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5G Beamforming

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Abstract

Spectrum is a scarce and expensive resource and thus operators are always looking to get the most bits out of every portion of spectrum they have. This is particularly important within a context of ever growing traffic demand. Maximizing the spectral efficiency, providing a good coverage and fair usage are the main drivers on mobile networks behind optimization procedures in general and adoption of advanced antenna technologies in particular. Beamforming enables directional transmission which is crucial to extend coverage on bands that can apply it, while also improving radiolink quality, reducing interference, and increasing cell capacity by exploiting resource sharing across spatially separated users.

This thesis provides a comprehensive account of the principles behind beamforming and its application in 5G networks. It examines the necessity of channel information for beamforming and explores different beamforming techniques in 5G that are used towards beam definition for broadcast and traffic purposes, each with its own advantages and disadvantages. This work explains those beamforming techniques, how they are used and on which scenarios they are most suitable.

Field tests were used to exemplify the benefits and drawbacks of each of the presented beamforming methods. SRS-based beamforming showed better results on near and mid cell scenarios, while codebook-based beamforming proved useful for better performance on the cell edge. Beam customization on real time showed also a great improvement on static and walking tests while no clear gain was shown at a driving pace.

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Dedication

*A mi padre, Gabriel, cuya curiosidad y conocimiento me acompañana
constantemente como referencia para buscar crecer como persona y profesional.*

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A mis tutores Claudina y Benigno que me apoyaron y motivaron a concluir el trabajo.

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Chapter 1

Introduction

Beamforming is an essential aspect of the 5th Generation (5G) of wireless technologies for mobile networks. It is arguably the most relevant introduction on the air interface and a key enabler to many objectives that the novel standard as a whole and its air interface in particular intend to cover. This thesis looks to summarize the most important aspects of 5G related to beamforming, as well as the different mechanisms that are used to gather channel information and carry out the beamforming processes.

In this Chapter, Section 1.1 provides context to this work, the motivation behind it and to what extent will the topic be addressed. Moreover, Section 1.2 introduces the general aspects of 5G, while 1.3 looks to explain what beamforming is and the general idea of beamforming applied on 5G. Finally Section 1.4 goes over the content of the following Chapters in the document.

1.1 Motivation and Scope of Work

Telecommunications are a crucial element of our daily life. Once a commodity, Internet connectivity is now widely regarded as a basic human right. The United Nations (UN) has emphasized the relevance of Internet access and how the recent COVID-19 pandemic has accelerated our dependence on connectivity [1], an aspect that is often taken for granted today.

The role of 5G in enhancing and further developing Internet connectivity, both in terms of traffic capacity and coverage, cannot be overstated. Moreover, beamforming is a crucial part of 5G. While it already existed in other technologies before, such as LTE and WiFi, this is the first time it is widely available and used. It is

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exploited in 5G as an enabler to increase capacity and enhance high bandwidth connection availability.

This thesis intends to take a deep dive into beamforming and its use on the 5G radio interface. While nowadays the industry has a very big role on driving the development of new beamforming related techniques, it is important that anyone who works on telecommunications has a good understanding of what is going on under the hood when it comes to this novel application of a not-as-novel technology such as beamforming.

The approach taken on this document is to first describe the most relevant aspects of 5G, beamforming, and beamforming applied to 5G. Some of the aspects mentioned are then further covered with real case field tests performed on an up and running 5G network from a local Mobile Network Operator (MNO). These takes do not intend to be conclusive on how beamforming performs. Instead, they look to exemplify how beamforming is applied on 5G. The actual beamforming perceived by customer will in the end depend on many aspects of the network, most notably the hardware and software used on both the base station and on the user side.

These tests allow to get some sense and insight of what to expect when using this technology on live 5G networks, how radio performance can be improved through beamforming, and how that varies across different coverage scenarios and beamforming methodologies. Furthermore, the tests carried out on this work and the theory behind them allows an operator to understand on which scenarios each of the beamforming algorithms available and presented on this document are most suitable.

