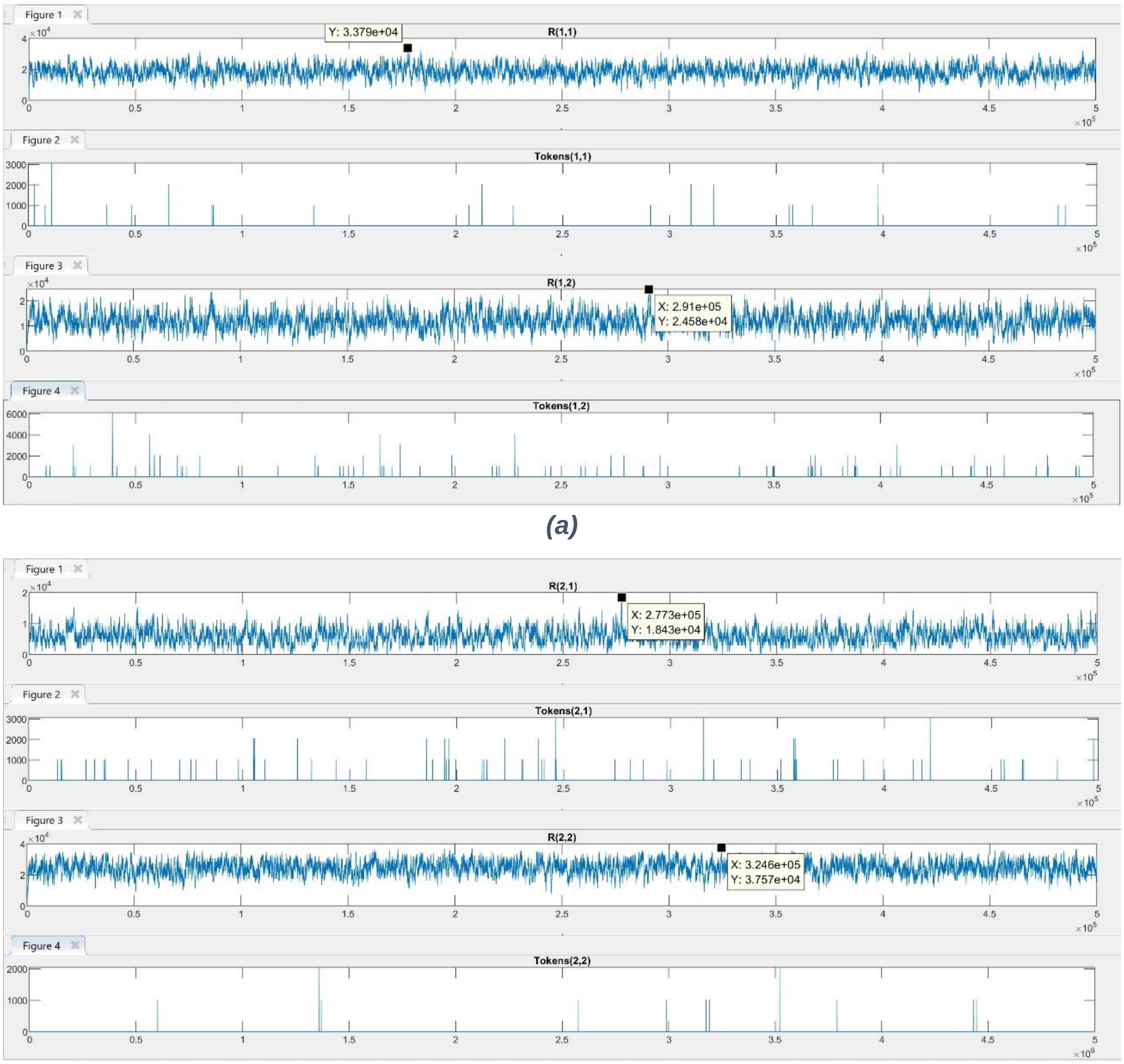
To study the dynamic evolution of the tokens, we will include the development of the bit rate admitted for each tenant. We consider two different distributions of offered load: The first distribution examines Traffic B, that presents the distribution (H) and (L) in cell 1 and (L) and (H) in cell 2; the second distribution considers $\lambda(1)$ and $\lambda(2)$ = 0.8 equally distributed between the cells.

The first distribution assists to show the flexibility of the term *Tokens(s)* under different traffic distributions.

The dynamic tokens evolution for each tenant during the complete simulation, along with the corresponding aggregated bit rate evolution, are illustrated in fig. 5-9. In (a), the instantaneous bit rates of T1 and T2 are represented respectively, for each 0.1-sec time_step, throughout the 50,000-second simulation, for cell 1. In (b), it is described the same for cell 2.

We notice that the one tenant with the highest offered traffic load, uses more cell resources, so it employs fewer tokens than the opposite tenant. In cell 2, the traffic distribution is (L) vs. (H), so T1 uses its tokens several times, reaching 3 Mb/s, while T2 does not.

