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Master‘s Thesis

Implementation of interference coordination techniques within a dynamic functional split adaptation

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With my signature below, I assert that the work in this thesis has been composed by myself independently and no source materials or aids other than those mentioned in the thesis have been used.

München, 25.03.2022	
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Quiero dedicarle esta tesis a mis padres por haberme permitido llegar hasta donde me he propuesto, y apoyarme en las decisiones que he ido tomando.

También a mi familia, sin la que no sería la persona que soy hoy.

To my friends which I have met during this exchange, we chose to come here and life chose to cross our paths. And to my then colleges, now friends, knowing you doing this Master has been a gift.

To my longlife friends, your support and friendship during these years helped me to get here.

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Kurzfassung

Die fünfte Generation von Mobilfunknetzen hat mehrere wichtige Parameter von Interesse, darunter hoher Durchsatz, niedrige Latenzzeiten und eine große Anzahl gleichzeitig angeschlossener Geräte. Diese KPIs erfordern einen neuen Ansatz, und die 3GPP-Spezifikationen enthalten einige Lösungen. Eine der Lösungen, die der 3GPP-Standard für 5G anbietet, ist eine funktionale Split-Anpassung. Diese optimiert die Leistung, während mehrere Verarbeitungseinheiten vorhanden sind. Sie unterteilt die Basisstationen in zwei Verarbeitungseinheiten: die Distributed Unit (DU) und die Centralized Unit (CU). DUs befinden sich in der Nähe einer Basisstation und haben weniger Verarbeitungsleistung als eine CU, die weiter von der Basisstation entfernt ist. Auf DUs und CUs laufen Netzwerkfunktionen (NF) wie Medium Access Network (MAC), Radio Resource Control (RRC) und andere. Es gibt drei verschiedene Szenarien: Alle NFs laufen auf den CUs, was den Vorteil hat, dass die Kosten für die Bereitstellung von 5G-Netzen gesenkt werden, aber ein Fronthaul-Netzwerk mit hoher Kapazität und geringer Latenz zwischen der CU und den entfernten Standorten erfordert. Die zweite Variante, bei der alle Funktionen in den DUs ausgeführt werden, bietet u. a. eine bessere Skalierbarkeit und eine bessere Anpassung an die Nutzerdichte, hat aber eine geringere Leistung, da sich diese nicht an momentane Interferenzsituationen anpassen kann. Die dritte Variante ist eine Mischung aus den beiden vorgenannten, wobei einige Funktionen in der CU und andere in den DUs ausgeführt werden. Dadurch können verschiedenen DUs koordiniert werden, was zu einer besseren Leistungsoptimierung führt, selbst wenn nur ein begrenztes Fronthaul-Netz verwendet wird.

Die im letzten Szenario verfügbare Koordinierung wird genutzt, um verschiedene Probleme zu lösen, die auftreten können (z. B. Interferenzen). Um die KPIs von 5G zu erreichen und die Vorteile eines flexiblen, geteilten Netzwerks zu nutzen, kann eine Bereitstellung mit hoher Dichte erfolgen, bei der mehrere DUs von einer CU gesteuert werden. Da die Anzahl der Einheiten groß ist, kann es zu Interkanalinterferenzen kommen. Diese Art von Interferenz führt zu einer drastischen Verringerung des Durchsatzes und der Konnektivität des Systems, was sich direkt auf die Vorteile der Funktionsaufteilung auswirkt. Da das System seine NF in beiden Einheiten hat, kann die MAC-Funktion in der CU angesiedelt sein und eine Koordinierung durch alle DUs ermöglichen. Diese Koordinierung kann genutzt werden, um Interferenzen zwischen den Kanälen abzuschwächen, da der von der MAC-Funktion verwaltete Planer an die jeweilige Situation angepasst werden kann. Eine der Änderungen, die auf diesen Scheduler angewandt werden kann, ist die Änderung der Anzahl der verfügbaren Ressourcenblöcke (RB) in Abhängigkeit von der überlappenden Bandbreite. Das Ziel dieser Arbeit ist die Erforschung einer Koordinierung mehrerer DUs durch die CU, wobei vor jeder Ressourcenzuweisung dynamische Änderungen am Scheduler vorgenommen werden, um die Interkanalinterferenzen zu reduzieren, die bei einem Einsatz mit hoher Dichte auftreten.

Abstract

The Fifth Generation of mobile communication networks has several Key Parameter of Interests (KPIs) including high throughput, low latency, and a high number of simultaneously connected devices. These KPIs require a new approach, and 3GPP specifications include some solutions. One of the solutions that the 3GPP standard for 5G describes is a functional split adaptation. The functional split adaptation optimize the performance while having several processing units. It divides the base stations into two processing units: the Distributed Unit (DU) and the Centralized Unit (CU). DUs are located near to a base station and has less processing power as a CU, which is located further from the base station. On DUs and CUs, network functions (NF) like Medium Access Network (MAC), Radio Resource Control (RRC) and others are running. There are three different scenarios: all NFs running on CUs which has the advantage of reducing the costs of deploying 5G networks but requires a high capacity and low latency Fronthaul network between the CU and remote locations. The second is running all of the functions at the DUs, having a better scalability, adaptation to user density, among others, but it will have a poor performance as it fails to adapt to instantaneous interference situations. The third is a mixture of the previous, running some functions on into the CU, and some other into the DUs. This will need also a capable Fronthaul network, but it will take the advantages of both scenarios. As some functions are on the CU, it can coordinate the different DUs associated, leading to better performance optimization even using a limited Fronthaul network.

This coordination available at the last scenario is used to solve different issues that might appear like interference. In order to accomplish the KPIs of 5G, and using the advantages of a flexible split network, a high-density deployment can be deployed with multiple DUs controlled by a CU. As the number of units is great, it may lead to Inter-Channel Interference. This kind of interference will drastically reduce the throughput and connectivity of the system, affecting directly into the benefits of the functional split. As the system has its NF in both units, the MAC function can be at the CU providing a coordination of it through all the DUs. This coordination can be exploited to mitigate Inter-Channel interference, as the scheduler which is managed by the MAC function can be adapted according to the situation. One of the modifications that can be applied to this scheduler is changing the number of available Resource Blocks (RB) depending on the overlapping bandwidth. Therefor, the goal of this thesis is to research into a coordination by the CU of multiple DUs, applying dynamical modifications to the scheduler before each resource allocation to mitigate the Inter-Channel interference that appear on a high-density deployment.

Contents

Chapter 1

Introduction

Communication networks have been in continuous development since their early stages. We can define it as the evolution of their technical capabilities, architectures and services provided to the user. In this decade, we are facing the evolution of the 5th generation of wireless communication network, called New Radio (5G NR). This generation appears after a wide deployment of the previous generation, Long-Term Evolution (LTE), providing mobile broadband data services.

After the development of high-performance data rates and high-quality voice services over LTE, the new generation is being developed with the idea of increase the quality of those services as is the primary application, but also providing services to new applications of the Internet of Things (IoT), as well as being ready for the Fourth Industrial Revolution.

The International Telecommunication Union has defined multiple new scenarios and usage for 5G NR. These are enhanced Mobile Broadband (eMBB), Ultra-Reliable Low-Latency Communications (URLLC), and massive Machine-Type Communications (mMTC). This new generation will use advanced technologies to produce better data speeds, lower latency, increased capacity, and more efficient spectrum utilization.

The foundation of the next generation of radio access networks is about decoupling and centralization of radio functions between two split units: Centralized Unit (CU) and Distributed Unit (DU). The functions that reside in each of the units could be dynamically assigned to be more flexible depending on the requirements of the users or the network at a time. The DUs can be deployed nearby the base station, where the CU that controls them relies..

While there is a higher number of DU in a deployment area, the frequency that are used by each base station may interfere with a neighbor one. This is the interference known as Inter-cell interference. There has been proposed several methods to mitigate them like Inter-cell Interference Coordination, but there is not any approach with a dynamic functional split.

In this thesis, the advantages of switching different network functions between the different units in order to coordinate the mitigation of those interference are analyzed. When the MAC layer functions relay at the Centralized Unit, it also has the scheduler capabilities of the transmission system. It coordinates between the units that are sharing the frequency, giving the permission to transmit at the interfered spectrum to one of the units.

As the instances of the Centralized Unit can be connected through an interface, the different instances of the Centralized Unit can agree who can transmit prior any transmission and allocation of resources. Also the information regarding the frequencies can be sent from the Distributed Unit to the Centralized Unit instances, and then calculate which part of the spectrum is overlapping and how the scheduler should be modified to avoid transmitting at the same frequency at the same time.

This Master's Thesis is composed by the following chapters. An introduction of the fifth generation of cellular system is done at Chapter 2, including a description of the Radio Access Network (RAN) and softwarized RAN implementations. Also, it includes, an explanation of the different functional splits and the ones that are used in this thesis. Furthermore, it includes a brief introduction on the different type of interference that can appear at cellular systems, and some coordination and mitigation techniques. Finally this Chapter is ended with the Problem Statement. The third Chapter includes theoretical concepts regarding the resource coordination and enhancing them by using a dynamic functional split adaptation. In Chapter 4, the theoretical concepts described in the prior Chapter are implemented. It includes a explanation of the composition of the testbench system, in order to have a better overview of the whole implementation. It has been included the prior state of the testbench, and the modifications and implementation that have been applied to the testbench. This Chapter includes a detailed explanation of the different APIs that have been created or modified and the modifications of the scheduler. Finally, in Chapter 5 the results of the system are presented showing the improvement that can be achieved with frequency coordination techniques in comparison to when there is no coordination. The last Chapter includes the conclusion of this Master's Thesis and the future work.

Chapter 2

Background

In this Chapter, a resume of the current state-of-the-art is given. Firstly with a brief introduction of 5G, including the Core Network and Radio Access Network (RAN), which will give a better comprehension of the whole system. Secondly, this chapter includes an explanation about open-source solutions for 5G networks, which are used in the implementation and development of this thesis. And finally, the Flexible Functional Split Network concept and the problem statement are explained as both are essential parts of this thesis.

2.1 Fifth generation of mobile networks

The fifth generation of mobile communications get all the knowledge and improvements of previous generations and try to fix some problems that have been occurring after the deployment of them.

This new generation promises to deliver an improved end-user experience and enable new services, new ecosystems, and new revenues. 5G is expected to provide substantially better data rates, lower latency, more capacity, and more efficient spectrum utilization than previous generations. With these more advanced capabilities, 5G will be able to handle a wide range of situations and applications.

The new use cases defined by ITU-R are the following:

- eMBB is the evolution of the mobile broadband data services that started with the third generation. This is the primary application of mobile communications systems. This generation provides a high data rate and supports large traffic volumes.
- URLLC corresponds to services that require ultra-high reliability and low latency. This will be a key factor for traffic safety and control in intelligent transport systems. Also, it will be an important factor when talking about the control of industrial manufacturing and production processes.

- mMTC is the management of a massive number of devices connected to the network. It is expected to be used by IoT services which applications include smart cities, smart home, remote monitoring. The key requirements are low device complexity, long battery lifetime and significant coverage extension. These services don't require high data rates nor low latency.

2.1.1 5G System

The 5G System is composed by the 5G Core Network (5GC), the New Generation Radio Access Network (NG-RAN) and the User Equipment (UE), as it can be seen at Figure 2.1.

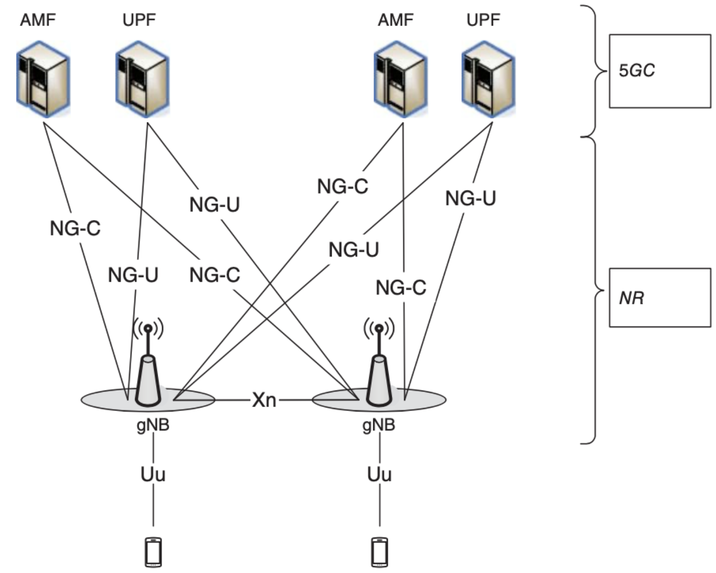


Figure 2.1: 5G Core Network and NR-RAN including interfaces. The composition of the system is explained at Section 2.2 and Subsection 2.1.2. [3GP21]

The main characteristics of the 5G System are the following:

Compared to 4G, this generation will increase by 10 times the data rates, expecting to offer a 20 Gbps peak in downlink and a 10 Gbps peak data rate in uplink. Urban environment can support up to 100 Mbps in downlink and 50 Mbps in uplink [LL21].

Its spectral efficiency is going to be increased, even supporting different user spectral efficiencies depending on the variety of the environments. The spectral efficiency will be improved around 3 times compared to 4G [LL21].

New Radio is expected to offer 1ms of user plane latency, reducing 4G's latency by 10 times. Also it greatly improves reliability performance, even in urban macro environments [LL21].

The improvements at the network will add significantly improved mobility performance, with 0-ms mobility interruption time, and QoS with speed of the UE in movement up to 500 km/h. 5G will be able to manage a connection density of 1 million devices per square kilometer [LL21].

As this master thesis is part of the 5G Radio Access Network, it will be described more in detail in the next subchapter. In this subchapter, we will explain the basics of the 5G Core Network to have a better understanding of the 5G system.

2.1.2 5G Core Network

The 5GC is composed of two main elements , the Access and Mobility Management Function (AMF) which receives all information of connection and session that is related to the User Equipment (UE) and handles connection and mobility tasks. And the User Plane Function (UPF), responsible for forwarding and packet routing, inspection, QoS management, and external PDU session for interconnecting Data Network.

Some tasks that 5GC include are, like among other previous generations of 3GPP systems, storing information of subscribers, perform authentication, registration of UEs and tracking its location, establishing data sessions to different networks as requested by UEs, providing QoS, and performing lawful interception [Sir20]. But apart of the tasks that shares with previous generations of communication networks, this system also defines new or updated paradigms.

In contrast, with the Evolved Packet Core (EPC), core network of the 4G System, 5GC is a Service-based architecture (SBA) [Sir20]. The procedures are defined based on generic services that are exposed by network functions. As they are generic, they can be reused by different systems and accessed by different functions. It simplifies the standardization of system features and reduces the implementation effort. Also, the network function services are defined as APIs.

There is a separation between the Control and User plane (CUPS) [Sir20]. The User Plane carries the network traffic in packets, and the Control Plane handles the signalling messages exchanged between the base station and the UE. This separation allows for independent scaling and evolution of the functions in both planes, as well as deployment leading into closer user plane functionalities to the access network while the control network could be kept centralized. This was included in the late stages of the development of 4G LTE, but it was considered at the architecture design phase of 5G.

The Core Network is a common access agnostic network that uses the same architecture and interface between the access network and the core network for 3GPP accesses and non-3GPP accesses [Sir20]. A common non-access stratum protocol is used regardless of the access technology.

Low latency is one of the key features of 5G. Some examples of application of this KPI can be the application in some industries replacing their wired networks into a wireless network [Sir20], or it could be used for communicate vehicles and sensors, or at Telehealth connecting the equipment to a 5G network. Traditional cellular networks are based on a distributed radio network and a centralized core network. In this generation private networks deployments are enabled so parts or even the whole network could be deployed on-site.

As previous generations also included the concept of network slicing, this concept was centered on increasing the degree of flexibility for selecting core network functions and network configurations. With 5G systems, the network slicing concept has incrementally extended the concepts introduced in early 3GPP generations [Sir20, LL21]. Some of the new concepts are an increment of deployment flexibility and isolation for session-related network function, extension of the slicing into the Radio Access Networks and provision of new UE policies, so the operator can choose the network slice depending on the applications running on the UE. The network slicing will deploy multiple independent and isolated Core Network functions at the same network, including multiple configurations and the dynamic implementation and configuration of the slicing of functions.

As it can be seen in Figure 2.1, a schematic of the 5G System including the NR and 5GC, their main components and the interfaces that connect between the NG-RAN and 5GC, and at the NR is shown.

2.2 5G's Radio Access Network

As shown in the previous Subchapter, 5G systems are composed of the Core Network and the Radio Access Network (RAN). RAN implements the Radio Access Technology, which is the physical connection method of a wireless communication network, and thus, connects parts of the network (i.e. User Equipment) with other devices through a radio link. The RAN has evolved since the first generation of cellular networks, especially during LTE. The 5G's RAN has more similarities with LTE's RAN than with previous networks, there are some changes at the interfaces and some elements, some of which will be explained in the following subchapters. The components of this generation's RAN are the following, as they can be seen in Figure 2.1:

- gNB (next-generation NodeB): It is the base station of the NR-NSA and NR-SA networks. It includes the physical radio capabilities including antennas and radio equipment to be able to transmit the signal to the UEs. It can work with multiple MIMO options, and its range of frequencies works at the sub-6GHz bands and Millimeter Wave (mmWave) bands.
- UE (User Equipment): It is any device used by the end-user to communicate which is connected to the base station to establish the communication.