1.2 5G New Radio

When talking about 5G, there are always three main objectives and use cases that are addressed to introduce this technology. In summary, 5G aims to fulfill three main overlapping objectives: Enhanced Mobile Broadband (EMBB), Ultra Reliable Low Latency Communications (URLLC), and Massive Machine Type Communications (MMTC). These service objectives can be outlined as shown in Fig. 1.1.

The ITU-R report *Minimum requirements related to technical performance for IMT-2020 radio interface(s)* [2] outlines the numerical objectives that the 5G radio interface should achieve. Fig. 1.2 shows some number targets presented on [3], which mark objective improvements of IMT-2020 over the previous IMT-Advanced.

1.2. 5G New Radio

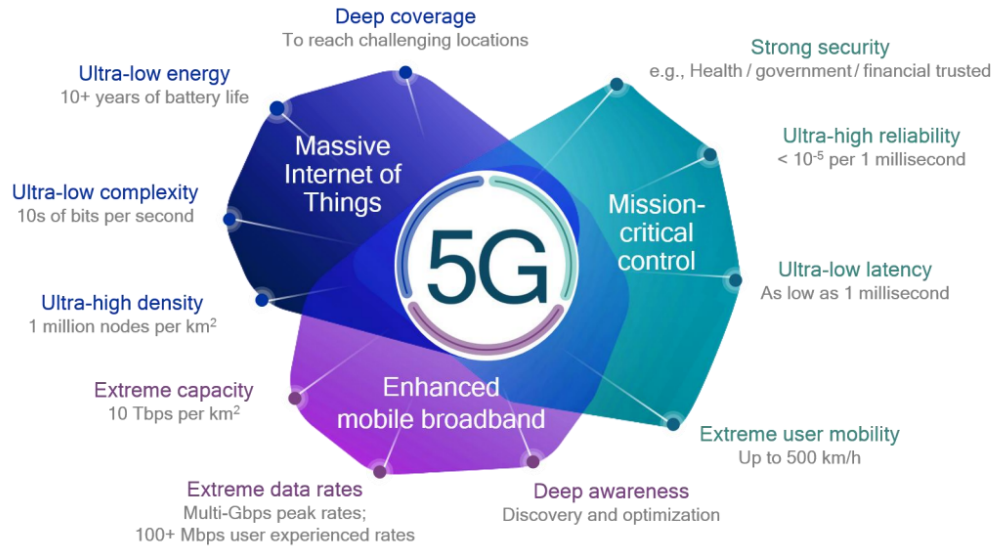


Figure 1.1: Qualcomm summary of 5G objectives: Enhanced Mobile BroadBand, Mission-critical Control (or URLLC), Massive Internet of Things (or mMTC) (source [4]).

Enhanced Mobile Broadband focuses on increasing data transfer speeds and capacity. According to Ericsson's Mobility Report, data traffic has been increasing over the past four years [5]. Although the annual growth rate has decreased from approximately 50% to 20%, it still indicates significant growth year-on-year. Fig. 1.3 presents this increase in traffic. Therefore, 5G networks must be able to accommodate the increasing demand for data. Not only that but the more content one wants to download, the higher the data rate demand needed.

Moreover, another focus point is Ultra Reliable Low Latency Communications. This objective involves ensuring wide availability of 5G with minimal outages and quick communication to target servers. Augmented Reality (AR) and Virtual Reality (VR) are typical use cases which require interaction between environment and some processing that goes on in the cloud. Vehicle related communications, like Vehicle-to-Vehicle (V2V) or Vehicle-to-Anything (V2X) could be some interesting use cases in which an autonomous vehicle could leverage information from other near-by entities exchanging road or traffic information, or whichever other data could be of interest for autonomous mobility purposes. Those are scenarios that will potentially demand very low latency on the radio interface. Thus, this objective intends to comply with these use cases.