Distribution 1: $\lambda(1,1)$=0.62, $\lambda(1,2)$=0.39, $\lambda(2,1)$=0.2, $\lambda(2,2)$=0.82 (TRAFFIC B)



(a)

(b)

Fig. 5-9: Bit rate and Tokens evolution during the complete simulation: (a) cell1, and (b) cell2.

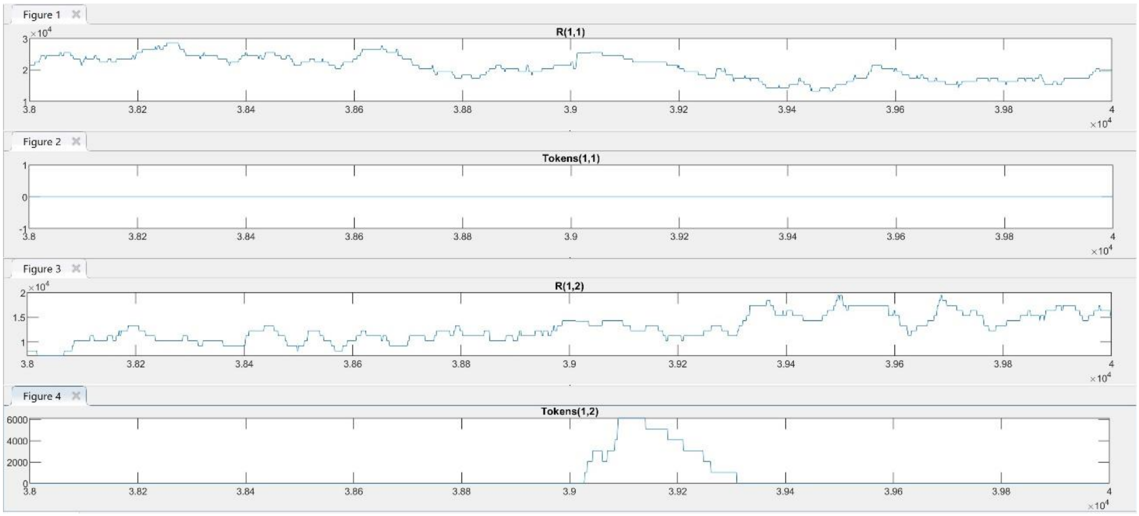
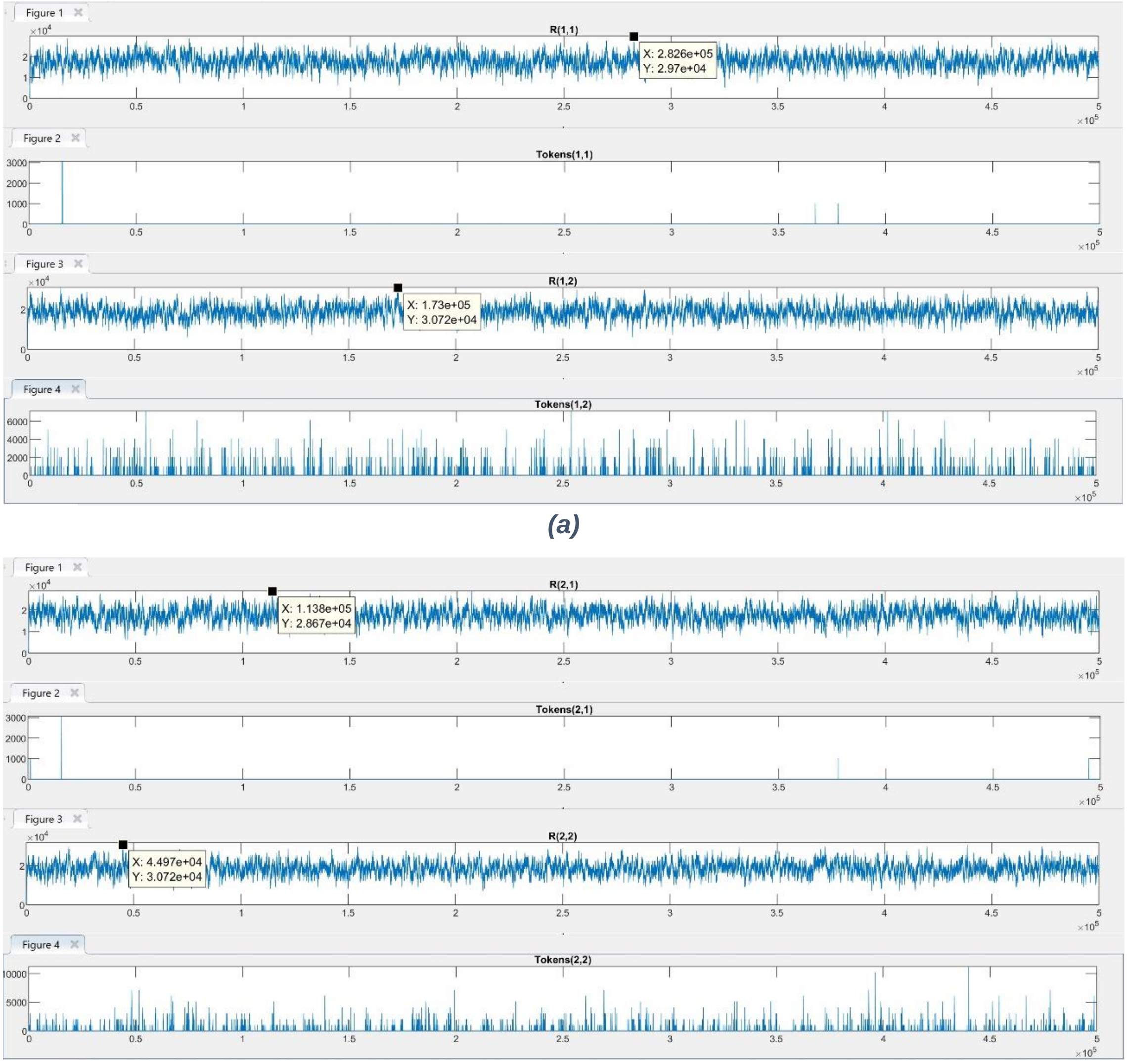