And the interfaces that connect the different components of the network among them, and with the Core Network are the following:

- NG-C: It is the interface that connects the gNB with the AMF unit of the Core Network. The control plane is used to conFigure and manage the radio interface connection.
- NG-U: This interface connects the gNB with the UPF unit of the Core Network. This interface takes care of the transmission of the IP packets of the user plane. The primary role of the user plane is to transfer data across the radio interface efficiently and with the required QoS.
- Xn: Interface that connects multiple gNB between them. It is used for UE mobility control, UE data forwarding for lossless mobility, Resource coordination, Network energy-saving, Dual and multi-connectivity.
- Uu: This is the last interface that is used between the gNB giving connection to the UE as an air interface.

With the knowledge of 5G elements, now the description of the transmission structure is detailed. As it was briefly described at the gNB definition, this is the first generation that supports millimeter wave bands. The range of 5G NR goes from sub-1 GHz up to millimeter wave band [LL21]. Using this broad spectrum enables to deliver of multiple gigabit-per-second data rates and mitigate the spectrum crunch in sub-6 GHz. With inter-networking between high and low bands, 5G can be used to provide a higher throughput through its higher bands, or better coverage with the lower bands.

Regarding the multiplexing capabilities of 5G, New Radio includes the support of different flexible duplex options like Frequency Division Duplex (FDD), Time Division Duplex(TDD) with semi-statically conFigured UL/DL configuration and dynamic TDD. Again, the duplex option depends on the requirements and use of different bands. For example, FDD is often used in low-frequency bands, where the spectra allocations are often paired; TDD is more common in higher-frequency bands with unpaired spectra; semi-static TDD is used for over-the-rooftop cells handling Inter-Cell interference issues; dynamic TDD allocates dynamically radio resources depending on UL/DL traffic, which is new compared to LTE [Sir20].

Throughout this chapter, multiple comparisons will be made between NR and LTE. In LTE, multiple functions are always-on, like the cell-specific reference signals (CRS). CRS are used for cell search and initial acquisition, Downlink channel quality measurements and Downlink channel estimation for coherent demodulation/detection at the UE. This scenario was rethought at NR where the reference signals are on by demand. This is called ultra-lean design and is laid into a higher network energy efficiency and lower interference [LL21].

As low latency is one of the main requirements and characteristics of this generation, the radio access network must consider it. It supports mini-slot transmission which means that the transmission can start at any Orthogonal Frequency Division Multiplexing (OFDM) symbol, and its length is as much as needed for it [Sir20]. The decoding delay is managed with some frontloaded reference and control signals that are located at the beginning of the transmission which makes the processing of the data earlier without buffering it.

New Radio was designed with forward compatibility and backwards coexistence. Its design helps to introduce of new technologies and applications, as resources can be left empty for future usage. In addition, as signals and channels can be packed in scheduled radio resources, it is highly forward and backwards compatible due to its flexible design. Second, NR at its initial deployments includes an option called non-standalone (NSA), where NR uses the LTE network for control plane functions. Also, NR supports the overlapping of the NR carrier with the LTE carrier, sharing its spectrum.

New Generation Radio Access Network (NG-RAN) provides NR and Evolved Universal Mobile Telecommunications System (UMTS) Terrestrial Radio Access (E-UTRA) radio access. The NG-RAN node is a logical mode that is characterized by a set of logical functions and interfaces towards other logical nodes. Both are linked, so if one is changed, the other has to be changed. Logical interfaces are defined starting at the physical layer, transport requirements and protocols for Control and User Planes. The design of the RAN allows different deployments like co-located, virtualized, centralized, etc.

The NG-RAN node can be a gNB providing NR access which is commonly known as a 5G Base Station, or an new generation-evolved NodeB (ng-eNB) providing E-UTRA access, which is an enhanced 4G Base Station. Then, the NG-RAN is connected to the 5G Core Network through the NG interface, and between the gNB/ng-eNB through the Xn interface [LL21].

As explained before, there are two different modes of operation at New Generation: non-standalone (NSA) and standalone (SA) [LL21, Sir20]. In NSA, gNB and ng-eNB interoperate between each other and are connected to the same core network. This core network could be the EPC, which would be “NSA within 4G RAN”, or to 5GC which will be “NSA withing NG-RAN”. With NSA, a higher bit rate can be provided to the UE due to the Dual Connectivity. On the other hand, in SA the gNB is connected to the 5GC, where both RAN and Core Network are part of 5G.

Dual Connectivity is a technique via which an UE with multiple reception and transmission capabilities is conFigured to utilize resources offered by two separate nodes. One would be the Master Node and the other is the Secondary Node. Both are connected through the network interface, and at least the Master Node should be connected to the core network.

Some enhancements have been done at NG-RAN compared with E-UTRAN: This new RAN supports two air interfaces, as it was introduced previously supporting both NR and LTE air interfaces where both gNB and ng-eNB are considered NG-RAN nodes [LL21].

Dual Connectivity allows slicing, enabling operators to offer different Services Level Agreements (SLA) [Sir20]. The previous subchapter introduced the concept of network slicing at the Core Network which RAN slicing could not be possible without both parts. In this generation, the slicing concept was in mind since the beginning of its development.

This generation adds the Integrated Access and Backhaul functionality, supporting multi-hop backhauling with topology adaptation and redundant links for better performance, which will give better failure avoidance [Sir20]. As it has Integracted Access, there is also support non-terrestrial networks like satellite connections included [Sir20].

Even the specification of 3GPP does not include virtualization, it has been in mind since the early stages of this generation. Some provisions have been done to allow deployment in virtualized environments.

But the more important part, as this thesis is based on it, is the split architecture. NG-RAN supports an architecture with a two-split gNB, referred to as the CU and DU logical nodes [Sir20, LL21, AVK19]. Both are connected through the F1 interface which supports control plane and user plane separation, it separates Radio Network Layer and Transport Network Layer and enables exchange of UE associated information and non-UE associated information. The Central Unit can be deployed as separate control and user plane logical network nodes. And the low-level split, which is the CU when it has all the network functions, can be split into two network nodes splitting the network functions between them. Also, thanks to virtualization, the CU hosting the high-level protocols can be virtualized, and the separation of both planes in NG-RAN and Core Network make it well suited to be used with software define networks (SDN).

The air interface protocol stack of NR consists of a user-plane that handles the transfer of data across the radio interface taking care of the QoS, and a control-plane that handles the configuration of the radio interface connection.

The user-plane protocol stack consists of SDAP, PDCP, RLC and MAC layers, as seen in Figure 2.2 [LL21]:

- SDAP (Service Data Adaption Protocol) is a new protocol introduces in NR. It maps a packet into a Data Radio Bearer (DRB) based on QoS Flow ID (QFI), even the bearers are no longer used in 5GC, the concept of radio bearers is kept in NR.
- PDCP (Packet Data Convergence Protocol) provides encryption, integrity protection and IP header compression capabilities, and it is responsible for reordering.
- RLC (Radio Link Control) provides segmentation and reliability with ARQ functionality.
- MAC (Medium Access Control) multiplex data from different logical channels into a transport block and scheduling.

The control-plane protocol of NR is Radio Resource Control (RRC), which is similar to LTE's [Sir20]. It has several transparent containers that can be used to convey. It supports three different UE states: IDLE, INACTIVE and CONNECTED. INACTIVE state is similar to IDLE, but NG-RAN maintains the UE context and connection to 5GC.

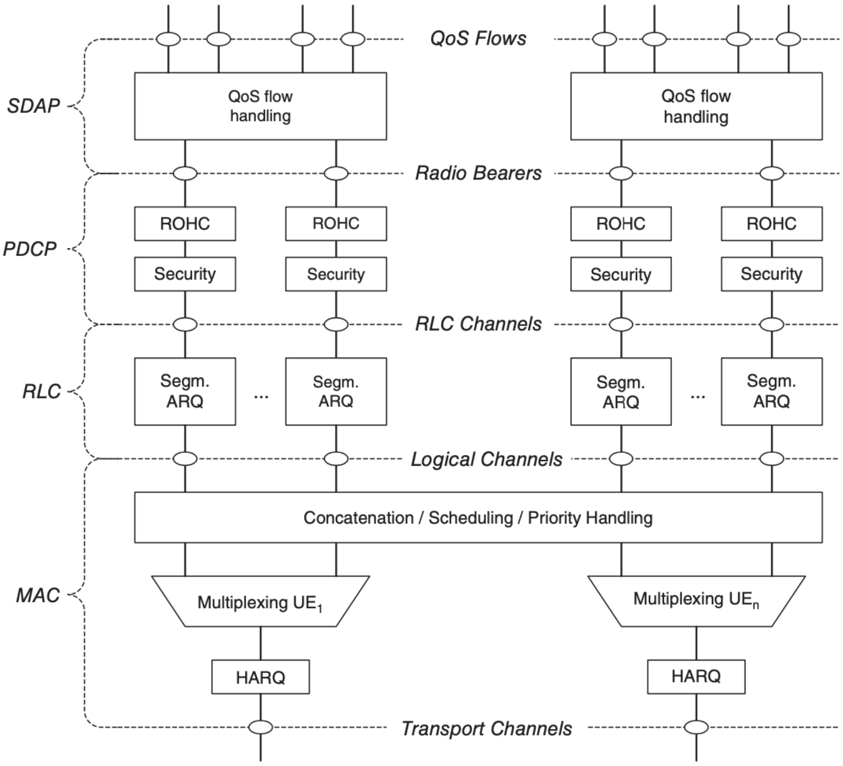


Figure 2.2: Downlink Layer 2 Structure. [3GP21]

The protocol layers of the user plan can be divided if there is a split in the NG-RAN architecture and hosted in different logical network nodes. Also, they can be in a single gNB which hosts all the functionalities.

2.3 Softwarized RAN implementations

The development of Open-Source systems has been very successful in different fields like Linux. The idea of applying the same efforts in telecommunication was thought by different projects that already exist in other fields.

Since the early stages of the wireless communication networks, the RAN development has been included in standards like the 3GPP. The standard is developed first, and then it is implemented later by different vendors who will follow the standard.

This way of implementation ensures interoperability between different vendors, but also it allows vendor-specific enhancements.

On the other hand, an Open-Source implementation is contributed by different members that could be from vendors to academia or volunteers, which will develop source code to a common base, and everybody is able to use it to create products. As these products have been developed based on the common code, they will be interoperable, and it will reduce the costs as it is shared between the community members. This is in line with the intention of operators to reduce the costs of NG-RAN implementation.

Open-Source implementation could be open hardware or software, but in terms of feasibility it is more convenient to use an Open-Source software that can be used by anyone, but what is more important, it can be modified by anyone. By now, most Open-Source projects related to wireless communications are focused on the core network and Operations Administration and Maintenance (OAM). There are not yet any RAN Open-Source implemented, but it could be important in the future.

Open-Source RAN is possible by the implementation of Software Defined Radio (SDR) networks, where everything except the analog radiofrequency elements is implemented in software running on general-purpose hardware. This is because it cannot be entirely implemented by software as it is highly related to a physical mean. Thanks to SDR, which is configurable by software, implementations of Open-Source RAN can be deployed.

Mostly all of these projects are still in development and cannot be used to deploy a commercial 5G network, but they are a good opportunity to develop and research several ideas based on 5G. Some of them are OpenLTE, OpenBTS, Open Air Interface, TIP, O-RAN, or the software used in this Master's Thesis, srsRAN.

2.3.1 srsRAN

srsRAN, formerly known as the srsLTE project, started in early 2014. It was developed as a free Open-Source SDR component library for 4G LTE. Since early 2020, the software was updated to add support to 5G NSA. It is a free open-source software radio suite. It features UE and eNB/gNB applications, which can be connected to a third-party core network and completes an end-to-end mobile wireless network. All software runs in Linux.

The suite includes:

- srsUE: full-stack 4G and 5G NSA UE application. It is a modem implemented entirely in software and connects to any LTE network providing a standard network interface. It requires SDR hardware to provide physical access. The software includes L1, L2 and L3, providing Control and Data functions like PHY in L1; MAC, RLC and PDCP in L2; and NAS and RRC in Control L3 and GW in Data L3.
- srsENB: full-stack 4G eNB and 5G NSA gNB application. It is a base station implemented entirely in software. It connects to any EPC creating a local LTE cell. To transmit and receive via radio signals requires SDR hardware. It includes protocol layers L1, L2 and L3. In L1 it is the PHY layer; L2 includes MAC, RLC and PDCP functions; L3 in Control includes RRC and S1-AP, while in user-plane includes GTP-U.

- srsGNB: full-stack 5G SA gNB application
- srsEPC: lightweight 4G EPC implementation with MME, HSS and S/P-GW.

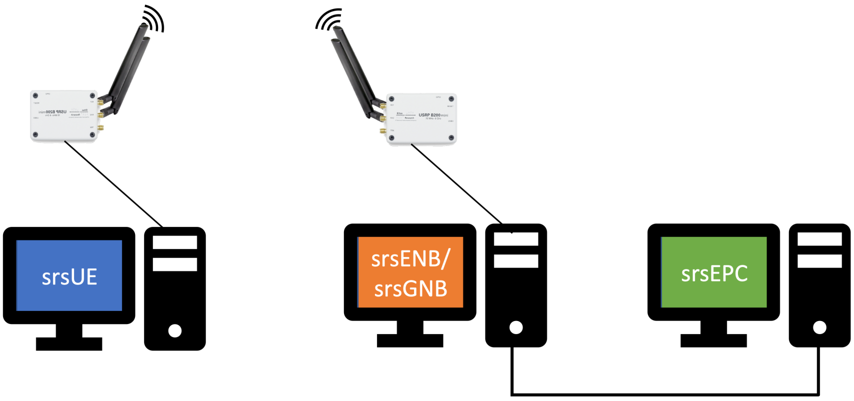


Figure 2.3: Basic srsRAN network including srsUE, srsENB/srsGNB and srsEPC equipments and connections.

Figure 2.3 shows a simple srsRAN network composed by 3 computers executing the srsUE, srsENB/srsGNB and srsEPC instances respectively and independently. The srsENB/srsGNB is connected through the radio interface of the SDR equipment with the srsUE's radio equipment, and each SDR equipment is connected by a USB connection to each computer. The srsEPC is connected through an Ethernet connection with the srsENB/srsGNB acting as a backhaul connection. Tthe equipment representing the srsUE and srsENB/srsGNB can be scaled, and each srsENB/srsGNB will be connected to the Core Network at the srsEPC, through a wired connection.

2.4 Flexible Functional Split Network

As it has been proposed for 5G networks, the processing of all databases is centralized into a data center. This decision reduces the cost of deploying 5G networks and increases the coordination between the gNBs reducing Inter-Cell interference. But also there are some issues regarding this centralization like the requirement of a high capacity and low latency fronthaul network that connects the datacenters and the remote locations.

The use of functional Split in gNB is very practical for more flexible deployment in different scenarios. The split consists of the division between several logical or physical nodes. Before 5G, these split architectures have been proprietary which in some cases would cause the problem that they could not interoperate between different vendors. Since 5G, 3GPP has standardized a different number of split gNB architectures. The different splits can be seen in Figure 2.4. This leads to a more flexible network that frees in part the fronthaul network due to the split of functions between the different units.

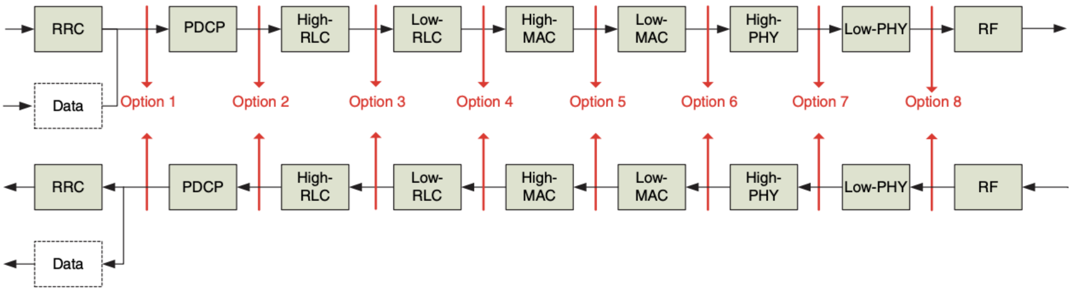


Figure 2.4: Multiple split options that appears in the Specification [3GP17].

The gNB is split between two different logical nodes, the Centralized Unit (CU) and the Distributed Unit (DU). This split has some benefits like more flexibility while implementing the hardware, which is translated into better scalability, better adaptation depending on user density and load demand in a geographical area, better coordination of features and load management which leads to a better performance optimization.

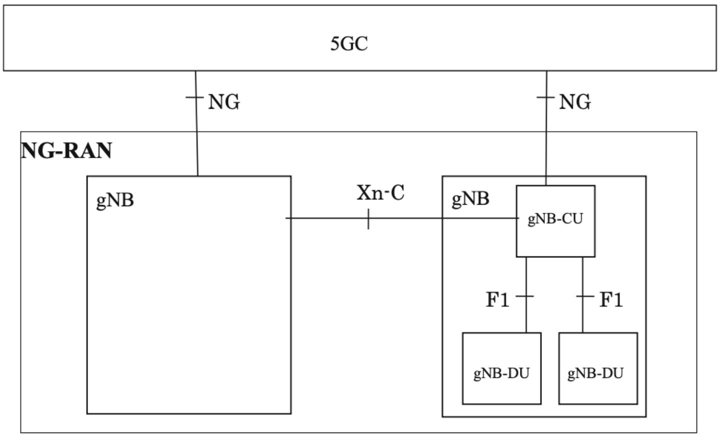


Figure 2.5: Centralized Unit and Distributed Unit split connected to other gNB and 5G Core Network [3GP17].