The 3rd and last goal is Massive Machine Type Communications. The 5G network should allow several simpler devices to be connected on the network, such as home appliances, widely spread measurement equipment, or whichever device that needs a simple Internet connection. These devices may also rely on low energy consumption, enabling a long battery lifetime thus avoiding having to change its

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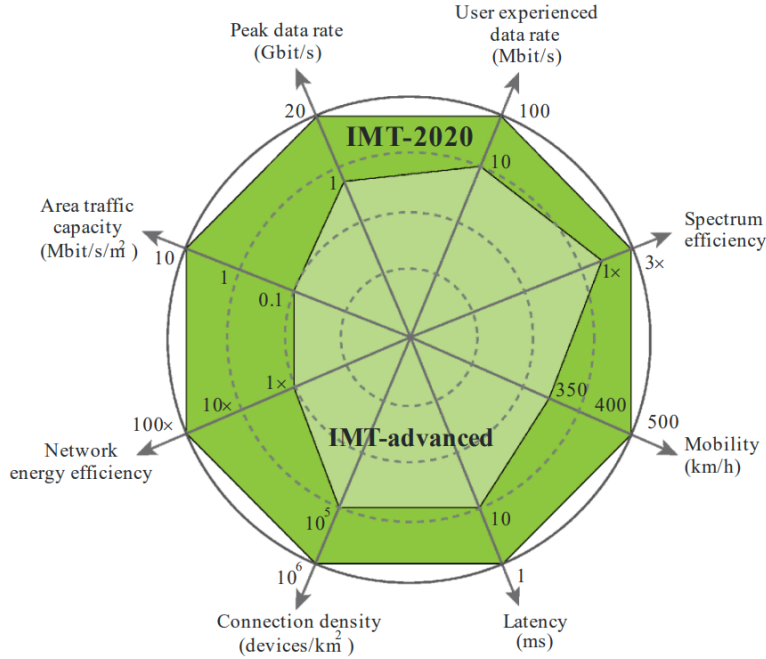


Figure 1.2: Enhancement of key capabilities from IMT-Advanced to IMT-2020 (source [3]).

batteries every now and then. This is an evolution to LTE's approach to IOT services, with its NB-IOT and LTE-M variants.

5G tries therefore to be *one network to rule them all*, able to accommodate several very different use cases. A flexible network and radio interface is therefore needed, which can be molded to serve any of those very diverse purposes.

The radio interface has to change in 5G when compared to LTE, with these objectives and flexibility in mind. This new radio access technology is called New Radio (NR), the new radio interface that is used in 5G.

The fact of the matter is, though, that as of the moment of this document there have not been any *killer apps* for 5G. Every new generation has had its main use case or main application. It was digital voice or SMS on GSM/GPRS, or emailing and Internet browsing on HSPA. On LTE the smartphone boom and with it the app-based approach to the mobile Internet services required much more data and faster speeds than the ones we had before.

On 5G there is none, not yet. That is certainly not to say that it is useless. On the contrary, 5G has come to allow for that data consumption curve to keep on increasing, to serve all this new data and in a faster manner with a better user experience of Internet connectivity. But, at the end of the day, this is what we used to do on LTE, only better. We have the same applications with the same