Fig. 5-10: Zoom of 200 seconds in the bit rate and token graphs, cell 1.

In fig. 5-10, we execute a zoom in the tokens and bit rate graphs of both tenants in cell 1, showing in detail how the tokens increase and decrease. The time range shown is 200 sec, so the X-axis ranges from 3 800 to 4 000 sec, within the total simulation. Here we can see that in the graph of *Tokens(1,2)*, the tokens increase by 3 900 sec, but we see that the bit rate of T2 remains almost the same. However, when the tokens decrease to zero, it means that the network is accepting the RABs of T2 again, so the bit rate assigned to T2 increases immediately.

Distribution 2: $\lambda(1)$ and $\lambda(2)$ = 0.8 for both cells



(a)

(b)

Fig. 5-11: Bit rate and Tokens during a whole simulation, distribution 2: (a) cell1, and (b) cell2.

Distribution 2 presents more accurately the variation of the current bit rate, along with the *Tokens(s)* variation. Fig. 5-11 depicts the bit rate and tokens of both tenants for the two cells. T1 shows a peak bit rate of 30.7 Mb/s but uses many tokens, increasing them to 7 Mb/s in cell 1 (Fig 5-11a). In cell 2 (Fig 5-11b), we see that it is also T2 who uses many tokens. The reason may be because both consume many resources, but T1 covers its demand first when T2 still needs RBs, so T2 increases its tokens by not finding available resources.

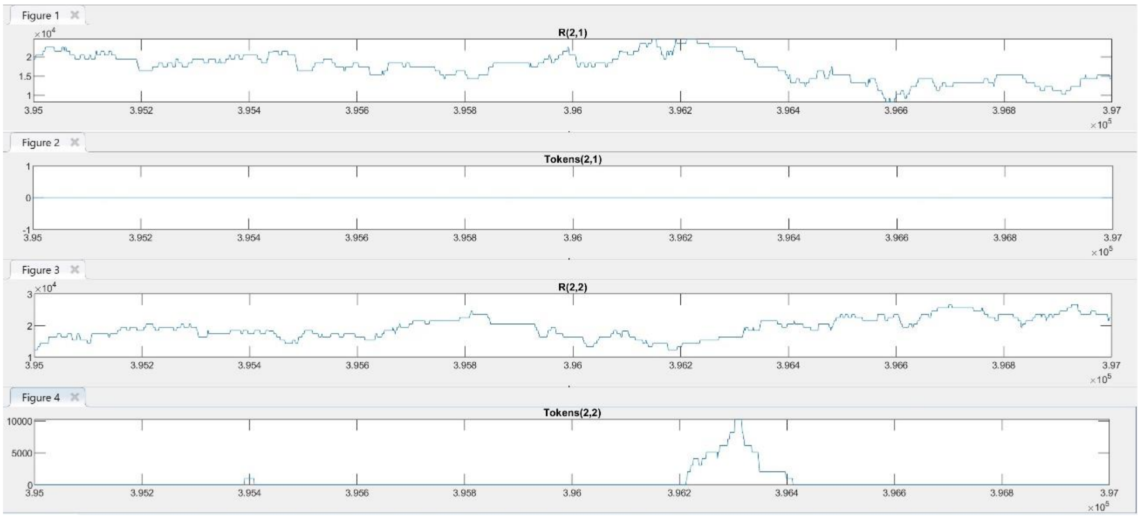


Fig. 5-12: Zoom of 200 seconds in the bit rate and token graphs during dist. 2, cell 1.