Both units are connected as it appears at the specification between the F1 interface with control and user plane functions. The gNBs of the 5G Core Network see both, a monolithic gNB and a functional split gNB equally regardless of what is inside, whether it is composed as full gNB or with CU and DU units. The 5GC is connected to the CU through the NG interface, and to the gNB through the Xn interface. This split can be seen in Figure 2.5. Each CU can connect one or more DUs, but a DU connects to only one CU.

Some of the tasks of the CU that are of interest to this thesis, are managing the UE context and requesting the DU to allocate or modify the radio resources that are required for the UE. The CU encodes also all the System Information messages except the SIB1 (System

Information Block 1). The DU is responsible for scheduling and broadcasting. It encodes the MIB (Master Information Block) and the SIB1.

Although there are different splits as shown in Figure 2.4, in this thesis we are focussing on the ones that are used by the testbed, as it is based on the splits that are referred in [AVK19]. Some of the ones proposed by 3GPP are not valid for implementation. Because of the advantages and simplicity, we are focusing on PDCP-RLC and MAC-PHY splits.

2.4.1 PDCP-RLC split

In the PDCP-RLC split, the PDCP function are centralized in the CU, and the other functions (RLC, MAC, PHY and RF) are located at the DU.

This split is considered in Release 15 because it includes some advantages like reducing the operating cost due to the high computational cost that has the ciphering done by the PDCP layer; fronthaul traffic is similar to user traffic due to the adding of a small PDCP header to each IP packets, and it is similar also to the LTE backhaul traffic which enables to reutilization of the backhaul infrastructure.

2.4.2 MAC-PHY split

On the other hand, this split proposal relays into the centralization of the PDCP, RLC and MAC functions into the CU, while keeping the PHY and RF functions in the DU.

This centralization of functions makes the operating costs are smaller than the ones of the PDCP-RLC split, and also it is better to coordination techniques thanks for the centralized MAC layer. Even the functions are centralized, the fronthaul traffic is smaller than the one at Intra-PHY or C-RAN splits.

Although there are some benefits of using this split, there are also some disadvantages like the inclusion of additional headers and controls signals between the MAC and PHY layers. This addition makes the fronthaul capacity and latency higher than in the PDCP-RLC split.

2.5 Interferences and mitigation techniques

2.5.1 Interference in radio frequency systems

Among the various interference that can appear in Radio Frequency communication systems, two different groups can be defined regarding the type of propagation medium: propagation on free spaces or with obstructing paths.

This subchapter will focus on the different types of interference that can occur at radio frequency systems. More specifically a more detailed outlook of interference in cellular communication systems and the most critical interference that can occur in 5G systems will be described.

Interferences while propagating on free spaces

This first part of this subsection discusses the propagation of electromagnetic waves without atmosphere and the different losses and interference that can occur on this medium. These kinds of interference might appear during the transmission with obstruct.

The transmission of radio waves can be defined by the proportionality:

$$P_r \propto \frac{P_t}{R^2} \tag{2.1}$$

Where P_r is the received power measured at the distant end, P_t is the transmitted power in terms of the EIRP, and R is the range. This proportionality give us the idea that a signal decreases as the square of the distance. It can be expressed as an equation with the Friss' Formula, taking into account the receiving antenna gain and the wavelength, this is usually used

$$P_r = P_t G_r G_t \left[\frac{\lambda}{4\pi R}\right]^2 \tag{2.2}$$

Where G_r is the receiving antenna gain, G_t is the transmiter antenna gain and λ is the wavelength. This equation can be converted into dB as it follows:

$$P_r = EIRP - A_0 \tag{2.3}$$

where $A_0 = -147.6 + 20\log_{10} f + 20\log_{10} R$ in dB and $EIRP = G(\text{dBi}) + P_t(\text{dBW})$.

This equation is accurate for computing the free space loss in dB and the received power (at the antenna) in dBW, based on a line-of-sight path where the only loss is due to the "spreading" of the signal as it propagates out from the transmitting antenna. The different number of losses will be included inside the equation of P_r.

Once this unrealistic definition of propagation in free space has been introduced, it is important to develop a more realistic way, including the different path geometry inside this free space environment. There are three different transmission paths regarding the application of a Fresnel Zone; It is the locus of a total path length that is half a wavelength longer than the line-of-sight path and extends between transmitting and receiving antennas. Reflection on the Fresnel Zone is still an issue and can introduce constant or time-varying fading [Elb16].

The first type of path geometry is ground-to-ground communications. With High-Frequency signals, there is sky-wave propagation produced by the reflection by the ionosphere. But terrestrial mobile wireless propagation can be complex to various user conditions.

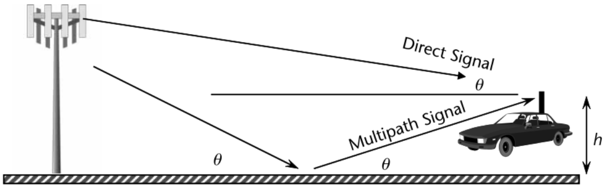


Figure 2.6: The direct line-of-sight path can experience cancellation from a reflected multipath signal [Elb16].

In an analysis of an open non-urban environment, the signal can experiment multiple paths due to the reflection of it by the ground. The longer path of the reflected signal will have a time delay that is equivalent to a difference of phase with the direct wave. Also, as they are in the same carrier, they can produce enhancement or cancellation, and there will be a loss of energy at the point of reflection. This example can be shown in Figure 2.6, where a macro-cell is transmitting in a significant radius. While in urban scenarios, it is recommended to use smaller cells to provide greater frequency reuse [Elb16].

The second type of wave propagation is through air-to-ground communications between aircraft and stations on the ground. The third type of wave propagation is space-to-space, which are the communications between spacecraft and space artifacts [Elb16].

After discussing the different path possibilities, the effect of adding various losses that affect the atmospheric effects that introduce attenuation through absorption and scattering of RF energy is going to be studied. But only on the impact that affect the ground-to-ground communication paths as are the most interesting depending on the view of cellular communication systems.

The troposphere contains gasses that attenuate radio signals, particularly above 1 GHz; as 5G systems can also transmit in frequency ranges over 1 GHz, this should be considered. Up to 6GHz regarding the attenuation provided by ITU is around 0.0.1 dB/km [Elb16].

Rain is also one of the dominant sources of attenuation and signal, but it affects a range of higher frequencies, around 10 GHz and above. Also, it has a scattering effect causing them to traverse beyond the local horizon, and it should be considered when frequencies are reused with a range of 100km [Elb16].

Interference with obstruct paths

This subsection considers different types of obstructed radio paths experienced on Earth, specifically in terrestrial communications. The discussion of the previous subsection also applies unless the obstructed path substantially alters the environment.

Regarding Figure 2.6, two different mechanisms can be observed in the presence of reflections and under the influence of heavy obstructions. These are the Ricean fading and Rayleigh fading. Both will form multiple vector addition of various samples of the same radio signal represented as a phasor [Elb16].

Regarding the direct and reflected signal, the addition of both signals can be represented as follow

$$A_r e^{i\varphi_r} = A_1 e^{i\varphi_1} + A_2 e^{i\varphi_2} \tag{2.4}$$

where two sine waves at the same frequency are added but have different amplitude and phase angles. This addition can be seen in Figure 2.7.

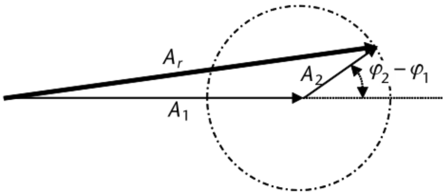


Figure 2.7: Addition of two vectors of frequency f_0, amplitudes A_1 and A_2 and phase φ_1 and φ_2 [Elb16].

The conditions where one of the signals is constant and not significantly attenuated by other signals because shadowing is the definition of a Ricean fading in recognition of its statistical behavior [Elb16].

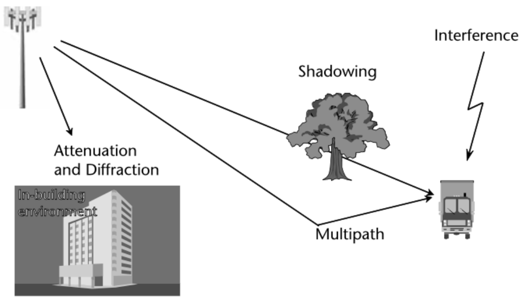


Figure 2.8: Multi-path example of terrestrial communication system [Elb16].

On the other hand, the Rayleigh fading is more prominent in cellular communication systems. Most of the time, the direct line-of-sight between our device and the base station is blocked and were using signals that are part of multipath because some of them might be stronger than the direct signal. An example of this effect is shown in Figure 2.8 [Elb16].

2.5.2 Interference on cellular systems

The 5G cellular networks offer aggressive spectrum reuse, the extreme density of base stations and wireless devices, and the integration of several communication methods to accommodate the increased demand for heavy data traffic. As a result, interference management is vital for the network to maintain its high performance. First, some interference management difficulties for 5G networks are addressed in this Section. After that, various practical interference coordination strategies are presented.

Several types of interference that will appear in cellular systems, specifically in 5G networks are as follows:

Intra-Cell and Inter-Cell Interferences

On cellular systems, users can suffer from two types of interference: those which are generated by other users in the same cell, known as Intra-Cell interference, and the interference produced by other users from colliding cells known as Inter-Cell Interference.

There are multiple methods to handle the problems of interference within the same cell which have been applied several generations of communication networks before. These methods are Time-Division Multiple Access (TDMA) or Orthogonal Frequency-Division Multiple Access (OFDMA) [YZ15]. OFDMA was introduced at LTE, and it was a key advantage to solve interference problems inside the cell. It is a transmission technique that multiplex a set of carrier signals of different frequencies, where each of them transports some information, and it is modulated in Quadrature Amplitude Modulation (QAM) or Phase Shift Keying (PSK). As it has orthogonality between the different subcarriers, crosstalk is eliminated, and it is not needed any kind of guard between symbols. It allows a high spectral efficiency near the Nyquist data rate. This orthogonality is represented by the following expression:

$$S_N(t) = i_N \cos \omega_N t + q_N \sin \omega_N t \tag{2.5}$$

where S_N is the symbol, ω_N is $2\pi f_n$ where f_n is the frequency of the signal, and i_N and q_N are phase and quadrature components of the signal respectively. This equation refers to full orthogonality between symbols.

In OFDMA, at a given time, multiple user can split the full spectrum into multiple frequency segments and communicate simultaneously with base station. In this scheme, each

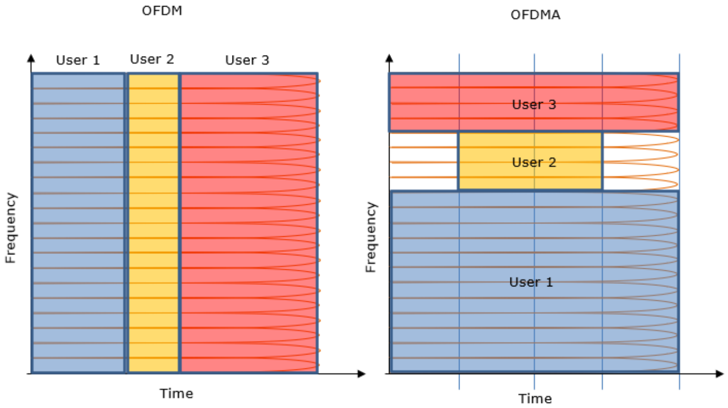


Figure 2.9: OFDM vs. OFDMA frequency-time-user split [Sha19].

user using the different frequency spectrum the signal from each of the user does not collide each other, this can be observed in Figure 2.9.

On the other hand, this orthogonality cannot be guaranteed for Inter-Cell Interference. Therefore, different users may use the same time-frequency resource blocks, causing interference to each other [YZ15]. These interference cause multiple problems from throughput loss to connectivity among the users. As coordination techniques relay in the MAC layer, when a functional split is working and this layer is at the distributed units, no modifications upon coordination can be applied. Therefore, coordination can only be mitigated while the MAC layer functions reside at the centralized unit. A deeper solution approach is delivered in the following Subchapter and Section.

Cross-tier Interference

One of the characteristics of 5G is that enables devices to communicate between each other without using any infrastructure node. This Device-To-Device (D2D) network coexists with cellular networks in the same spectrum. This will trigger multiple challenges and risks due to the difficulty of interference management, becoming this D2D signals a new source of interference [YZ15].

This interference will affect cross-tier interference from D2D transmissions, and D2D links will suffer cross-tier from cellular transmissions and inter-D2D interference. Therefore, an effective coordination mechanism is required to ensure the coexistence of cellular and D2D connections.

2.5.3 Interference coordination techniques

Several coordination techniques show great potential among the challenging problems that must face this generation regarding interference. Some of the solutions as follows:

Beamforming Techniques

Beamforming refers to a class of signal processing algorithms that can guide broadcast signals so that their negative influence on receivers is minimized in the context of dealing with interference. Beamforming techniques have been used to improve system performance in terms of a range of metrics, including signal-to-interference-and-noise ratio (SINR), bit error rate (BER), outage probability, and degrees of freedom, as a potent tool for interference management (DoF) [YZ15].

With phased array antennae systems, beamforming is used to focus the wireless signal in a given direction, usually towards a specific receiving device. As a result, the signal at the user equipment (UE) improves, and there is less interference between different UE signals.

The radiation patterns from each element combine constructively with those from neighboring elements to generate an effective radiation pattern known as the main lobe that transmits energy in the desired direction in phased antenna arrays. Simultaneously, the antenna array is built so that signals directed in unwanted directions destructively interfere with one another, resulting in nulls and side lobes.

The transmitted signal is fed to each antenna in the same way, but the phase and amplitude of the signal are changed to steer the beam in the desired direction. The overall antenna array system is built to maximize energy radiated in the main lobe while keeping energy in the side lobes to a minimum. The radio signals applied to each of the individual antenna elements in the array are used to regulate the direction of the main lobe or beam.

Power Control

Power control is an effective method for reducing interference widely used in wireless communication systems. Rather than distributing equal power to all users, unequal power can be selectively distributed to different users based on particular criteria, such as channel gain, user distance, or power consumption constraints. As a result, interference may be reduced, but energy efficiency can also be increased. There has recently been a lot of research into power control approaches for D2D underlaid cellular networks [YZ15].

User Scheduling

When multiple active users are on a wireless network, multiuser diversity can be exploited by scheduling transmissions to users with good channel conditions. Multiuser diversity has, in general, provided another type of diversity in the system that can be used to combat interference. Opportunistic user scheduling is commonly employed in cellular networks and cognitive radio systems [YZ15].

Advanced Receiver Techniques

Interference-aware MIMO receivers are well known for drastically reducing interference and increasing network performance. In a MIMO system, the Maximum Likelihood (ML) multiuser detection is known to reduce the bit error probability. Due to the difficulty of implementing ML detection, a linear approximation of the ML receiver, known as the MMSE receiver, can be used [YZ15]. The MMSE receiver has the advantage of having a good balance of noise enhancement and interference suppression. In addition, receivers may need to be able to use the structure of interference signals, such as modulation constellation, coding scheme, channel, and resource allocation, to handle high interference that cell-edge users in the next-generation network will face.

2.5.4 Inter-Cell Interference Coordination (ICIC) and enhanced-ICIC

In LTE, since Release 8 has been established, several methods and proposals to coordinate the Inter-Cell interference are known as ICIC. LTE has a frequency reuse of 1, meaning that the transmission carried out on the same time-frequency resource will create interference at cell-edges. This frequency reuse is established to maximize spectrum efficiency. On the other hand, in NR there should be a higher frequency reuse so it can achieve higher speed and capacity.

ICIC was introduced to mitigate interference on traffic channels. In this coordination, the frequency domain is coordinated among other domains available like power or time. It manages radio resource blocks, so multiple cells can coordinate the use of frequencies. This signaling is done through the X2 interface in LTE, and in NR could be used the interface Xn. After the implementation of , it has shown that it does not provide a satisfacting solution because it has a limited extension that applies only to data channels, and control channels are out of this coordination.

To solve some of the issues that ICIC had [Elb16], an enhanced version of it was introduced called eICIC in Release 10. The major change is the addition of the time domain to ICIC. This time domain is realized through the use of Almost Blank Subframes (ABS), which are subframes with reduced transmit power in some physical channels. These subframes do not carry data or control information, but to facilitate backward compatibility, ABS has to transmit reference, synchronization, and broadcast signals.

At Release 11, further enhanced ICIC (FeICIC) was introduced to focus on solving the interference that can occur because of the transmission of some signals at eICIC. It is mainly implemented at UEs, in which the receiver first estimates the interfering signal and removes this interference from the received signal.

NR has been designed with the principle of having a flexible and efficient use of radio resources, ICIC framework should evolve with the new kind of radio access network that can centralized some of the functions of a remote number or radio deployments. It has been shown in [CCY^{+}15] that is easier to employ eICIC in Centralized Networks where all the MAC information is collected in a central unit. The data transmissions of all the radio units are managed by this unit so it avoid any interaction between base stations.

2.6 Problem Statement

In order to reach a faster data rate, the 5G communication network requires a higher bandwidth. It is characterized mostly by small cell deployments, with a radious of range of 50 meters per cell in urban locations.

High-density network installation has numerous benefits, including high data rate and short signal delay. However, it suffers from several difficulties, including Inter-Cell, Intra-Cell, and inter-user interference. In a multi-cell cellular medium with frequency reuse, one of the biggest challenges is the Inter-cell Interference mitigation, as it degrades the spectral efficiency and energy efficiency.

Several methods of Inter-Cell interference cancelling techniques in 5G networks have been proposed such as cooperative transmission, resource partitioning, beamforming, and interference alignment (IA) [QHD^{+}19].