1.2. 5G New Radio

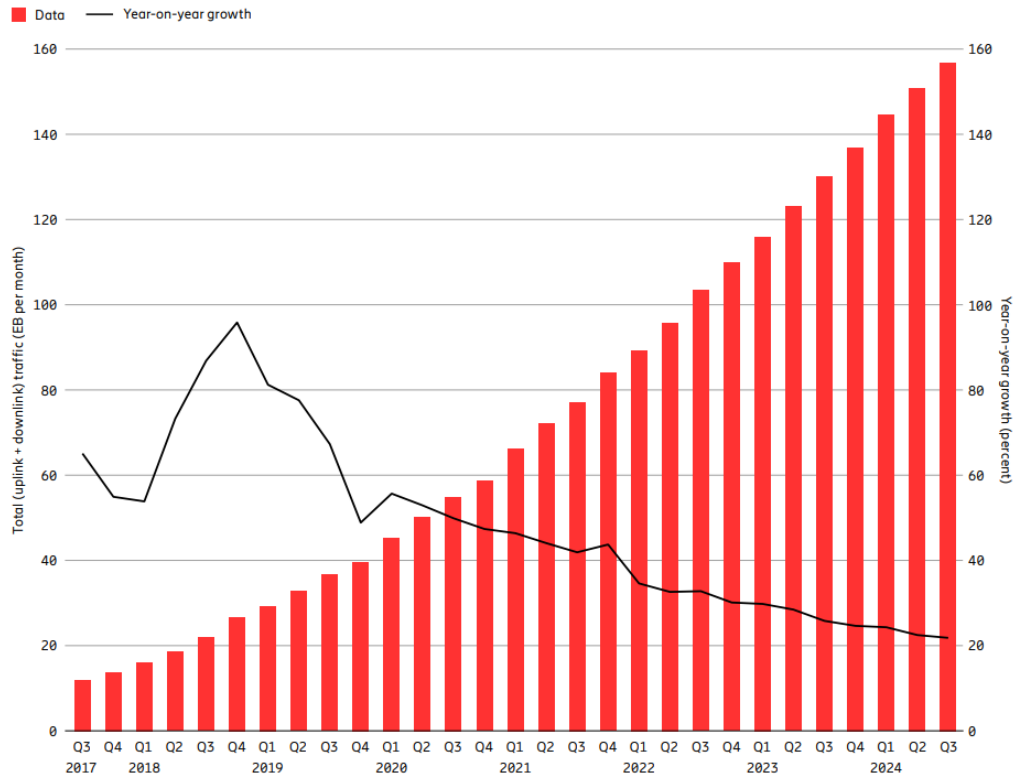


Figure 1.3: Global mobile network data traffic and year-on-year growth (EB per month) according to Ericsson Mobility Report [5].

sort of requirements, only more demanding. More data transfer, higher data rates, maybe somewhat lower latency... but that is not entirely new and not impossible to achieve with only LTE.

Thus, while 5G is evidently very important for the future of mobile networks and Internet connection, it has not found its killer app, that thing that can rely only on a 5G network and nothing else. Maybe it will be AR with devices like Apple Vision Pro starting to come out, or V2X with autonomous vehicles starting to become a reality... whichever it may be, the network needs to be there. As they say, *build it and they will come*.

As a technology, 5G aims then to fulfill all of these different objectives and services. Much more than an upgrade to existing LTE, 5G looks to be a change of paradigm on mobile communications, with a focus on flexibility to cover such diverse scenarios. As such, it introduces changes and the Radio Access Network (RAN) side but also on the Core Network (CN) side.

The RAN is comprised of the deployed base stations around the region. Beam-forming, which will be introduced on the next Section 1.3, is used to exploit much

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higher frequency bands and enable them for mobile communications. It also allows to improve the spectral efficiency and thus get more bits sent over the same radio frequency band which improves network capacity within a context of increasing traffic demand.

Meanwhile, the CN involves a completely revamped approach. It offers a cloudified approach to the core deployment. While back on LTE the Evolved Packet Core (EPC) could be deployed on COTS (Commercial Off The Shelf) hardware it was not how it was conceived from the start. The 5GC (5G Core) is introduced with separate instances and functions right from the start, that can be initialized and added as needed.

Furthermore, Control and User Plane Separation (CUPS) is a central aspect of the 5GC. While CUPS could be done on the EPC by disaggregating the control and user plane functions of some of its elements, those were not initially conceived as separate functions. The 5GC clearly separates the user plane from the control plane by separating those functionalities on different entities.

5G comprises therefore of a new approach towards mobile communications, which enables a more optimized and flexible form of communications, covering a wide variety of use cases and an expanding demand on mobile traffic.

1.3 Beamforming and 5G

Beamforming is arguably the most important aspect of the 5G radio interface. Massive MIMO (Multiple Input Multiple Output) involves using multiple antenna elements on the transmitter and receiver sides. These antenna elements work in conjunction to do the beamforming, which allows to focus the electromagnetic wave on a certain direction. It is called beamforming because a beam is formed through which the information is transmitted to the user or received from it.