We make a zoom at the graphs in cell 2, to analyze the bit rate and tokens of both tenants during the range of 39 500 – 39 700 sec. During that period, we focus on the tokens of T2, which star to increase from the 39 620 sec. We can observe that when the tokens increase, the bit rate of T2 is low, matching with a high peak in the bit rate of T1. Once the tokens begin to decline, the bit rate of T2 increases significantly, and the bit rate of T1 drops, proving the flexibility of the algorithm to reallocate resources among tenants.

Impact of Minimum and Maximum Tokens values

In the previous simulations, we have seen the behavior of the tokens under different traffic loads. We understand that the *Tokens(s)* term helps increase the bit rate and improve the flexibility of the algorithm. Still, now we are going to review the effect of varying the limits of the values of the token bucket.

- According to the agreements made with the infrastructure provider, there should not be a network debt with the MNOs, so under normal conditions, the minimum token value should always be zero.
- It is the maximum threshold that affects the behavior of the algorithm, and consequently, the performance of the cell and the QoS experienced by all the involved users.

Initially, we configure the algorithm with the threshold $MaxToken = cellSAGBR(s)$, since we establish that under no circumstance should the system debt exceed the total contracted capacity of the cell of the tenant. Nevertheless, analyzing the Tokens graphics under distribution 1 (Fig. 5-9), we see that the token pile only increases up to values of 6 Mb/s despite receiving high traffic loads, and being MaxToken(1)=12.3 Mb/s, and MaxToken(2)=18.4 Mb/s respectively. As a consequence, the Reserve condition does not become active. This situation is because the RBs occupation is set at 38.3 in cell 1 and 38.5 in cell 2.

$MaxToken$ serves to restrict the system's debt, and this happens when the cell becomes saturated. Consequently, we must analyze these cases where the base station reaches the limit of its capacity. This saturation may occur when several tenants share the NG-RAN (N > 2), or when the tenants receive a very high traffic load, for example in very particular conditions such as seasonal events, concerts or football matches. To simplify our simulations, we will continue using N = 2 tenants, but we will consider very high traffic loads, with $\lambda(1)$ and $\lambda(2)$ = 2.0.

First, we limit MaxToken to 25% of $cellSAGBR(s)$, considering more accurate agreed saturation values for a mobile network, and from there we extend the possible system debt with $MaxToken$ to the 100% of$cellSAGBR(s)$; we obtain the following results:

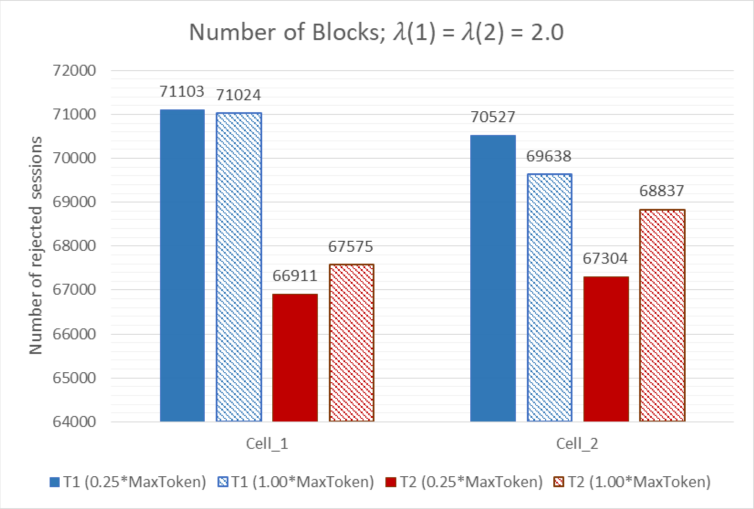


Fig. 5-13: System blocks by each cell; with 0.25 and full MaxToken

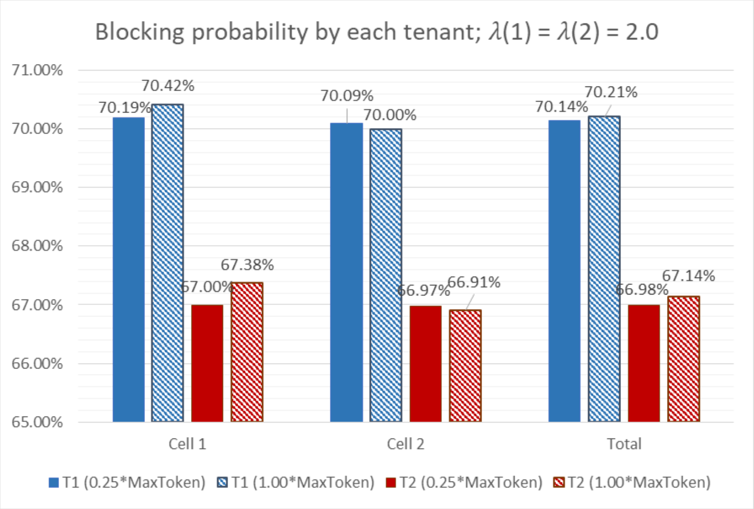


Fig. 5-14: Blocking probability by each tenant in each cell; with 0.25 and full MaxToken

Reviewing the operating parameters of the cells, we observe in Fig. 5-13 that when the system restricts its debt to $0.25 * cellSAGBR(s)$, the number of rejected sessions decreases. T1 remains at a similar value, but T2 does perceive a meaningful reduction. Both reductions translate into improvements in the blocking probability for each tenant in Fig. 5-14, where we observe that although the excessive load of traffic saturates the tenants, both T1 and T2 achieve a reduction when using $0.25 * cellSAGBR(s)$ vs. full $cellSAGBR(s)$, in both cells.