As in Flexible Functional Split Networks, the number of distributed units increases to achieve the 5G use cases requirements. The more distributed functions are given to the distributed unit, the fewer coordination capabilities has the centralized unit [HR18], as it can be seen in Figure 2.10.

The implementation of different techniques of interference coordination has not been experimented with before, so in this thesis, different strategies of mitigation will be implemented to fulfil the requirements of the use of 5G networks within a functional split network. Additionally, the optimization of those techniques while making changes on the provided testbed is analysed.

After different preliminary tests, it has been shown that, when there is an overlap between the different units, it provokes a downgrade on the quality of the transmission as some

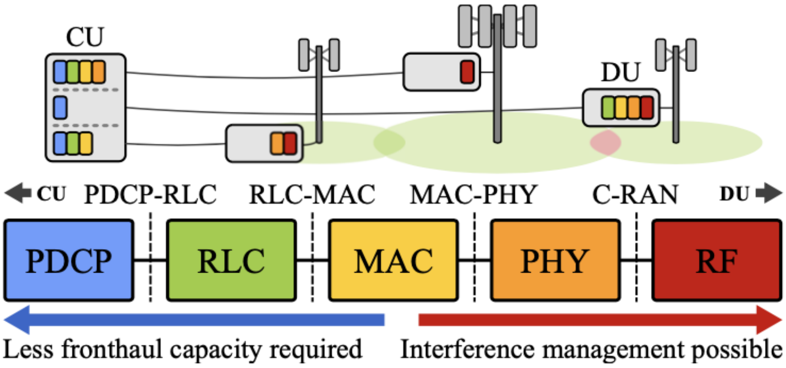


Figure 2.10: Possible functional splits in a 5G network including the fronthaul capacity and interference management [MAK19].

resource blocks are overlapped. This downgrade of quality means that the speed that can be achieved by the system is substantially lower compared to a no-interference scenario. The results of this test can be seen in Chapter 5.

As the spectrum is scarce, it is required to use, whenever it is possible, any kind of frequency reuse. As it has been described earlier in the previous subsection, when there are nearby or similar frequencies they can create interference between the different cells. Taking the advantage of having a coordination between the different distributed units can be used to deliver a more optimal solution that will mitigate the interference between the units and enhance the performance of the system. This approach will be dynamically as full centralization is not possible, so whenever an overlap is detected, it dynamically switches to centralized mode in case it was distributed and the centralized unit will take care of the coordination.

Chapter 3

Theory

After reviewing different approaches and types of interference shown in Section 2.5, we will focus on interference that appear at the testbed, the different strategies, and possible implementations in this Chapter. It has been shown in the previous Chapter that there are multiple solutions, and some of them are already available at the previous generation of wireless communication network. Taking the advantage of being in a deployment of a functional split network could use some of the benefit that it has.

In this Master's Thesis, the interference of two distributed units that are connected to one UE independently is researched. Both units are working on a bandwidth of 10 MHz, where there are 50 physical resource blocks allocated in 17 resource block group of 3 physical resource blocks each.

As both units are transmitting in by frequencies, the aim of this thesis is to research the interference between the units and how units can be coordinated to mitigate these interference while there is a dynamic functional split. A migration of functions between different units, especially migrating the MAC layer where the scheduler is established, makes a new approach to coordinate the interference mitigation.

There is a shared spectrum, and it is of high interest to research how the system behaves in terms of throughput and connectivity, as there is Inter-Cell interference between both units because they are working in very close frequency or at the same frequency. This will lead to some problems that can be solved from different approaches. The one used in this Master's Thesis is modifying the scheduler to make it work in a set of frequencies that the other unit is not using.

We have seen that ICIC and further versions of coordination can modify the frequency and time resources. As we have coordination of functions, we are taking this idea of changing frequency resources and applying dynamical management of radio resources depending on the shared overlap. This sharing of frequency is between the Distributed Units, which are controlled by each instance of the Centralized Unit, and then the CUs negotiate before each

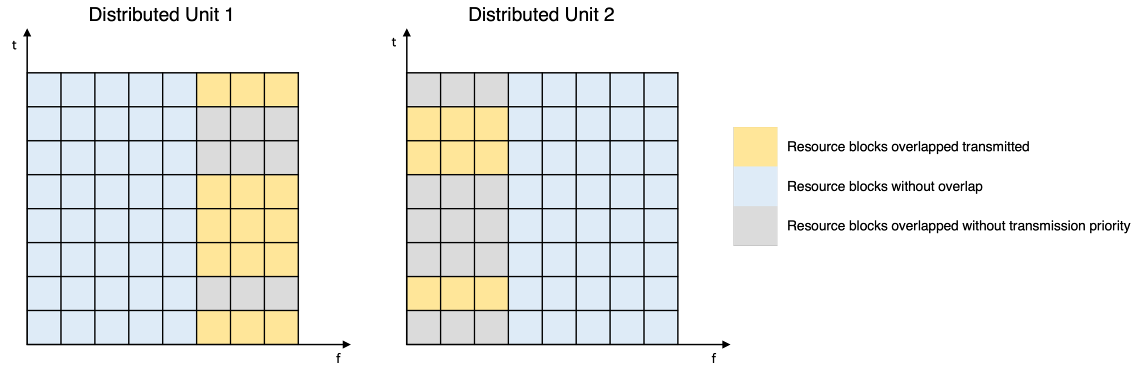


Figure 3.1: Resource grid in time and frequency of both distributed units that have a partially-shared frequency resources.

transmission which unit has the priority to transmit at the shared spectrum. In Figure 3.1, can be seen this management of radio resources within a resource block can be seen.

This approach can take advantage of having a unit that coordinates both distributed units, and the MAC layer relies on it. It establishes coordination of the scheduler and between functions, as it can change depending on the situation of interference between the distributed mode and the centralized mode.

For example, the functions can be in a PDCP-RLC split while there is no interference of another base station, making the load of the backhaul network lower and giving more functions to the distributed units, including all the benefits detailed in Section 2.4.1. When there is interference between the distributed units, it can switch automatically to MAC-PHY split, centralizing the MAC functions and coordinating the transmission of both distributed units mitigating the interference and delivering a higher throughput than when no coordination is available between the distributed units.

In order to manage the shared bandwidth of both units, some modifications should be made to the way the scheduler allocates the resources. The transmission frequency of both distributed units is shared to the instances of the centralized unit, via the Xn interface. Once the centralized unit knows the frequency used by the distributed units, it can compute the frequency overlap. Therefore, it can obtain the number of resource blocks that are overlapped. The system uses LTE channels; it uses the Resource Allocation Type 0, the simplest way of allocating resources. First, the Physical Resource Blocks (PRB) are divided into multiple groups of a definite number of resource blocks depending on the system bandwidth, so called Resource Block Groups (RBG). In our particular case, we use a 10 MHz LTE channel bandwidth, as it is defined at the LTE standard [3GP22], each subcarrier has 15 kHz of bandwidth and 12 subcarriers are within a Resource Block, then the Resource Block has a bandwidth of 180 kHz. The number of Resource Blocks can be obtained as follows:

$$Number\ Resource\ Blocks = \frac{Channel\ Bandwidth}{180\ kHz/RB} = \frac{10\ MHz}{180\ kHz/RB} \approx 50 \tag{3.1}$$

The number of PRB for a 10MHz channel bandwidth is 50, regarding Table 7.1.6.1-1 of [3GP22], the number of RB within a group is 3 regarding, because there are between 27 and 63 PRB. The calculation of the number of resource blocks overlapped is the following:

$$RBG_{overlapped} = \left\lceil \left(\left(f_{c_{low}} + \frac{BW}{2} \right) - \left(f_{c_{high}} - \frac{BW}{2} \right) \right) \times \frac{\frac{PRB}{RBG_{size}}}{BW} \right\rceil \tag{3.2}$$

where BW is the bandwidth, $f_{c_{high}}$ is the higher central frequency, $f_{c_{low}}$ is the lower central frequency, RBG_{size} is the number of RB that are allocated inside a RBG. As the number of resource blocks should be a natural number, it is taken as ceil of the operation to guarantee that all resources are used. Then the number of resource blocks available at the scheduler is modified subtracting the number of resource blocks overlapped.

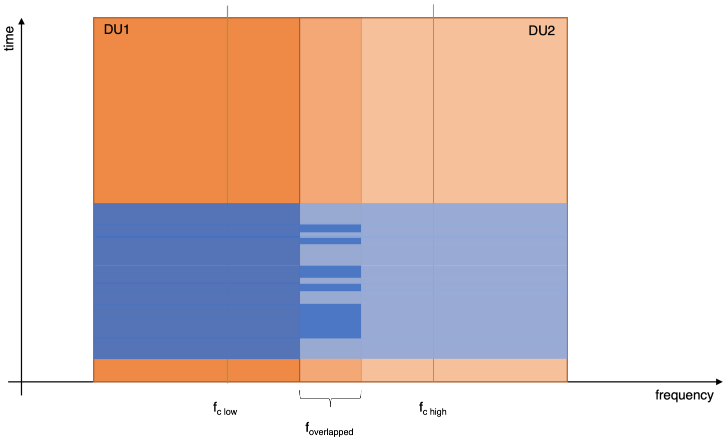


Figure 3.2: Bandwidth coordination between distributed units where each bandwidth is shown in orange, and the resource block used by each distributed unit are in blue, where dark blue represents DU1 and light blue DU2.

The target is to use the maximum bandwidth available and avoid having frequencies overlapped that are unused free. This approach requires coordination between the instances of the centralized unit that should agree about which distributed unit transmits at the overlapped resource block groups and which not. This agreement should be made at least before each transmission having a probability of 50% of using this set of frequencies. This will lead into a homogeneous bandwidth usage by all the units, where there is no overlap between any of the units at the same time and same resource block. A schematic representation of this idea is shown in Figure 3.2.

Chapter 4

Implementation

This Chapter introduces the current state of the Testbench system used in this Master's Thesis including an specification of the components of this system. In the development of this thesis, it has been required to make some modifications to the Testbench to be able to apply the different interference mitigation techniques. These modifications are also explained including the different problems that had occur during its development and modifications.

This Chapter also discusses the different implementations techniques that have been included to coordinate the mitigation of the interference within a dynamic functional split adaptation network.

4.1 Testbench System

This Master's Thesis is using an already developed Testbench available at the laboratory of the Chair of Communication Networks of the Technical University of Munich. This system is composed of several computers running Ubuntu as Operating System. Each computer is executing different instances of srsRAN depending on the functionalities that should be provided.

The instances of srsRAN are based on the version 16 of the suite, which has been modified to support the requirements of the functional split network. The srsENB instance has been split into two parts, one is executing the Distributed Unit and the other is executing the Centralized Unit.

In our Testbench there are 2 UEs that are connected one-to-one with a DU. Both DUs are connected to the CU, and this unit is connected to the Core Network. The Fronthaul connections, which are the connections between the DUs and the CU, the Backhaul connections, which are the connections between the CU and the EPC, are all connected through a switch. Also each equipment has an independent Ethernet connections to another switch in order to provide Internet connectivity to every computer. This deployment can be seen in Figure 4.1.

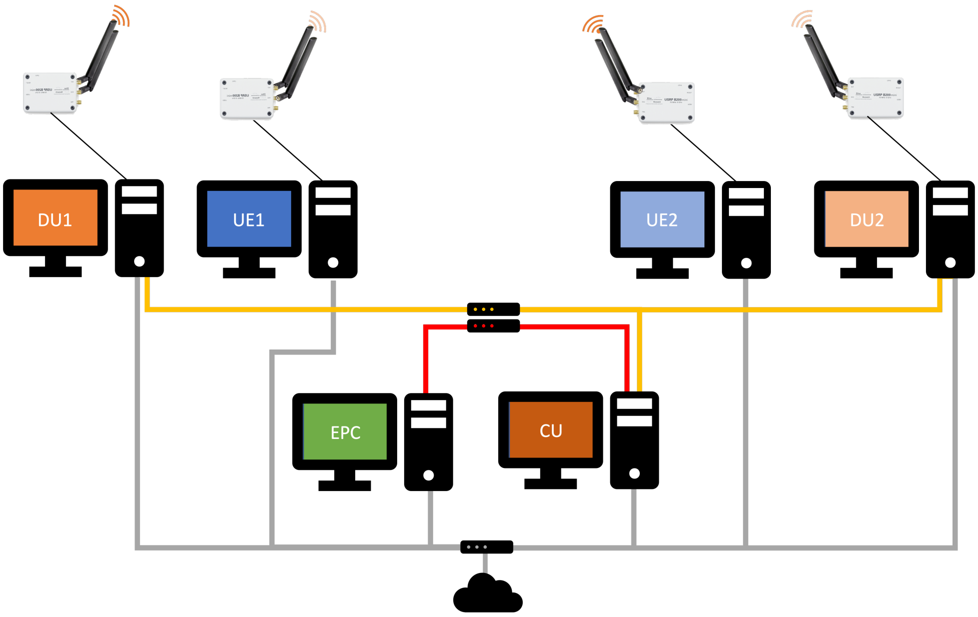


Figure 4.1: Testbed deployment: 2 UEs with USRP, 2 DUs with USRP, 1 CU, 1 EPC and 2 Switches. Yellow connections refers to Fronthaul; Red connections refers to Backhaul; and Grey Connections refers to Internet connectivity.

The equipments used are the following:

- UE_1: Intel x86 Core i7-6700 CPU @ 2.80 GHz x 4
- UE_2: Intel x86 Core i7-7700 CPU @ 2.90 GHz x 4
- DU_1: Intel x86 Core i5-6600 CPU @ 3.30 GHz x 4
- DU_2: Intel x86 Core i5-6600 CPU @ 3.30 GHz x 4
- CU: Intel x86 Core i7-4770 CPU @ 3.40 GHz x 8
- EPC: Intel x86 Core i5-6600 CPU @ 3.30 GHz x 4
- USRP: Ettus Research USRP B210 (mini) 70 MHz - 6 GHz

A GUI has been developed to make use of all functions, from start running each instance up to migration between the different splits based on *Qt*. This software is run at the Centralized Unit that works as main computer in this case. It connects via SSH to all the computers and executes the commands required.

Also, another USRP has been used as spectrum analyzer. This device is connected to a computer with the same characteristics as UE_2, running Ubuntu 21. The software *Gqrx* has been installed in order to have the spectrum analyzer capabilities. This device let us check when and how the Testbench is working, and define different solutions to the interference mitigation.

There are configuration files in each instance that lets modify some parameters from IP Addresses that are fixed to every device, up to Antenna Gains or Frequencies. During the configuration of the system, the Antenna Gains for both UEs and DUs has been modified in order to have at least -100 dBm in power reception. To fulfill this requirement and check in real time the power at the DUs and UEs, an utility available at srsRAN has been used.

Also, static IP addresses have been established for every interface of each device, excluding the air interface of the UEs which is assigned at the connection process. In the next Section 3.2, there are explanations about the IP assignments and interfaces.

4.2 Previous state and new modifications

For the development of this thesis, a testbed with 1 DU and 1 UE working at the same time has bene provided by the Chair of Communication Network. As one of the premises of this Master's Thesis is to investigate and implement mitigation techniques when Inter-Cell interference occurs. This type of interference appear when there are multiple DUs working at similar frequencies, where the spectrum is shared.

Because of that reason, the code of srsRAN and the interfaces of the equipment were modified to be able to connect multiple DUs to a unique CUs, and serve to at least one UE per DU at similar frequencies.

During this Section of this Chapter, the previous state including the modifications done previously at the Testbed is introduced , followed by the new improvements achieved during the development of this thesis.

4.2.1 Previous state

As it was stated on the description of this Master's Thesis, the state of the Testbed was minimally operable and it has to be modified in order to satisfy the current proposal. The prior Testbed was developed to implement the Flexible Functional Split Adaptation, it included a minimal working set-up with at least 1 UE, 1 DU, 1 CU and 1 EPC working in both splits. An further version of this Testbed including another UE can bee seen in Figure 4.2.

The srsRAN version was designed as a LTE architecture, some changes were introduced in order to go from an architecture like the one represented in Figure 2.3 to Figure 4.2, where

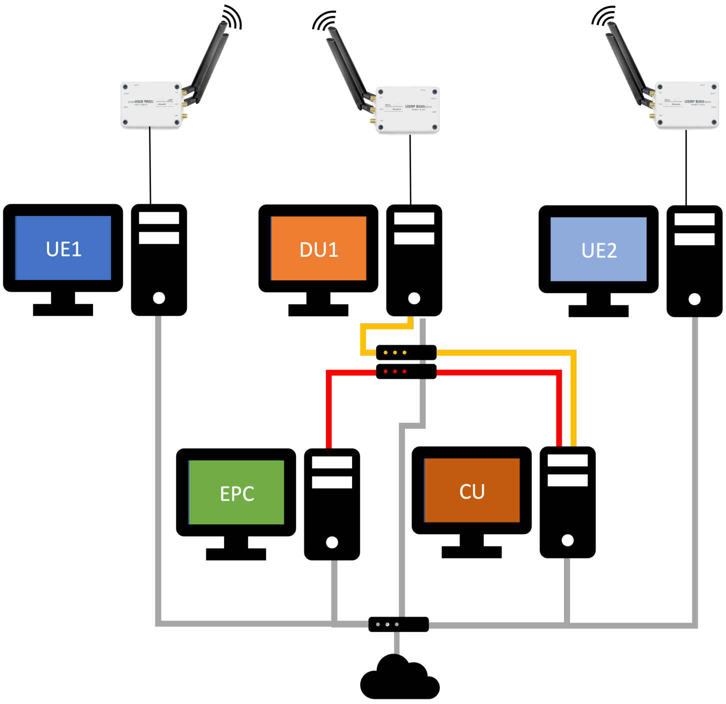


Figure 4.2: Testbed previous deployment: 2 UEs with USRP, 1 DU with USRP, 1 CU, 1 EPC and 2 Switches. Yellow connections refers to Fronthaul; Red connections refers to Backhaul; and Grey Connections refers to Internet connectivity.

there is a split of the gNB in a DU and CU. For this purpose, the instance srsENB was split into two different units: srsENB_CU and srsENB_DU. That deployment featured the following:

- The Distributed Unit always host the PHY layer.
- RRC and PDCP layer are always hosted on the Centralized Unit.
- Two new libraries has been created to achieve the communications through the Fronthaul between the CU and DU, depending on which split is being used.
- As the layers MAC and RLC should be on both units depending on the split working, they are duplicated in both CU and DU.
- Migration is coordinated and orchestrated by the migration_flex component hosted in both entities.