This technique can be used to improve the quality of the radio link between the user and the base station. Without beamforming the transmission power is sent through the whole coverage sector of the cell. By focusing the power in a specific direction the coverage can be improved as the transmission gain is increased. Not only that, but also less power is sent towards unintended directions, which helps reduce the overall interference in the network; power is only sent to where it is needed.

On top of that, beamforming allows to exploit the radio interface even further by enabling the use of MU-MIMO (Multi User - Multiple Input Multiple Output). MU-MIMO takes advantage of power focus in order to send traffic and power to multiple users on the same radio resources, given that they are far enough

1.4. Document Structure

from each other so as to avoid interference between the traffic beams used. This improves the spectral efficiency in the network, as the same radio resources can be used to transmit much more data, through as many beams as can be distinguished while keeping interference limited.

Massive MIMO cannot be applied on all frequencies, though. The higher the frequency the more little the size of each antenna is. Therefore higher frequencies allow to set up more antenna elements within a radio equipment. At above 2 GHz this becomes feasible and radio equipment that relies on Massive MIMO with beamforming can be used.

5G even introduces new bands when compared to LTE that would not even be usable for mobile communication if it were not for beamforming. Bands on 26 GHz, 28 GHz, 39 GHz are new options in 5G. In these frequencies the propagation loss due to Friis is very high and it is quite difficult to get a reliable radio link. Beamforming allows to partially overcome these limitations and allow the data transmission on mobile communications over this frequencies to be realizable.

Beamforming is the key enabler in 5G to exploit the air interface even further and increase the spectral efficiency and thus how many bits can be transmitted over each radio resource. Radio resources are scarce resources. It takes quite a lot of investment in order to acquire a license to transmit over a certain band on a certain region. Thus, it is of the utmost importance for mobile operators to get as much return as possible on that investment, to be able to exploit that band and being able to transmit as many bits as possible over those resources. On a context of persistently increasing traffic demand it is of paramount importance to be efficient on the radio resources and to be able to carry out such traffic without it taking its toll and degrading the user experience.

1.4 Document Structure

The following chapters further develop general aspects about 5G, its radio interface and beamforming related methods. Chapter 2 covers the main aspects of the 5G New Radio (NR) air interface and Chapter 3 covers general aspects of beamforming and how it applies to NR. Within that Chapter, Section 3.2 covers the Multi User - Multiple Input Multiple Output (MU-MIMO) aspects which allows to send traffic towards two or more separate users over the same radio resources. This is a fundamental aspect of the radio interface that allows a big increase on network capacity and therefore deserves its own chapter.

Chapter 4 covers the two possible approaches towards defining the beam that will be used for sending traffic towards the user. Codebook-based beamforming and SRS-based beamforming, respectively, are the main methods used to gather

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and exchange channel information in order to do the actual beamforming and select the best beam possible over which traffic will be sent to the user. After discussing the topics from a theoretical standpoint, Chapter 5 presents some field tests performed which allows to exemplify how beamforming works in 5G and how each beamforming method has its own advantages and disadvantages.

Finally, to close the thesis, Chapter 6 presents the general conclusions of this document. It also discusses some areas that could be interesting for further study as possible future works related to the beamforming application on 5G.

Chapter 2

NR Radio Interface

Before any beamforming is referred to, it is important to understand the main aspects of the 5G radio interface. Therefore, this Chapter covers general concepts of the New Radio (NR) radio interface, including physical channels, reference signals, and its protocol stack. The topics discussed in this Chapter are based on information available on books that were written by people who are on the industry and who have written books back on LTE as well. Holma et al. [6] is written by Nokia employees, while Dahlman et al. [7] also wrote their own Ericsson approach to the subject. There are even some books written by people across competing companies like Marsch et al. [8]. Moreover, Zaidi et al. [9] explore in more detail the 5G physical layer in their own book. Furthermore, the book by Afif et al. [10], which is written by a mix of industry and academic specialists, was introduced in 2016 and offered back then an idea of what was in store for 5G, and even introduces some concepts that did not make it to the actual standardization, at least not in the first releases of 5G. Some papers like [11] also look to summarize the main aspects of 5G.