From the obtained data, we can conclude that the importance of the $MaxToken$ value appears when:

- In particular situations with massive loads of traffic for the tenants, the proposed algorithm performs very well from the perspective of the tenants, since the bit rate and blocking probability values do not vary much.
- In similar situations, $MaxToken$ becomes valuable when we see the performance of the cells from the perspective of the infrastructure provider. With $MaxToken$, it is possible to reduce the number of requests blocked and blocking probability in each cell, which matters a lot for the provider since being able to manage these Values helps control the levels of QoS offered by the network to all users.

Impact of using $Reserve$

In section 3.2, the description of the algorithm presents $MaxToken$ as the maximum value to which the system's debt can rise. This term works directly with the $Reserve$ and $Limit$ restriction because when MaxToken is activated, $Reserve$ is also enabled to control the allocation of RBs to tenants. According to this, we conclude that the limitation does not influence directly into the capacity received by the tenants. Still, it does help to handle the RBs better to avoid cell congestion.

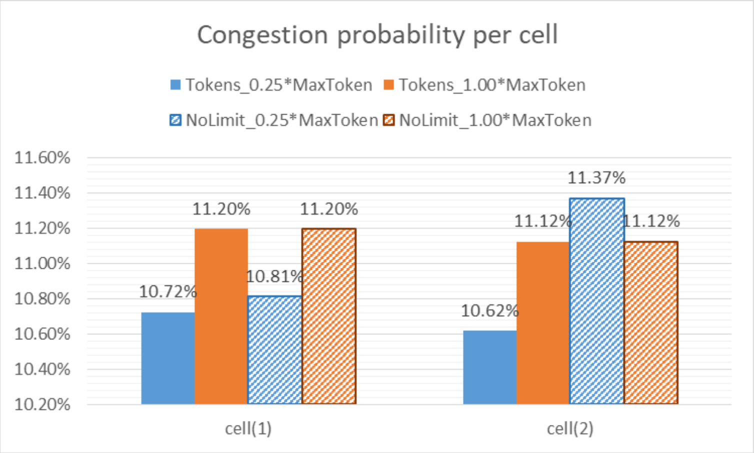


Fig. 5-15: Congestion probability per cell, using Limit vs. NoLimit.

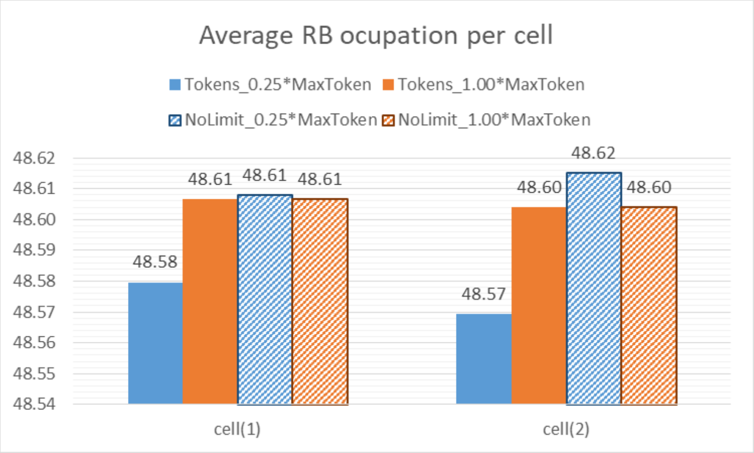


Fig. 5-16: RB occupation per cell, using Limit vs. NoLimit.

Fig. 5-15 depicts the congestion probability for each cell when excessive traffic load is received ($\lambda(1)$ = $\lambda(2)$ = 2.0), using the complete algorithm with 25% of $MaxToken$ and 100% $MaxToken$, and comparing it with a version without the $Limit$ restriction.

As we had already mentioned, when $MaxToken$ = $cellSAGBR(s)$, the system accepts very high values of debt, so $Reserve$ and $Limit$ are not activated, and performance is the same using the algorithm with or without $Limit$. The effect of the restriction is best observed when comparing the proposed algorithm with 25% of $MaxToken$, with the algorithm without $Limit$ and 25% of $MaxToken$. In this way, we find in cell 1 that using the restriction reduces the congestion probability from 11.2% to 10.7%, and from 11.12% to 10.6% in cell 2.