During this set-up, we tried to include another DU in order to connect multiple DUs to one CU, and at least one UE to each DU, as it was included in further steps in a previous Thesis and Forschungspraxis related to this testbed. After making the connections and no modifications to the code, the connection was possible at the same time only one UE to one of the DUs, but it wasn't possible to connect at the same time both UE each to the designed DU.

One of the main issues was that both UE were connecting to the first DU that was registered and up. Therefore, the EPC could not differentiate between the two DU and then the UE anchor point was not set correctly.

After the modifications done previously, more had to be done due to Testbed's incapability of connecting multiple UEs to multiple DUs simultaneously. Different approaches were applied until a solution was implemented that works consistently and fullfils the requirements.

4.2.2 Differentiation of sockets for each distributed unit

In the early stages of the development of this thesis, an in-depth research on the code and system was done. As there are some logs available at each instance and with different levels of information, which can provide a deepest information on what it is or is not working and how.

The first approach to solve the connectivity issue was to create new sockets that can make the connection between the Distributed Unit and the Centralized Unit. Before the implementation of this approach, it was checked that the EPC cannot differentiate between the different attachment process of both distributed units as they were using the same ports and IP connections.

Every socket is defined by a source IP address, destination IP address, source port and destination port. The APIs and different systems that interconnect uses this schema to transfer the information through the fronthaul and backhaul networks. This information was hard-coded in every file, so the first step was to modify every class that include sockets and change it in a way that they can be specified in a configuration file.

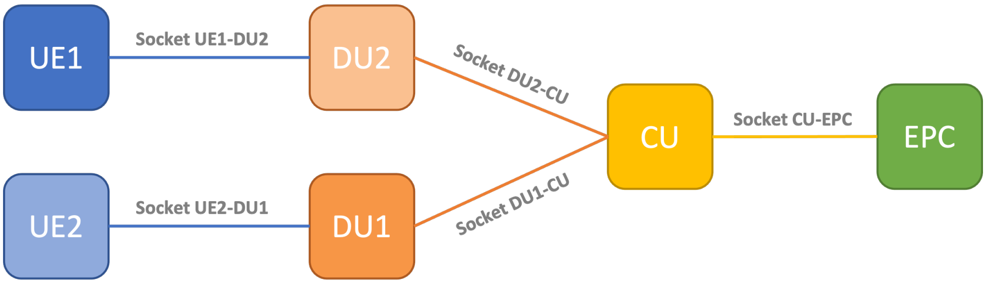


Figure 4.3: Multiple different socket connections between CU and each DU.

Once every socket information was included, a new socket was defined with new source and destination ports, but the same IP addresses. A schema of this approach can be seen in Figure 4.3. As there are different ports, there are different connections so every information sent from one unit to another is channelized through it. After the deployment and configuration in each computer, it was tested that the connections were working, but the system was not working as expected. Therefore, this required a detailed analysis of what was happening on it. This analysis concluded with the discovery that the problem was at the EPC source code. The latter wasn't modified and it wasn't registering the connectivity of new user equipment, as well as there was only one instance of the centralized unit that cannot manage both distributed units at the same time. This required a modification of the EPC that was out of the scope of this Master's Thesis, so another solution by modifying the composition of the system was researched.

4.2.3 Virtualization of the centralized unit

The solution to the previous problem was to have multiple instances of the Centralized Unit and a new virtualized network available, so each Distributed Unit has a connection and is centralized by one instance independently. Inside the computer running the Centralized Unit, an Ubuntu server was created as virtual machine running with VirtualBox. Also a new virtualized network was created that was connected to the host network, but with different IP addresses. A representation of this composition can be seen in Figure 4.4. The centralized unit including the virtual and the host units was connected through a unique socket with the EPC, avoiding any modification on it as it was required by the previous approach.

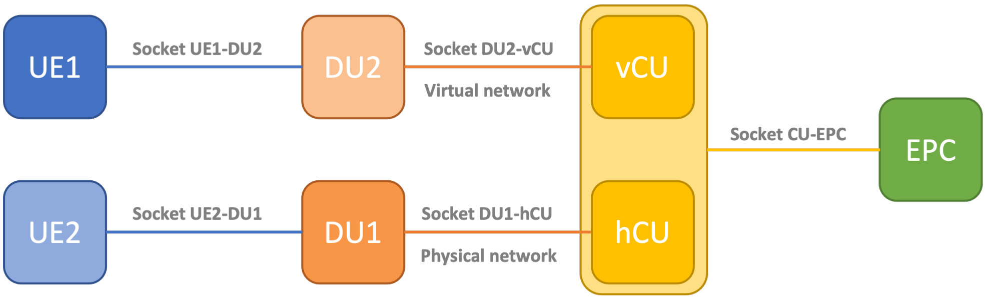


Figure 4.4: DU1 is connected with a virtual network to a virtual CU, and DU2 is connected through a physical network to a CU instance at the host computer.

Then each of the distributed units was connecting via a unique connection to each of the instances of the Centralized Unit. After making some test to the system, some connectivity issues appeared. Having a deeper outlook on the issues showed that there was a latency of more than 1 milliseconds, even between 1 to 5 seconds in some cases. This was against the definition of the URLLC case of 5G system explained in Chapter 2. A modification of the configuration was applied following the recommendation of VirtualBox to avoid issues and latency at the virtual network, but a similar result was obtained.

The virtualized instances are a copy of the host srsENB_CU instance. It was virtualized on Oracle VM VirtualBox under a Linux server compilation, with access to multiple resources of the host computer like 6 GB RAM and 4 Cores. Also. The virtual machine included bridge-network to each network adapter of the host computer, supposing that the connectivity through them is available. VirtualBox provides up to eight virtual PCI Ethernet cards for each virtual machine, the emulated hardware used was the Paravirtualized network adapter, as it is recommended for a lower latency and better performance. While using the Bridged Mode, it connects to the network cards selected and exchanges network packets directly, circumventing the host operating system's network stack. It uses a device driver on the host system that filters data from the physical network adapter. This driver is called net filter driver and intercepts data from the physical network and injects data into it. In the host system side, it is view as a new interface that connects the guest system physically to the host computer.

In order to improve the network, the segmentation offloading was enabled at the host system. The segmentation allows a device to segment a single frame into multiple frames with a specific data payload size. This is established as one of the typical methods to improve the network while working with virtual machines as it reduces the CPU's overhead for TCP/IP operations. After setting up the virtual machine, some test were done in order to check if this approach was correct. Now, a new IP address assigned to the virtual machine is available. The next steps were making one of the two DUs connect to the IP assigned and check if everything works. It was detected that the delay while executing PING commands between the virtual CU and the DU was between 5 to 6 times bigger than the host CU, and between the EPC and the virtual CU it was between 10 and 300 times bigger. This led into an unacceptable performance of the virtual machine as it does not accomplish the low latency requirements of 5G.

4.2.4 Virtualization of the network

As it was shown that the previous approach might solve the problems that appeared at the first iteration, but it included too much delay. A mixture of both approach was thought as solution. Using the capabilities of Linux of creating a virtual IP address that it is associated to a network adapter, it can create new IP connections from each distributed unit to each instance of the centralized unit that they are assigned to. A composition to this can be shown in Figure 4.5.

For this purpose, there are many Centralized Unit instances hosted at the same computer that are connected to a unique Distributed Unit. Each DU is under the centralization of the complete unit that includes all of the instances. Each of the instances creates a socket connection between the Distributed Unit and the Centralized Unit where ports are the same but there are different IP addresses. Linux offers a feature included at the IP command that creates address aliases at the network interfaces as a solution to have multiple IP addresses at the same network interface. This can be done using the command:

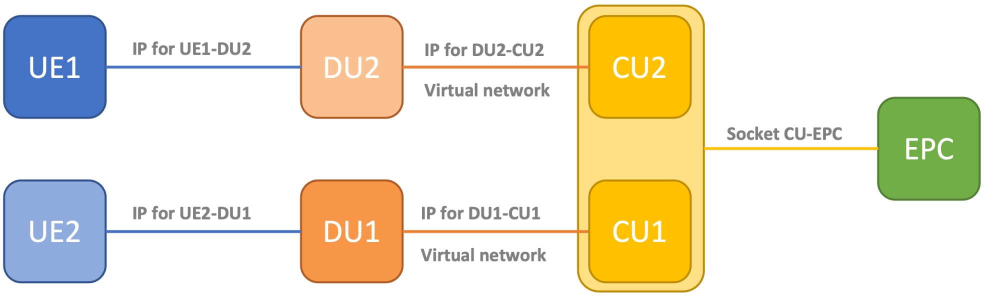


Figure 4.5: Multiple instances inside the centralized unit connected through a virtual network to each of the assigned distributed units.

```
$ ip address add IP_ADDRESS/MASK dev NETWORK_INTERFACE
```

As this command set the new IP addresess for the current session, in case of restart of the computer they will disappear. To solve this, it has been modified also in the interface configuration file at */etc/network/interfaces*.

Due to this approach, the connectivity and latency issues were solved. It is also a better approach because, as each instance is executed as independent processes within the system, the computer resources and radio resources can be used in parallel as they are executed independently at the same time. These modifications were also applied at the GUI of the Testbed.

Also, both instances of the centralized unit, and both of the distributed units share the same code, having their IP addresses and ports defined among other parameters defined in configuration files. This led into a more consistent code as it is easier modifiable because all the files are synced with each other at GitLab. Once the system was set up, the main development stage of the thesis started as without solving the different problems mentioned above it wouldn't have been possible. The next steps include the modification of the code to implement the coordination between the units when there is interference between the distributed units in centralized mode. There are new APIs that have been included, and also a modification of the scheduler that it is used to transmit.

4.2.5 Implementation of new APIs

In order to communicate and execute different functions within the current system like migration of functions between the distributed mode and centralized mode, among others, several APIs have been established that communicate through the sockets between the different units. Taking this approach as example, new APIs have been defined to be used to coordinate the transmission scheduler and when it has availability to transmit.

The following connections have been established:

- DU1 and CU2: This connection serves to transmit the frequency that it is used by the distributed unit to transmit to the centralized unit and calculate the resource blocks that are overlapped following the expression 3.1.
- DU2 and CU1: Identical to the previous explanation.
- CU1 and CU2: In order to make the calculation and modification of the resource blocks that are in used and overlapped, it is required that both instances of the centralized unit know in which frequencies both distributed unit are operating. To achieve this, a connection between both instances is proposed. As it is a connection between two different instances of the centralized unit, it can be implemented through the interface Xn described at Section 2.2, which connects multiple gNB between them. Also is important that this connection has a low latency as the coordination messages will be sent and received through this connections, having a requirement of less than 1ms of latency. After some testing, it can be seen in table 4.1 that it is $17,8\%$ of the top requirement.

Samples	65
Mean	0,0178 ms
Standard Deviation	0,0033

Table 4.1: Latency between the CU instances.

The following API has been defined or modified and can be accessed by the repository: *interference_api, migration_flex* and *north_api*. Every API class connects each unit through UDP socket defined by IP addresses and ports. Depending on which type of API, they can work as sink, source or both types of socket. As Migration Flex and North API are both implemented at the Centralized Unit and Distributed Unit, they have been modified in both source codes, in order to send messages through them.

	interference_api		**north_api**		**migration_flex**	
Type	Sink/Source		Sink/Source		Sink/Source	
CU1	50.0.0.101	1313	50.0.0.101	8080	50.0.0.101	4545
CU2	50.0.0.102	3131	50.0.0.102	8080	50.0.0.102	4545
DU1	-	-	-	-	40.0.0.101	4545(src) 5454(dst)
DU2	-	-	-	-	40.0.0.102	4545(src) 5454(dst)

Table 4.2: API details with IP, Ports and Type for each unit.

After briefly defining which APIs have been modified or created, a definition of each class and method is needed in order to have a better understanding of the implementation of the modifications to the system.

Interference API

This new class takes care of the management and coordination of the interference. This API is running as part of the instances of the Centralized Unit. It is a sink and source API, because it sends and receives messages through the socket. As first approach a description of the sink functionality is done. This API is receiving from each of the Distributed Unit their working frequency and stores it as part of an object of the Scheduler Class. Also, it is receiving the decision that is made by each centralized unit in order to have priority to transmit at the overlap frequencies.

Regarding the source functionality, it is capable of sending multiple information through the socket:

- Send Frequency: This method let the CU send the received frequency to another CU. This frequency is then received by this API and stored in an object with the frequency that was sent previously by the assigned DU.
- Send Decision: This method will send through this API the result of the probability of transmission in form of a Boolean priority of transmission.

But also, new methods have been defined and included in this class that manage the decisions and frequencies received and sent. This class computes a random value with probability of 50% and stores it as Boolean value the result. This value will enable the unit to use the overlap part of the spectrum, but this should be sent to the other unit and compared. If both of the units are enabled to transmit at the overlap frequencies, there will be a collision. Then once both centralized units have both decision values, they compare both and in case they are the same, ask both units to generate a new one until they are different. Once one of the units receives the decision of the other, it triggers the generation of their own decision so if there is any matching between, them it only has to send a new decision value and will trigger all the methods until comparison again. This generation of values is done every time before any resource is allocated to transmit, and as it is shown in Table 4.1, it accomplishes the restriction of being done before 1ms.

Migration Flex

This API is used for managing the migration between the different functions at the Distributed Unit and Centralized Unit. But it has been modified to receive the frequency that is used by the distributed unit and to call the method available at the Interference API to send the frequency to the other centralized unit. Also, this API stores in an object the values of both frequencies. This API is used because it is active at the initialization of the system and can access receives messages from DU and CU. At the initialization of each DU, they send their own operating frequency to the CU and it is received by this API.

It is a sink and source API depending on which unit is the packet being observed. It works

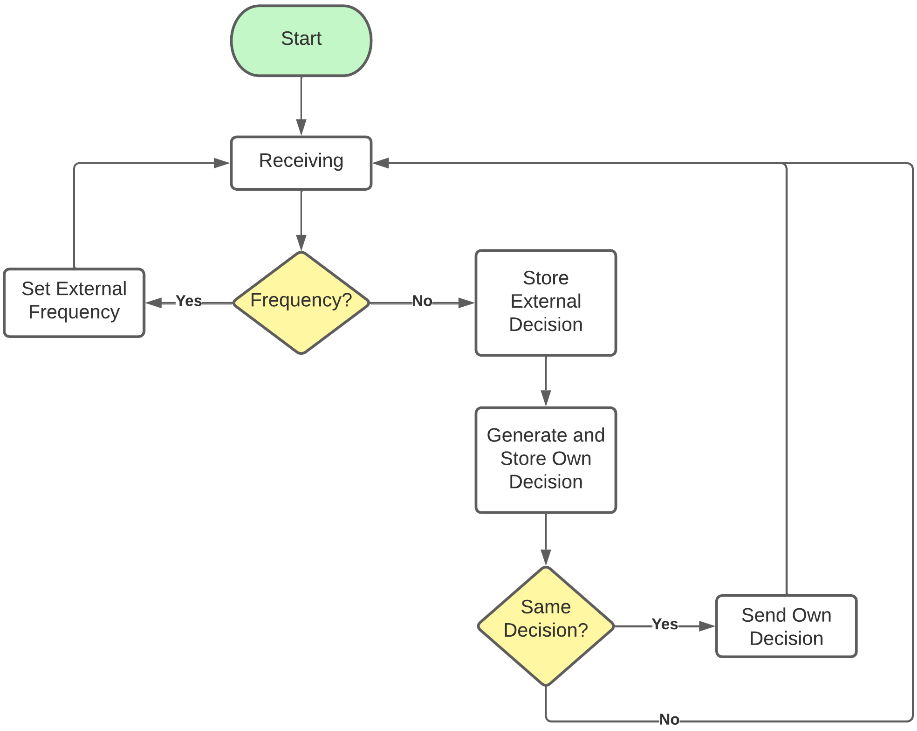


Figure 4.6: Interference API flow.

as source of messages sending the frequency from the distributed unit to the centralized unit, that, works as sink.

North API

North API is used also to manage the migration between the different types, Hard, Soft or Custom. But also it has been implemented a possibility of changing the scheduler according to the message received at this centralized unit. This could be used and improve in future work.

4.2.6 Modifications done to the Scheduler

After introducing the multiple APIs that are in control and management of the coordination, a deeper look inside the class that have multiple functions of the decision and modifications the scheduler is over-viewed in this subsection.