These books and references in general cover varying aspects of the 5G technology. This Chapter introduces and summarizes some of those aspects based on the information presented on those documents, focusing on those which are considered more relevant to beamforming on 5G networks.

LTE's use of Orthogonal Frequency Division Multiple Access (OFDMA) enabled a more spectrally efficient and scalable approach to data transmission over the air interface when compared to its predecessor. Wideband Code Division Multiple Access (WCDMA) had to rely on a quick chip-rate that was harder to scale to wider carriers. This permitted using wider band size on cells, thus increasing 3G's 5 MHz maximum bandwidth to LTE's 20 MHz. Larger bandwidths and a widespread use of Downlink (DL) MIMO allowed LTE to surpass the 100 Mbps mark on application layer throughput.

Chapter 2. NR Radio Interface

NR maintains OFDM as its waveform for the air interface, although it tweaks and flexibilizes its configuration. Further, its protocol stack is very much similar to that of LTE. The Service Data Adaptation Protocol (SDAP) allows for a per-flow instead of per-bearer Quality of Service (QoS) management, but other than that all other layer 2 protocols that were defined on LTE, which are the Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC) and Medium Access Control (MAC), maintain their general functions.

In 5G the RAN is comprised of the 5G nodes which communicate with the user using this novel NR interface. These nodes are called Next Generation Node B (GNB) as an improvement over their LTE counterpart, the Evolved Node B (ENB). Pompous names aside, the GNB's duties within the network are the same that the ENB had before. The architecture within the GNB can be separated in a Centralized Unit (CU) and a Distributed Unit (DU), which allows the GNB to be deployed partly within the cloud and to reduce the footprint on site. This, though, is not always the case and it is deployed as a classical base station, just as the ENB was, more often than not.

These following Sections look to offer some insight and background of the 5G air interface and other 5G-related processes. It is important to have some understanding of how 5G works on the RAN side in order to get a better understanding of how the beamforming is applied and constructed.

Section 2.1 introduces the frame structure and how it is used on 5G, on both Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD) scenarios. The latter is of particular importance because it will determine how flexible the assignment of resources can be. For instance, Section 4.2 is focused on SRS-based beamforming which employs a reference signal sent from the user. This reference signal needs to be scheduled on UL resources, which are defined by the frame structure chosen.

Section 2.2 covers the physical channels which are important to comprehend how the communication is setup between the user and the node and how each one of the channels serves different purposes, as well as when are they transmitted and on what resources. Not only that, but it is also important to understand how they are used in order to understand what sort of beamforming can be applied to those channels. It also addresses the main reference signals that are used for channel estimation on different circumstances. These reference signals are what beamforming will be using to gather channel information.

Section 2.3 explores the NR physical layer, which provides some context to the actual beamforming process. This allows to get a grasp of on which stage of the transmission and reception it is applied and to get some sense of what other physical layer mechanisms are in place to improve the radio transmissions. Single User MIMO (SU-MIMO) and the concept of MIMO layer is an important aspect

to beamforming. A MIMO layer is an independent data transmission over MIMO resources. It introduces the usage of different transmitters and receivers to try and get independent transmissions through the radio interface. It sets the stage for beamforming as whichever beam or set of beams are chosen for the transmission it should be able to accommodate more than one MIMO layer. The concept of layer is then extended on MU-MIMO to also consider separate simultaneous transmission to different users, which is further discussed on Section 3.2.

Section 2.4 allows to have some understanding of the protocols that make up the radio interface in NR, how the data comes to the beamforming processes and which mechanisms are in place to make up possible failures on the physical layer.