Likewise, the use of RBs in Fig. 5-16 is improved, where using $Limit$ and $0.25 * MaxToken$, a decrease of 48.61 to 48.5 is achieved in the occupancy of RBs in cell 1, and from 48.62 to 48.5 in cell 2.

A lower congestion probability and less occupation of RBs is beneficial for operators, not directly as throughput, but in the quality of service delivered to all sessions attended.

6. Budget

In this section, we present the costs associated with the development of a research project on a new AC algorithm.

A single person, with a degree in telecommunications engineering, has executed the project. The approximate value of cost per labor [€/h] is assigned, equivalent to the expenses of a junior engineer, and the time of dedication for implementing the project, considering all the stages, as well as planning, research, implementation, simulations, and conclusion of the project. Table 6-1 summarizes the obtained costs:

Personnel	Salary [€/h]	Task	hours	Total cost
Junior Engineer	10.00 €	Bibliographic study	100	**1,000.00 €**
		Implementation of algorithm	150	**1,500.00 €**
		Simulation	200	**2,000.00 €**
		Memory elaboration	300	**3,000.00 €**
Total			**750**	**7,500.00 €**

Table 6-1: total project costs

The time dedication considers 30 hours of work per week for 25 weeks, which gives us 750 hours of total employment. As a consequence, the total cost for the entire project is a total of 7 500 EUR.

Regarding the costs related to the material used, the use of a MATLAB license, valued at 500 EUR, is considered. However, since we developed the project under the supervision of the university, we used a license provided by the administration, which absorbs these costs.

7. Conclusions and future development

This chapter concludes the presented research work of this thesis. We offer a summary of the investigation, along with some conclusions we arrived after completing the analysis of the results.

We have studied the considerable impact that future networks bring, and how the current telecommunications landscape will change with the implementation of technologies such as 5G, IoT, and M2M. Due to this, it is crucial to implement all the tools that can provide us with the advantages and capabilities of future networks, such as Network Slicing, SDN, and edge computing.

Throughout this work, we have presented a detailed review of future networks, Multi-tenancy, and the operation of the Admission Control under this scenario, with the focus on increasing available capacity for tenants by implementing a policy simpler to use and capable of managing the end-to-end QoS through the network. Consequently, we propose a new Admission Control algorithm based on Tokens, which we design using the traffic policy of Token-bucket as motivation. This mechanism provides the simplicity and fairness of the algorithm. To this end, the algorithm relies on two control conditions: the global contracted capacity condition, and the capacity check at the cell-level. On the first check, the algorithm ensures that the requests met the SLA agreements fairly. The latter check guarantees that the cell has sufficient capacity to accept incoming connection requests.

The motivation for this work was to find an enhanced scheme capable of increase the usage ratio of physical resources, which should lead to a higher capacity for tenants. After designing the proper algorithm, we performed a simulation-based analysis to evaluate the performance of our scheme under a multi-tenant, multi-cell NG-RAN for future networks. The assessment focused on analyzing the bit rate increase for each tenant and examinating the flexibility of the algorithm under different traffic distributions. Simulation results show that our proposal can obtain a bit rate of 67 Mb/s, which translates into a bit rate increase of 127% concerning the “NoDelta” scenario, and a bit rate increase of 17%, when comparing the achieved 44.2 Mb/s, vs. the 37.7 Mb/s obtained with the “Delta_C” reference.

The algorithm proves its flexibility by reducing the blocking probability, and our proposal obtains substantial reductions from the “NoDelta” benchmark. Still, it also makes significant reductions when comparing to the “Delta_C” reference, decreasing from 42% to 10.5% when the distribution of traffic is homogeneous, and from 22% to 3% when the load is uneven at each cell.

Throughout all the simulations performed, we have been able to evaluate the behavior of the multiple tenants by sharing the same NG-RAN and how they respond to different traffic loads. Since the *Tokens(s)* term provides its flexibility to the algorithm, we focus on analyzing its dynamic evolution throughout all simulations.

We notice that when the offered load of the entire cell is low, tenants do not use tokens. As the total cell load increases, the tenant that receives the highest traffic load is the one that makes more connection requests, so it is usually the tenant with the lowest traffic that finds less available resources in the cell. Therefore it has to increase its token account more. We establish this behavior as selfish: the one who receives the most traffic uses the most resources. However, we find that the overall benefit is more significant, since it optimizes the re-use of resources, and increases the available capacities of all tenants.

Thanks to the results graphics, we can determine how to properly configure the parameters of the algorithm $MaxToken$ and $Reserve$, which play an essential role in helping to manage the behavior of the cells, controlling the congestion probability and occupancy of RBs when they approach the limit. $MaxToken$ serves as a limit value that protects the network. When its value is very high, the $Reserve$ restriction is not activated, since $MaxToken$ allows the system debt to be high. Nevertheless, once correctly configured, $Reserve$ will be enabled to manage the resources available to other tenants. Thereby, it benefits the network operation, avoiding saturation of the cells or degradation in the QoS of the involved.