The Scheduler class has multiple methods, and defines also a structure which contains the type of scheduler and the frequencies of both distributed units. The methods that are included in this new class are the following:

- change_scheduler: This method receives the value that is sent through the North API and changes the value at the object according to it. This value is read at the resource allocation choosing between the different schedulers available.
- rbg_overlap_calc: This is the implementation of the Expression 3.2 and sets the value in a local variable. This calculates the number of resource blocks group that are overlapped within two values of central frequencies.
- get_nof_rbg: With this method, we can access the value of the number of resource block groups that are overlapped.
- set_freq: This method sets the value of the frequencies that are received from the Interference API, and when both values are set, it calls the method which calculate the number of resource block groups overlapped.
- get_freq: This method returns the value of the frequency for a specified unit, and it is used when a new frequency arrive to a unit through the API.

Now, it is possible to obtain the number of resource blocks that are overlap thank to the use of different APIs and methods. The next step is to make modifications on the scheduler that reflect the number of resource blocks that should be dynamically assigned to one of the distributed units, as it is explained at the Section 3. To achieve this, after a research on how the scheduler works, the best approach was to modify it directly and make the decision before any allocation of resource blocks.

The scheduler allocation is done in the file */srsenb/src/mac/scheduler_metric.cc*. That file defines the process where the allocation of resources are done. It takes the number of resource block group, the type of scheduler, the number of resource blocks overlaped and the priority and creates a mask of bits defining the number of resource block groups that are available.

The system includes a very basic scheduler that fills the resource blocks from the lowest frequency up to the higher depending on the requirements of the transmission. These requirements are mainly the throughput speed and the delay between packets. In the first iteration of creating a new scheduler, it was mirrored the default scheduler, so both units can have a common set of frequencies that are overlapped and if the conditions allows, they do not overlap. This was used to test whether the main approach of the thesis was valid.

As typical scheduler of base stations are switching between different resource block groups and do not transmit filling all at the same time because they are switching to the best resource blocks in terms of channel quality. The approach to simulate this was to making the scheduler switching randomly between the different resource block groups available. In order to implement this, there is a new vector filled from 0 up to the total number of resource blocks that is shuffled using C++ function *random_shuffle(pos_init, pos_end.*

After that, it is using the same procedure as the default scheduler but with the difference that the position that says which resource block and mask bit are selected comes from the set of randomly shuffled vector. Also, as once per transmission one of the units has the permission to use the shared spectrum, it is included into the function the Boolean value received as input variable and processed at the Interference API. Then the API changes the number of resource blocks overlapped between the real number or 0, changing the number of iterations that the for loop assigning the different mask bits will have. A flowgram of the whole process of selecting the scheduler and its different allocation can be seen at Figure 4.7

After the implementation of the system, it was tested to check that all the improvements were correctly implemented. Using the Spectrum Analyzer it is possible to see how the system is working graphically. Following the statements of Chapter 3 and and the representation of Figure 3.2, in Figure 4.8 can be seen a real representation of the system. In this screenshot, there is an overlap of 8 MHz and it can be observed how the shared spectrum is used only by one unit each time.

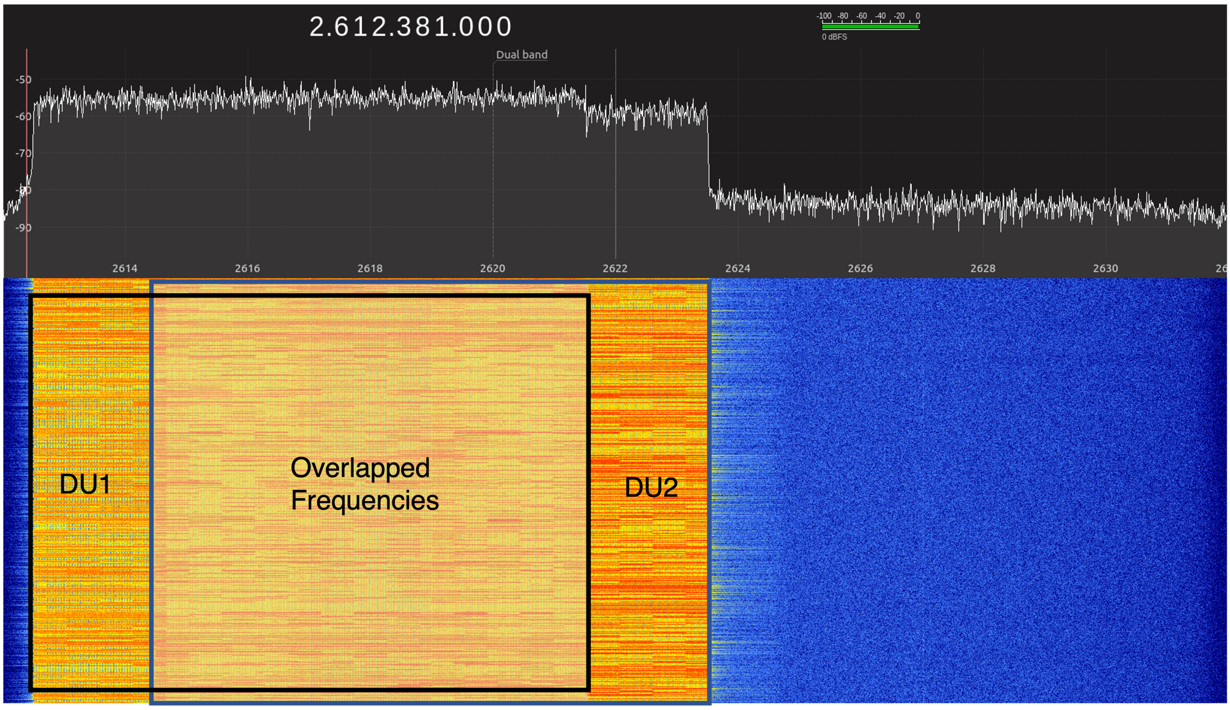


Figure 4.8: Screenshot of the spectrum analyzer showing both DUs working at the same time with an overlap of 8 MHz.

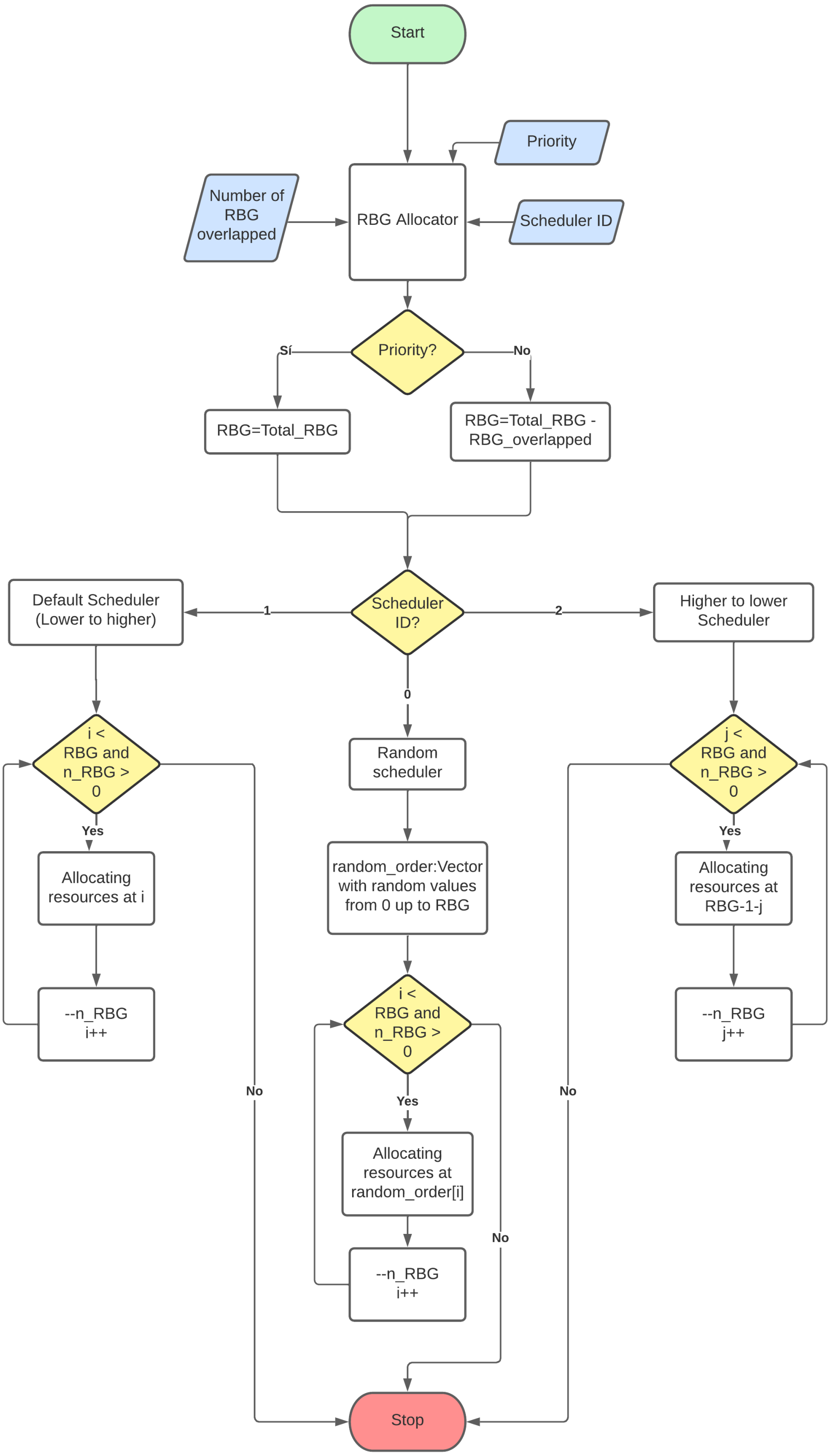


Figure 4.7: Flowgram of the scheduler selection and allocation of resources with the input of priority, number of RBG overlapped and Scheduler ID.

Chapter 5

Results

At the beginning of this thesis, the system was tested to check the hypothesis, verify the system's performance, and research what was the problem and how it could be solved. To achieve this, some results were taken and are presented in the first Section of this Chapter. After implementing and verifying the improvements described in the previous Chapter, the system results with the new deployments and coordination are shown in this Chapter.

5.1 Baseline results

The results of a test with around 65 samples per MHz overlapped is shown in the following figures:

As it can be seen in Figure 5.1, after the first MHz overlapped, there is a drop of the mean download speed around 60% less, and it continues to decrease while the overlap increases. It can be observed at Figure 5.2 that there is a high dispersion in some of the frequencies; this occurs when there are re-connections, or one of the devices is not transmitting at the same time, and therefore one of both can reach a high speed.

The test was done using TCP to obtain the highest throughput without taking care of the acknowledgment of the packets. The test was performed using a download stream from the Distributed Unit to the User Equipment, where DU1 and UE2 are connected; and in a parallel connection DU2 and UE1. The system is sending one TCP packet per second to the user equipment. The pair DU1-UE2 is connected first.

In Table 5.1 and Table 5.2, the analysis of the different samples that have been obtained during tests at the testbench can be seen. These tables show the different mean speeds, median speed, and standard deviation depending on the overlap. It can be seen that in these results that the system is highly affected while there is increasing overlap. Also, in Table 5.3 it can be seen the different connectivity test, and the system can make a

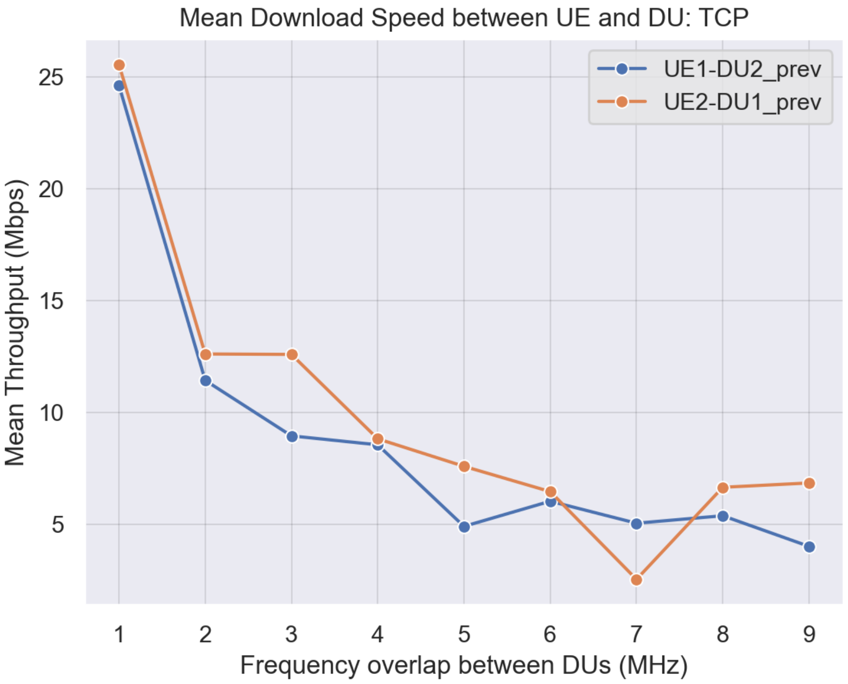


Figure 5.1: Mean download speed from each DU to assigned UE.

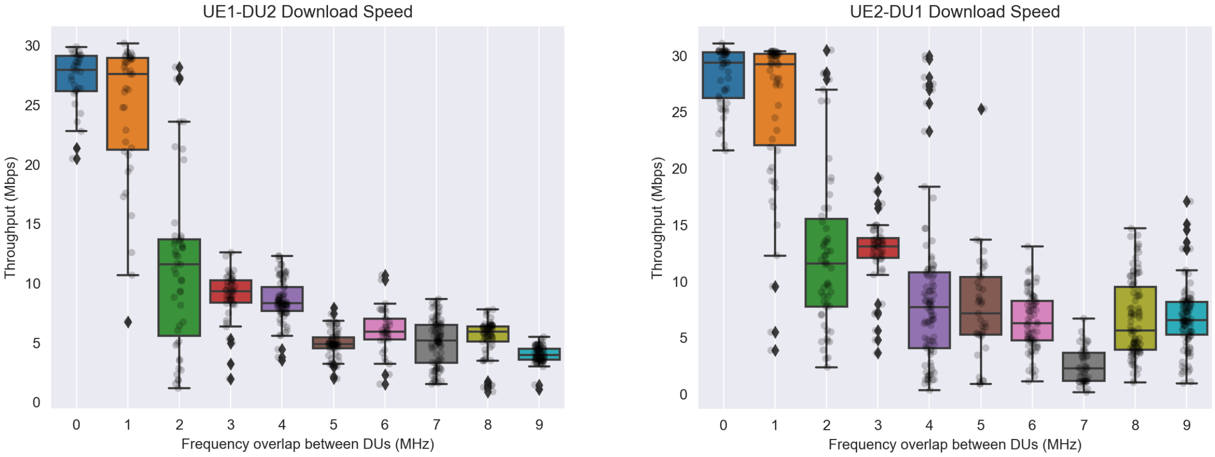


Figure 5.2: Boxplot of different samples of download speed between assigned UE and DU. Left: UE1 and DU2; Right: UE2 and DU1.

connection between the different distributed units and its user equipment with the only exception that when the system is fully overlapped, it cannot connect both of the user equipment.

Overlapping (MHz)	**Mean Speed (Mbps)**	**Median Speed (Mbps)**	**Standard Deviation**
0	27.18	27.95	2.443
1	24.64	27.60	5.896
2	11.44	11.60	7.211
3	8.96	9.34	2.069
4	8.56	8.33	1.796
5	4.91	4.88	1.216
6	6.03	5.93	1.900
7	5.05	5.20	1.951
8	5.38	5.93	1.652
9	4.01	3.98	0.733

Table 5.1: Mean and median download speed in Mbps including standard deviation for the download stream of UE1-DU2 including overlapping of frequencies.

Overlapping (MHz)	**Mean Speed (Mbps)**	**Median Speed (Mbps)**	**Standard Deviation**
0	28.23	29.40	2.619
1	25.57	29.25	6.775
2	12.12	11.50	6.895
3	12.48	13.10	3.147
4	8.83	7.85	7.018
5	7.60	7.18	4.781
6	6.46	6.29	2.552
7	2.54	2.32	1.545
8	6.66	5.65	3.459
9	6.85	6.58	2.932

Table 5.2: Mean and median download speed in Mbps including standard deviation for the download stream of UE2-DU1 including overlapping of frequencies.

Overlapping (MHz)	**UE1**	**UE2**
1	Yes	Yes
2	Yes	Yes
3	Yes	Yes
4	Yes	Yes
5	Yes	Yes
6	Yes	Yes
7	Yes	Yes
8	Yes	Yes
9	Yes	Yes
10	Yes	No

Table 5.3: Connection of UE1 and UE2 to the respective Distributed Units while there is an increasing overlap.

5.2 Results with coordination

After seeing the multiple results obtained before the usage of coordination techniques, a test with a similar procedure was done. For these experiments, there will be tested the throughput in two modes. The first one is testing in TCP following the same procedure as before, transmitting one TCP packet per second and varying the overlap bandwidth in Mhz.

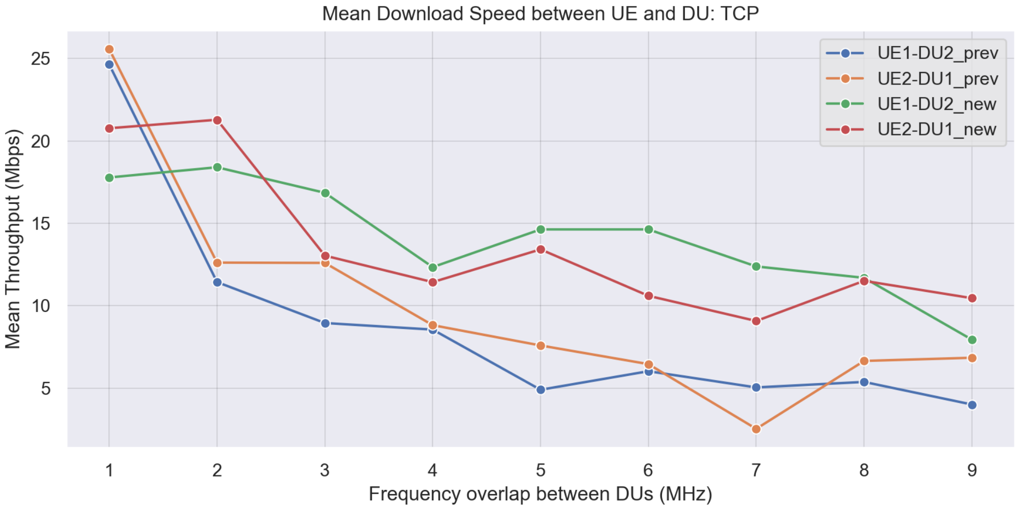


Figure 5.3: Mean Download TCP Throughput without coordination and coordinated.

Figure 5.3 shows the mean values of the download speed compared to the values prior to the coordination. This Figure shows the throughput between the difference is higher in all the overlaps, except when there is one megahertz overlapped. The mean values are between 20 Mbps and 10 Mbps when it drops from 25 Mbps to 5 Mbps at the previous configuration.

The coordination system is above the no-coordinated connections at every point where the throughput has been recorded. The explanation for an overlap of 1 Mhz might be that it is because there are at least three resource blocks that are not in use when there is no priority. When there wasn't coordination, even though interference from the other unit exists, it didn't affect that much in terms of throughput, and it could reach up to the maximum throughput. In Table 5.4, there are included the possible values that the variable rbg_overlap can get, and these values came from the expression 3.1.

The next experiment was to send UDP packets to check how the throughput was performing while ensuring the transmission of the data. As the usable bandwidth was reduced megahertz by megahertz and the throughput was increased, it will show a decreasing and

Overlap	RBGs Overlapped	RBGs Available	% RBGs Overlapped
1 MHz	2	15	12%
2 MHz	4	13	24%
3 MHz	6	11	35%
4 MHz	7	10	41%
5 MHz	9	8	53%
6 MHz	11	6	65%
7 MHz	12	5	71%
8 MHz	14	3	82%
9 MHz	16	1	94%

Table 5.4: Number of resource block groups that are overlapped, available and its availability percentage.

limiting speed, which could not be surpassed. For this experiment, 1 UDP packet per second was transmitted, and the download throughput was varied between 5, 10, 15, 20, and 25 Mbps. The following figures illustrate a boxplot showing the different values that the system achieves. At the same time, there is active transmission of both distributed units, and it is coordinating which transfer in each allocation at the overlapped frequencies.

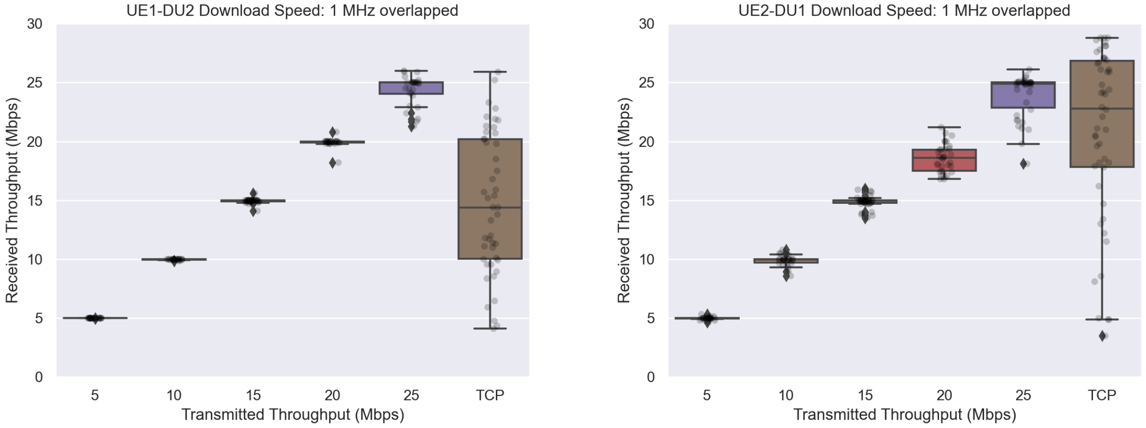


Figure 5.4: Download throughput transmitted and received for 5, 10, 15, 20 and 25 Mbps in UDP mode, and without requirements at TCP mode for 1 MHz of overlap.

In Figure 5.4, it can be observed that the download throughput is mainly stable in both units, having the pair that is connected later less stability. We can see that it perfectly achieves the required download throughput required in UDP mode. Also, we can see that it has a higher dispersion while in TCP mode depending on the conditions of the transmission, but it reaches in some points the top throughput that the system can achieve.

After increasing 1MHz, it can be seen that the system starts to decrease it capabilities to

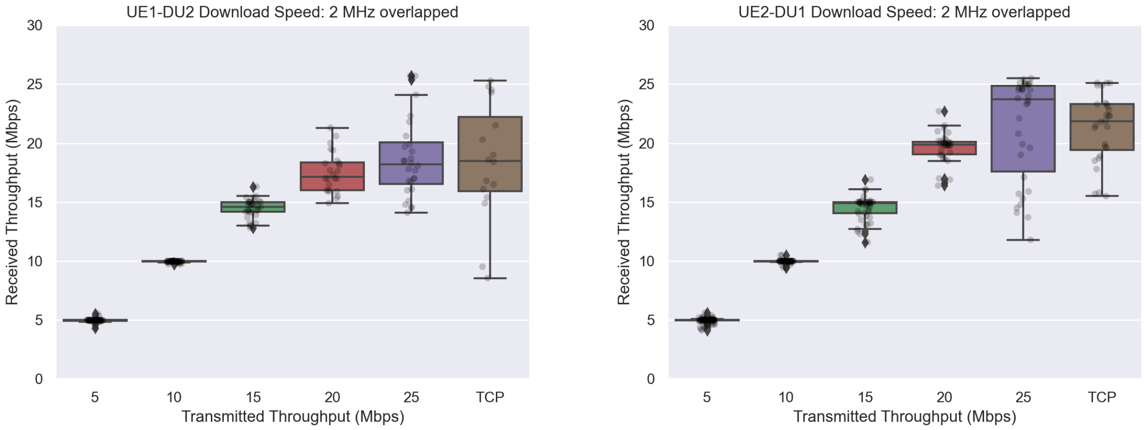


Figure 5.5: Download throughput transmitted and received for 5, 10, 15, 20 and 25 Mbps in UDP mode, and without requirements at TCP mode for 2 MHz of overlap.

reach peak throughput. Figure 5.5 reflects that when there is low throughput around 5 to 15 Mbps, it is stable and transmit at the desired speed. But on the other hand, when we increase this throughput to 20 or 25 Mbps, the system starts to have more problems, even if it reaches around 15 and 20 Mbps as mean values. In this case, there is still a good performance of the system, but the effects of having fewer resource block groups available all the time start to appear.

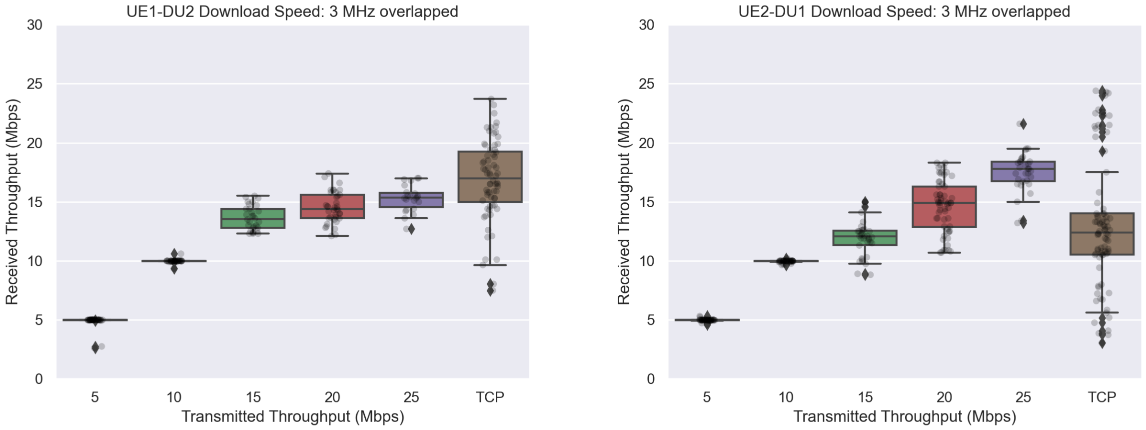


Figure 5.6: Download throughput transmitted and received for 5, 10, 15, 20 and 25 Mbps in UDP mode, and without requirements at TCP mode for 3 MHz of overlap.

In the following figures and increased frequency overlap, it is observed that the peak throughput is getting limited as the speed increases due to the availability of resource block groups because of the overlapping. This number of resource blocks that are available is increasing at Table 5.4 and for the 3 MHz overlap, it is more than one-third of the resource block groups that are overlapped.

In Figure 5.6, it can be seen that the peak throughput that the system can achieve is around 15 Mbps, even it is set to transmit higher throughput. It still has an acceptable throughput because there is coordination at the bandwidth, and some of the transmissions are not using the total bandwidth and only two-thirds of it. A similar response can be observed in both of the units.

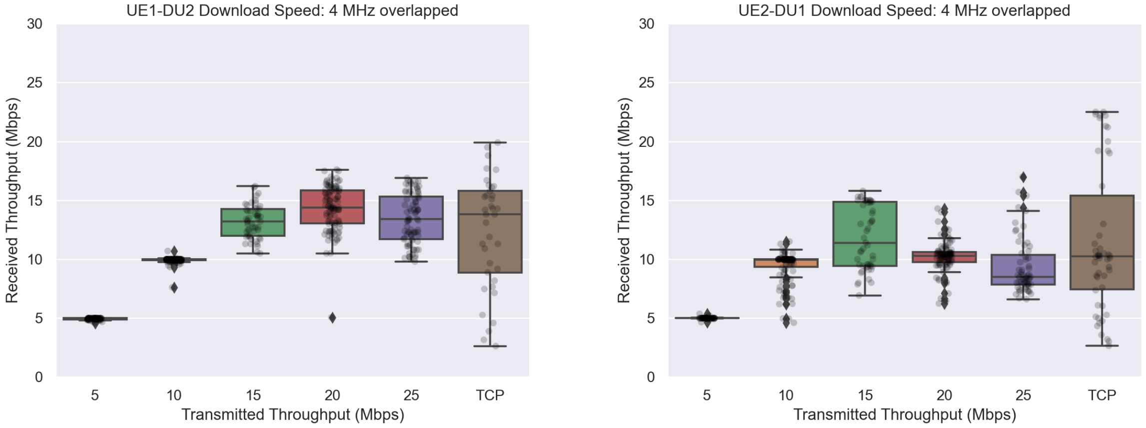


Figure 5.7: Download throughput transmitted and received for 5, 10, 15, 20 and 25 Mbps in UDP mode, and without requirements at TCP mode for 4 MHz of overlap.

In Figure 5.7, the peak throughput maintains around 15 Mbps as maximum. For lower throughput, it keeps a stable download speed around the required values, but for throughput higher than 15 Mbps, it cannot reach more than it. In this case TCP throughtput is also reducing its capabilities, and for higher throughput, the stability of the system is worst because there is a higher difference between the first and third quartile. This is because there is a higher dispersion of values and the transmission speed is not stable at one value.

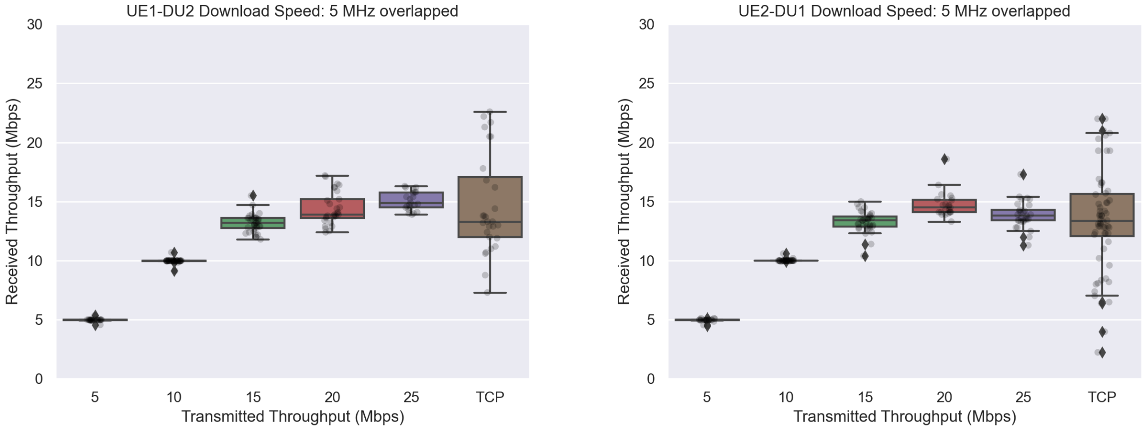
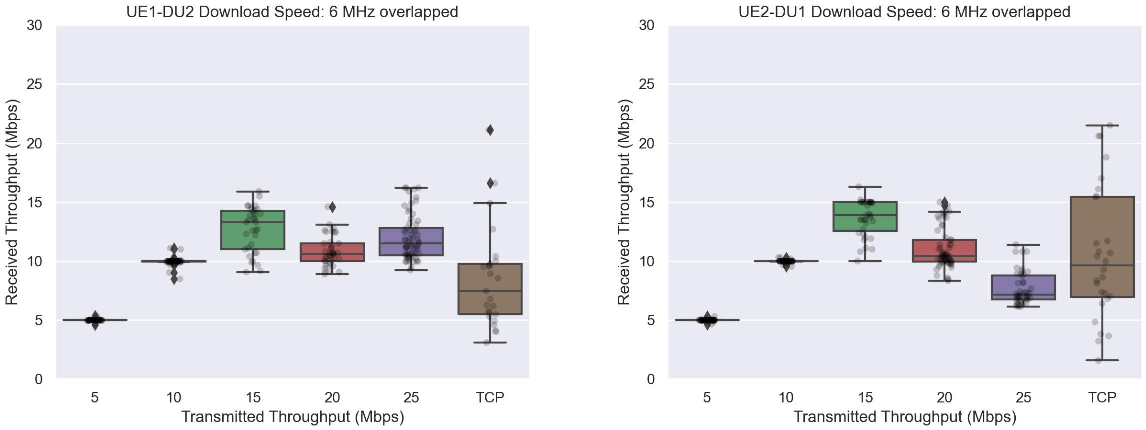


Figure 5.8: Download throughput transmitted and received for 5, 10, 15, 20 and 25 Mbps in UDP mode, and without requirements at TCP mode for 5 MHz of overlap.

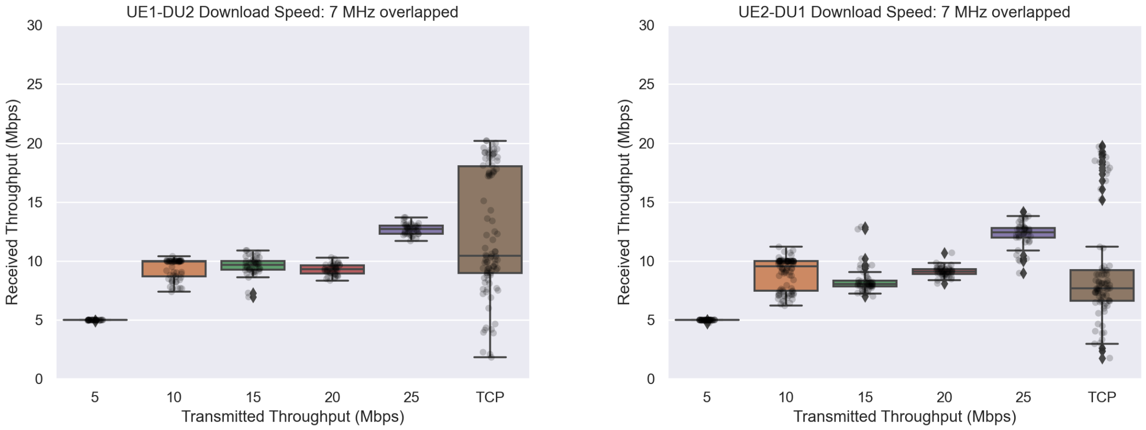
In Figure 5.8, the same conclusion as before is maintained. A reduction of the peak speed is shown in the figure, but there is less variability between the throughput reached in this case. Both units are working around the same values, so it is sharing the shared spectrum equitably.

The following Figure 5.9, shows the overlap of 6 MHz. Now, it is above half of the bandwidth, and there is more overlapped spectrum than not. For this and the subsequent increments it will be sharing more than half the spectrum, which will be translated into a reduction of the speed that can be achieved. The median speed value for the throughput above 10 Mbps is between 10 and 15 Mbps. Also, the TCP transmission has been reduced to these values. Once again, if the transmitted throughput is lower, it can be perfectly achieved, but as the overlap increments, it is harder to obtain the desired speed.


UE1-DU2 Download Speed: 6 MHz overlapped

UE2-DU1 Download Speed: 6 MHz overlapped

Figure 5.9: Download throughput transmitted and received for 5, 10, 15, 20 and 25 Mbps in UDP mode, and without requirements at TCP mode for 6 MHz of overlap.