The focus of this work has been to optimize the usage of radio resources. However, the requirements of 5G services also require other resources, such as computational, storage, and networking elements. Based on these needs, future research possibilities emerge to satisfy future services completely. As future work, the optimization of the AC function must be studied along with the optimization of the packet scheduling function, with a higher focus on its operation under the whole multi-cell RAN scenario.

Finally, in the results, we have seen the importance of $MaxToken$ and $Reserve$ when controlling cell performance when the traffic load levels are high. These values must be analyzed together with the blocking probability of tenants, trying to find a trade-off between cell performance and offered capacity to operators. One possible improvement could be introducing an adaptive $MaxToken$ value.

Bibliography

[1] GSMA. “Charting the Course to 5G.” 2019 [Online]. Retrieved May 29, 2019, from https://www.gsma.com/futurenetworks/technology/understanding-5g/5g-innovation/

[2] GSM Alliance. (2017). An Introduction to Network Slicing. White Paper.

[3] Kwan, R., Arnott, R., & Kubota, M. “On radio admission control for LTE systems.” *In IEEE Vehicular Technology Conference,* (1), 1–5. https://doi.org/10.1109/VETECF.2010.5594566

[4] Pérez-Romero, J., Sallent, O., Ferrús, R., & Agustí, R. “Admission Control for multitenant radio access networks.” *In* IEEE International Conference on Communications Workshops (ICC Workshops), Paris, 2017, pp. 1073-1078. Doi: 10.1109/ICCW.2017.7962801

[5] Khan, N. K., & Hamdan, A. A. “ITU-T Future Networks : A Step towards Green Computing.” *In Proceedings of the World Congress on Engineering and Computer Science 2014 Vol. I.* WCECS 2014, 22-24 October 2014, San Francisco, USA.

[6] ITU-T. “Focus Group on Future Networks (FG FN),” 2019 [Online]. Retrieved June 10, 2019, from https://www.itu.int/en/ITU-T/focusgroups/fn/Pages/Default.aspx

[7] Editors. “Draft Deliverable on “Future Networks: Design Goals and Promising Technologies” Focus Group on Future Networks - FG-FN OD-72 Rev.1, December 2010.

[8] GSMA. “Future Networks,” 2019 [Online]. Retrieved May 29, 2019, from https://www.gsma.com/futurenetworks/

[9] GSMA. “Engage with Future Networks,” 2019 [Online]. Retrieved May 29, 2019, from https://www.gsma.com/futurenetworks/about-us/

[10] GSMA. “Technology”, 2019 [Online]. Retrieved May 29, 2019, from https://www.gsma.com/futurenetworks/technology/

[11] GSMA. “RCS Business Messaging,” 2019 [Online]. Retrieved May 30, 2019, from https://www.gsma.com/futurenetworks/technology/enriched-calling-with-rcs/

[12] GSMA. “RCS Market”, 2019 [Online]. Retrieved May 30, 2019, from https://www.gsma.com/futurenetworks/rcs/rcs-market/

[13] J M Meredith. “NR: 3GPP’s 5G radio access technology”. *3GPP presentation*, April 2018.

[14] *3GPP TR 29.915 v1.1.0 “Release 15 Description; Summary of Rel-15 Work Items (Release 15)”,* March 2019

[15] E Borcoci. “End-to-end, multi-domain and multi-tenant aspects in 5G network slicing”. *Presentation. University Politehnica Bucharest. Softnet 2018 Conference*, October 14 - 18, Nice.

[16] Dahlman, E., & Parkvall, S. "NR - The new 5G radio-access technology*". IEEE Vehicular Technology Conference,* 2018-June, 1–6. https://doi.org/10.1109/VTCSpring.2018.8417851

[17] *NR; NR and NG-RAN Overall Description; Stage 2* (Release 15). 3GPP TS 38.300 V15.5.0, March 2019.

[18] 5G Americas. “5G Network transformation”. December 2017.

[19] *Service Aspects and Requirements for Network Sharing, Rel.10*. 3GPP TR 22.951 May 2011.

[20] *Network Sharing; Architecture and Functional Description, Rel. 12*. 3GPP TS 23.251, March 2015.

[21] *Study on RAN Sharing Enhancements, Rel.13*. 3GPP TR 22.852, September 2014.

[22] Afolabi, I., Taleb, T., Samdanis, K., Ksentini, A., & Flinck, H. “Network slicing and softwarization: A survey on principles, enabling technologies, and solutions.” *IEEE Communications Surveys and Tutorials*, 20(3), 2429–2453, March 2018. https://doi.org/10.1109/COMST.2018.2815638

[23] 5G-PPP Architecture Working Group. “5G-PPP White Paper on 5G Architecture”. December 2017, 140. https://doi.org/10.13140/RG.2.1.3815.7049

[24] GSMA. “Network Slicing.” 2019 [Online]. Retrieved May 29, 2019, from understanding-5g/network-slicing/. Website: https://www.gsma.com/futurenetworks/technology/understanding-5g/network-slicing/

[25] Han, B., Sciancalepore, V., Feng, D., Costa-Perez, X., & Schotten, H. D. “A Utility-Driven Multi-Queue Admission Control Solution for Network Slicing.” (January 2019). Retrieved from http://arxiv.org/abs/1901.06399

[26] Han, B., Dedomenico, A., Dandachi, G., Drosou, A., Tzovaras, D., Querio, R., Schotten, H. D. “Admission and Congestion Control for 5G Network Slicing”. *In 2018 IEEE Conference on Standards for Communications and Networking*, CSCN 2018. https://doi.org/10.1109/CSCN.2018.8581773.