UE1-DU2 Download Speed: 7 MHz overlapped

UE2-DU1 Download Speed: 7 MHz overlapped

Figure 5.10: Download throughput transmitted and received for 5, 10, 15, 20 and 25 Mbps in UDP mode, and without requirements at TCP mode for 7 MHz of overlap.

Continuing with the increment of overlap, in Figure 5.10 it can be observed that there is less difference between the first and third quartile compared to the 6 MHz overlap. Also, the median speed is around 10 Mbps for throughputs from 10 up to 20 Mbps and TCP. It can be seen that when there is a 25 Mbps download throughput, it can achieve around 12 Mbps. The throughput limit can be observed that it is approximately 10 Mbps.

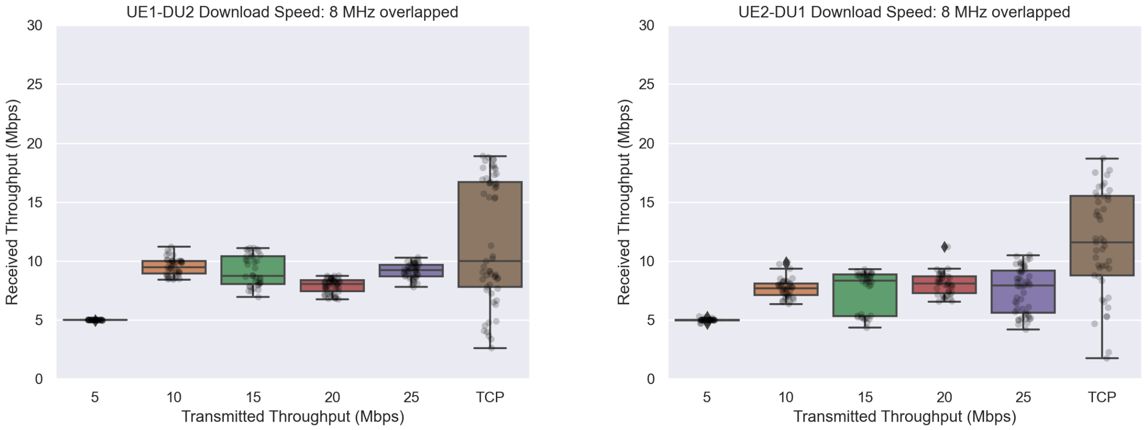


Figure 5.11: Download throughput transmitted and received for 5, 10, 15, 20 and 25 Mbps in UDP mode, and without requirements at TCP mode for 8 MHz of overlap.

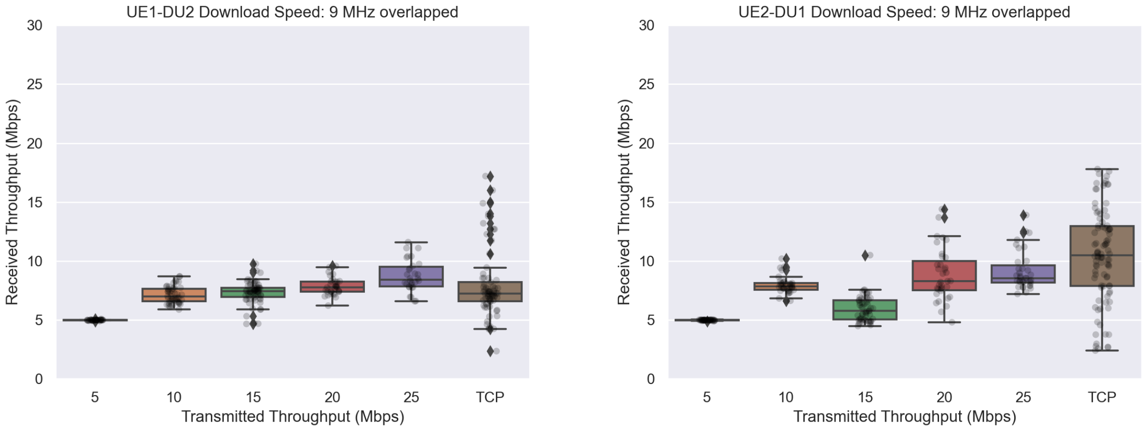


Figure 5.12: Download throughput transmitted and received for 5, 10, 15, 20 and 25 Mbps in UDP mode, and without requirements at TCP mode for 9 MHz of overlap.

And finally in Figures 5.11 and 5.12, the trend is the same. The upper throughput limit is getting lower with values near 10 Mbps, and the second-lowest download throughput is affected for the first time. As explained in previous cases, this is because of the availability of resource blocks and the number of resource block groups that are shared between the 82% and 94% of the total available without coordination.

During these tests, the connectivity was also affected. The system was able to connect in all the cases, but as the overlap increased, there were more issues while connecting.

Sometimes it took too much time to connect, or the other disconnected instantaneously when one unit was attached. Also, during the transmission, if it receives or detects any interference, the UE reports a worse channel quality. The DU decides to change into a lower modulation and coding scheme providing better error protection, but this decreases the spectral efficiency and therefore increases bandwidth usage.

More results, including the number of samples, mean, median and standard deviation for each overlap, and every throughput used in UDP and TCP mode are included in Appendix A.

Figure 5.13 shows that the system's performance is better in every frequency overlapped, except on the first. In some cases, it goes up to 3 times better. Even the system is limited because there are fewer resource blocks to transmit simultaneously at every instant. The coordination dynamically solves the problem of interference, distributing the bandwidth equative between the distributed units before every transmission.

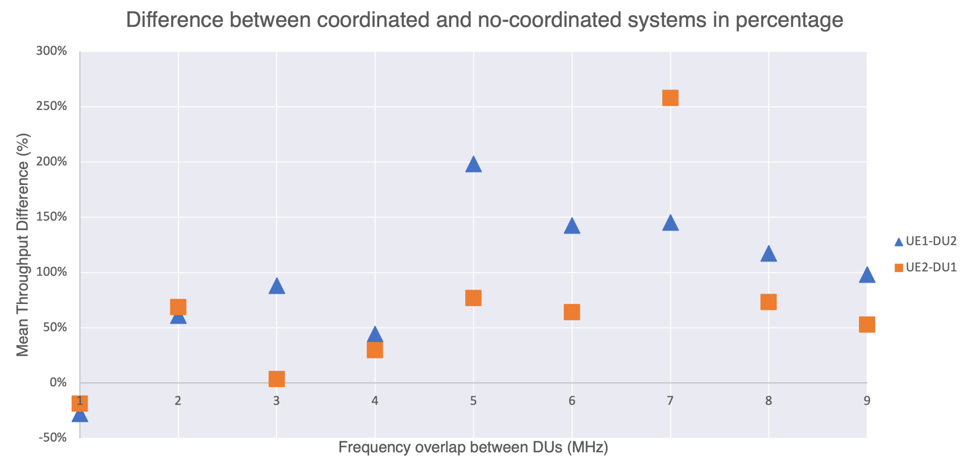


Figure 5.13: Difference between mean throughput in TCP while the systems are coordinated and not in percentage. Blue triangle: UE1 and DU2 connection; Orange square: UE2 and DU1 connection.

Chapter 6

Conclusions and Outlook

6.1 Conclusions

As we have seen during the report, there is a lack of research and contribution to mitigating inter-cell interference when there is a dynamic functional split. We have seen that when two units are transmitting in near-by frequencies, or at the same frequency, it appears interference that affects mainly in connectivity of the devices and the throughput and stability of the transmissions.

The Inter-cell Interference degrades spectral and energy efficiency, making it difficult to have a good performance of the whole system. Also, as there is a functional split working on the system, the MAC layer controls the scheduler, and sometimes, depending on the active split, it can relay the scheduling functions at the Centralized Unit or the Distributed Unit.

Taking advantage of this split of network functions, the system can switch between the different splits depending on the interference situation. While the system works in PDPC-RLC split, the MAC function is at the Distributed Unit, and the scheduling tasks cannot be coordinated with other units. But if the RLC-MAC split is active, the MAC layer relies on the Centralized Unit, and it can coordinate the multiple DUs that are interfering and assigned to that CU.

The Centralized Unit is receiving the information about the frequencies used by the Distributed Units. It calculates the overlap that the spectrum of the Distributed Units has. In case there is interference, it obtains the number of Resource Block Groups that are overlapped and modifies the scheduler according to this restriction. Also, as all the MAC layers, and therefore scheduler policies of each Distributed Unit assigned to the Centralized Unit can be modified, it can establish coordination between all the CU instances.

This coordination can be done through the Xn interface, as it connects multiple Centralized

Units to exchange information about the connectivity. Each centralized unit instance takes a number with a probability of 1/Number of DUs Interfered and shares it with the rest of instances. In case they match, the process is repeated. In the particular case of this thesis, it was tested with two interfering units, and then the probability is 50%. After verifying all the priorities, it assigns the capability of transmitting at the overlapped resource block groups. Before each transmission, the CU randomly allocates the use of the shared spectrum to avoid interference of other units and balances its usage having a better performance of the system.

As it is shown in the Results Chapter, the connectivity between the units is possible in all overlapping cases, except when there is a complete overlap, where only one of the units can connect. Regarding the performance, it has been tested in two different modes: TCP and UDP. TCP was used to check how the throughput can be reached without taking care of the reception and content of the packets. It was tested before any modification of the system was done to check that the premises of the problem statement were true. It was checked that the system, as it became more overlapped, it was reducing the throughput drastically. After the coordination was implemented, the system was also degrading but not as much as previously.

6.2 Future work

As future work could be the implementation for multiple distributed units. As it has been tested that it works with at least two distributed units, it would be interesting to see how the system behaves when there are more units connected at the same time. It will test how the coordination works between different units, as one unit should coordinate with at least two other units to use the spectrum. Also, the throughput will be affected, and the peak might be low because it might be that both units that are coordinating with the main one are using the resource blocks that are shared at the same time, and there might be less to be used by the system. This could be a situation similar to an 8 MHz or 9 MHz overlap where around 80% and 90% of the resource block groups are shared, and they are used with a probability of 50%. But probably it will be better than compared with no coordination between all the units, as including a new unit will add more interference to the main unit.

Also, a new modification could be the modification of the management of the migration of the functions that are changed between the Distributed Unit and Centralized Unit in order to switch between both splits dynamically and automatically when it detects that there is an overlap between the Distributed Units that are connected at the same Centralized Unit.

Appendix A

Results

A.1 Mean, median and standard deviation for coordinated mitigation

	5 MHz	**10 MHz**	**15 MHz**	**20 MHz**	**25 MHz**	**TCP**
Samples	26	26	42	33	38	50
Mean	4,985	9,903	14,890	18,579	23,939	20,770
Median	4,990	9,975	15,000	18,600	24,900	22,800
Standard Deviation	0,127	0,472	0,514	1,190	1,859	7,364

Table A.1: Number of samples, mean, median and standard deviation for 5, 10, 15, 20, 25 MHz in UDP mode, and in TCP with 1 MHz of overlap.

	5 MHz	**10 MHz**	**15 MHz**	**20 MHz**	**25 MHz**	**TCP**
Samples	71	48	43	34	34	28
Mean	4,937	9,971	14,493	19,603	21,350	21,286
Median	5,000	10,000	14,900	19,850	23,700	21,850
Standard Deviation	0,241	0,171	1,038	1,349	4,392	2,895

Table A.2: Number of samples, mean, median and standard deviation for 5, 10, 15, 20, 25 MHz in UDP mode, and in TCP with 2 MHz of overlap.

	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	TCP
Samples	42	37	34	58	31	82
Mean	4,981	9,956	11,898	14,626	17,529	13,045
Median	5,000	10,000	12,050	14,900	17,800	12,400
Standard Deviation	0,100	0,100	1,534	2,212	1,700	5,427

Table A.3: Number of samples, mean, median and standard deviation for 5, 10, 15, 20, 25 MHz in UDP mode, and in TCP with 3 MHz of overlap.

	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	TCP
Samples	61	111	51	98	63	50
Mean	4,997	9,379	11,832	10,226	9,386	11,437
Median	5,000	9,970	11,400	10,300	8,500	10,250
Standard Deviation	0,074	1,334	2,688	1,280	2,374	6,168

Table A.4: Number of samples, mean, median and standard deviation for 5, 10, 15, 20, 25 MHz in UDP mode, and in TCP with 4 MHz of overlap.

	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	TCP
Samples	20	34	35	23	29	60
Mean	4,949	10,016	13,286	14,748	13,886	13,424
Median	5,000	10,000	13,400	14,500	13,800	13,350
Standard Deviation	0,159	0,111	0,892	1,091	1,162	4,314

Table A.5: Number of samples, mean, median and standard deviation for 5, 10, 15, 20, 25 MHz in UDP mode, and in TCP with 5 MHz of overlap.

	5 MHz	10 MHz	15 MHz	20 MHz	25 MHz	TCP
Samples	52	43	35	61	44	28
Mean	4,991	9,983	13,663	10,998	7,692	10,608
Median	5,000	10,000	13,900	10,400	7,165	9,630
Standard Deviation	0,072	0,122	1,545	1,676	1,416	5,620

Table A.6: Number of samples, mean, median and standard deviation for 5, 10, 15, 20, 25 MHz in UDP mode, and in TCP with 6 MHz of overlap.

	5 MHz	**10 MHz**	**15 MHz**	**20 MHz**	**25 MHz**	**TCP**
Samples	46	93	50	47	42	82
Mean	4,988	8,984	8,338	9,108	12,287	9,081
Median	5,000	9,560	8,040	9,100	12,450	7,680
Standard Deviation	0,041	1,331	1,134	0,429	1,104	4,702

Table A.7: Number of samples, mean, median and standard deviation for 5, 10, 15, 20, 25 MHz in UDP mode, and in TCP with 7 MHz of overlap.

	5 MHz	**10 MHz**	**15 MHz**	**20 MHz**	**25 MHz**	**TCP**
Samples	38	42	38	40	50	45
Mean	4,991	7,705	7,529	8,068	7,530	11,516
Median	5,000	7,705	8,355	8,105	7,940	11,600
Standard Deviation	0,106	0,797	1,700	0,956	1,910	4,341

Table A.8: Number of samples, mean, median and standard deviation for 5, 10, 15, 20, 25 MHz in UDP mode, and in TCP with 8 MHz of overlap.

	5 MHz	**10 MHz**	**15 MHz**	**20 MHz**	**25 MHz**	**TCP**
Samples	39	37	53	35	35	94
Mean	4,987	7,939	5,954	8,846	9,162	10,464
Median	5,000	7,840	5,770	8,290	8,550	10,500
Standard Deviation	0,030	0,736	1,107	2,216	1,640	3,973

Table A.9: Number of samples, mean, median and standard deviation for 5, 10, 15, 20, 25 MHz in UDP mode, and in TCP with 9 MHz of overlap.

Appendix B

Abbreviations

3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5GC	Fifth Generation Core
ABS	Almost Blank Subframes
AMF	Acces Management Function
AP	Access Point
API	Application Programming Interface
BER	Bit Error Rate
CQI	Channel Quality Indicator
CU	Centralized Unit
CUPS	Control and User Plane Separation
D2D	Device to Device
DCI	Downlink Control Information
DL	Downlink
D-SR	Dedicated Scheduling Request
DU	Decentralized Unit
eICIC	enhanced Inter-cell Interference Coordination
EIRP	Effective Isotropic Radiated Power
eMBB	Enhanced Mobile Broadband
eNodeB	evolved Node B or E-UTRAN Node B
EPC	Evolved Packet Core
E-UTRA	evolved UMTS Terrestrial Radio Access
FDD	Frequency Division Duplexing
FeICIC	Further enhanced Inter-cell Interference Coordination
gNB	next-generation NodeB
GUI	Graphical User Interface
GW	Gateway
H-ARQ	Hybrid-Automatic Repeat Request

HSS	Home Subscriber Server
IA	Interference Alignment
ICIC	Inter-cell Interference Coordination
IoT	Internet of Things
IP	Internet Protocol
ITU-R	International Telecommunication Union
KPI	Key Parameter of Interests
LTE	Long Term Evolution
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIB	Master Information Block
MIMO	Multiple Input Multiple Output
ML	Maximum Likelihood
MME	Mobile Management Entity
MMSE	Minimum Mean Square Error
mMTC	Massive Machine-Type Communications
NAS	Non-access Stratum
NF	Network Functions
ng-eNB	new-generation enhancedNodeB
NG-RAN	New Generation Radio Access Network
NR	New Radio
NSA	Non-Stand Alone
OAM	Operations, Administration and Management
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiplexing Access
PCI	Peripheral Component Interconnect
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDSCH	Physical Downlink Shared Channel
PDU	Protocol Data Unit
PHY	Physical Layer
PRB	Physical Resource Block
PSK	Phase Shift Keying
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
RACH	Random Access Channel
RAM	Random Access Memory
RB	Resource Block
RBG	Resource Block Group
RLC	Reverse Link Channel
RRC	Radio Resource Control

S/P-GW	Serving/Packet Gateway
SA	Stand-Alone
SBA	Service-Based Architecture
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDAP	Service Data Adaption Protocol
SDN	Software Defined Network
SDR	Software Defined Radio
SIB	System Information Block
SINR	Signal to Noise Ratio
SR	Scheduling Request
SRS	Sounding Reference Signal
TCP	Transmission Control Protocl
TDD	Time Division Duplexing
TDMA	Time-Division Multiplexing Access
UDP	User Datagram Protocol
UE	User Equipment
UL	Uplink
UPF	User Plane Function
URLLC	Ultra-Reliable Low-Latency Communications

List of Figures

List of Tables

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