[27] Qian, M., Huang, Y., Shi, J., Yuan, Y., Dutkiewicz, E. “A novel radio Admission Control scheme for multiclass services in LTE systems.” *In GLOBECOM - IEEE Global Telecommunications Conference, 2.*

[28] Elayoubi, S. E., Jemaa, S. Ben, Altman, Z., & Galindo-Serrano, A. “5G RAN Slicing for verticals: Enablers and challenges”. *IEEE Communications Magazine*, 57(1), 28–34, 2019. https://doi.org/10.1109/MCOM.2018.1701319.

[29] T. Guo, R. Arnott. "Active LTE RAN Sharing with Partial Resource Reservation." *IEEE VTC Fall, Las Vegas,* Sep. 2013. https://doi.org/10.1109/VTCFall.2013.6692075

[30] Holma, H., Toskala, A. *WCDMA for UMTS – HSPA evolution and LTE*, 4th ed. West Sussex, England: John Wiley & Sons, 2007.

[31] *3GPP TS 36.300 v13.2.0 "E-UTRA and E-UTRAN Overall description;* Stage 2 (Release 13)", December 2015

[32] Gutierrez-Estevez, D. M., Bulakci, O., Ericson, M., Prasad, A., Pateromichelakis, E., Belschner, J., Calochira, G. "RAN enablers for 5G Radio Resource Management". *IEEE Conference on Standards for Communications and Networking*, CSCN 2017, 1–6. https://doi.org/10.1109/CSCN.2017.8088589

[33] *An Architecture for Differentiated Services.* IETF RFC 2475, December 1998.

[34] Jha, S., & Hassan, M. *Engineering Internet QoS.* Massachusetts, USA: Artech House, inc, 2002.

.

Glossary

A list of all acronyms and what they stand for.

3GPP 3rd Generation Partnership Project

5G 5th Generation wireless systems

5GC 5th Generation Core Network

AC Admission Control

AMF Access and Mobility Function

CBR Constant Bit Rate

CoMP Coordinated Multipoint Connectivity

DC Dual Connectivity

DiffServ Differentiated services

eMBB Enhanced Mobile Broadband

EPC Evolved Packet Core

E-RAB evolved-Radio Access Bearer

FG Focus Group

FN Future Network

FR1 Frequency Range 1

FR2 Frequency Range 2

GSM Global System for Mobile Communications

GSMA the GSM Association

GST Generic Slice Template

IntServ Integrated services

ITU International Telecommunications Union

ITU-T ITU Telecommunication Standardization Sector

KPI Key Performance Indicator

LTE Long Term Evolution; the 4th generation wireless system

SG Study Group

SLA Service Level Agreement

SlaaS Slice as a Service

MANO Management & Orchestration

MIMO Multiple Input Multiple Output

MME Mobility Management Entity

mMTC Massive Machine-Type Communications

MNO Mobile Network Operator

MOP Master Operator

MOP-NM MOP-Network Manager

ng-eNB Next-Generation Enhanced 4G base station.

NFV Network Function Virtualization

NFVI Network Function Virtualization Infrastructure

NFVO Network Function Virtualization Orchestrator

NG-RAN Next Generation Radio Access Network

NSA Non-Stand-Alone

NSB Network Slice Broker

NSI Network Slice Instance

NVS Network Virtualization Substrate

OFDM Orthogonal Frequency-Division Multiplexing

PLMN Public Land Mobile Network

POP Participating Operators

POP-NM POP-Network Manager

QoS Quality of Service

RAB Radio Access Bearer

RAN Radio access network

RB Resource Block

RBG Resource Block Group

RCS Rich communication services

RMSC Multitenant cell Slicing Controller

RRM Radio Resource Management

SA Stand-Alone

SAGBR Scenario Aggregated Guaranteed Bit Rate

SDN Software Defined Networking

SD-RAN Software-Defined RAN

SMF Session Management Function

TTI Transmission Time Interval

UE User Equipment

UMTS Universal Mobile Telecommunications System

UPF User Plane Function

URLLC Ultra-reliable Low-latency Communications

VBR Variable Bit Rate

VIM Virtualized Infrastructure Manager

VM Virtual Machine

VMM Virtual Machine Monitor

VNF Virtual Network Function

VNFM Virtual Network Function Manager

$\mathbf{X_n}$ Network Interface between NG-RAN nodes