Finally, Section 2.5 explains how the first 5G deployments are introduced on the networks. Dual Connectivity (DC) allows for a quick introduction of 5G and some of its benefits without having to setup a 5GC and without depending solely on 5G coverage for the radio communications, which may be lacking on some places as it is being deployed. Eutra New Radio Dual Connectivity (ENDC) has the user connected to LTE and then adding 5G on top of that. Beamforming on the DL can be much more exploited on these scenarios. DL coverage is often better than the UL. ENDC deployments allow to offload DL traffic to 5G without relying on UL 5G coverage, as the UL traffic can be carried out over the legacy LTE. This in turn enables greater 5G cell coverage which also allows to get the best of the 5G coverage improvement with beamforming gains.

2.1 Numerology and Frame Structures

While the waveform is the same OFDM introduced by LTE to mobile networks, the Sub-Carrier Spacing (SCS) used is now customizable. The μ parameter is defined for this purpose. The sub-carrier spacing is thus defined on 5G as $\Delta f = 15 \text{ kHz} \times 2^\mu$, with μ taking values from 0 to 4 and its configuration depends on the frequency range employed. This is called numerology as in μ can take different values depending on chosen deployment. There are two frequency ranges defined for 5G:

- FR1 covers bands below 6 GHz that can be either FDD or TDD.
- FR2 covers bands above 6 GHz on TDD, often called mmWave because of the small wavelength in these frequencies.

5G therefore covers a very wide range of frequencies which allows for a flexible deployment across available spectrum for different sort of purposes. Higher frequencies hold much more spectrum, at the expense of a lower coverage. 5G cells at around 28 GHz in FR2 can be as wide as 400 MHz, albeit at a much shortened service area when compared to FR1, and needing in many cases Line of Sight (LoS). On the other hand, cells on the lower end of the radio spectrum do not have as much available spectrum but can reach much further distances. This is depicted on Fig. 2.1, which represents the duality between coverage and capacity across varying frequencies used for mobile communications.

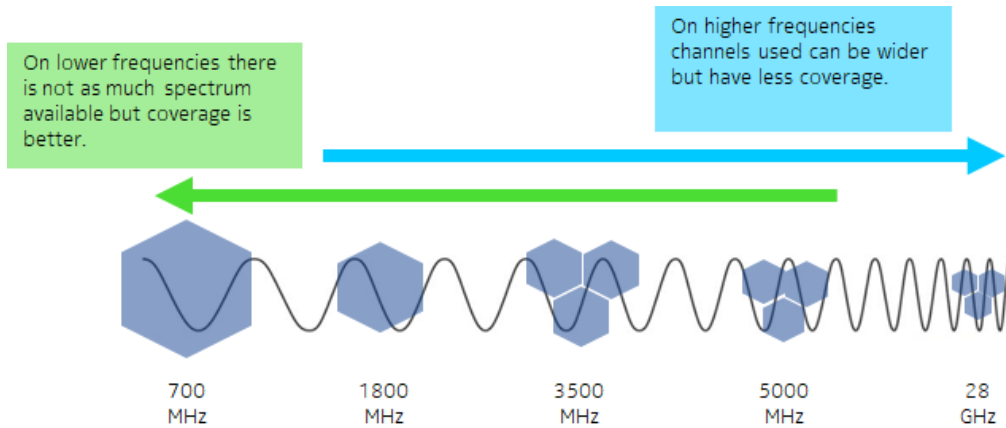


Figure 2.1: Depiction of the duality between coverage and capacity across possible deployment frequencies. As frequencies get higher the available spectrum, and thus capacity, increases. On the other hand, with lower frequencies the cell coverage is higher.

FR1 cells can use either 15 kHz, 30 kHz or 60 kHz SCS, while FR2 cells can be configured with either 60 kHz, 120 kHz or 240 kHz SCS. An increased SCS allows

2.1. Numerology and Frame Structures

to cover a wider band without having to resort to a very large number of sub-carriers and a larger FFT size. It also allows for a shorter symbol time, which may help decrease latency on the air interface. This, though, comes at the expense of a diminished Cyclic Prefix (CP), which is also shortened and thus the Delay-Spread (DS) requirements become more stringent. As per OFDM design, the CP should be designed to be bigger than the DS to avoid inter-symbol interference.

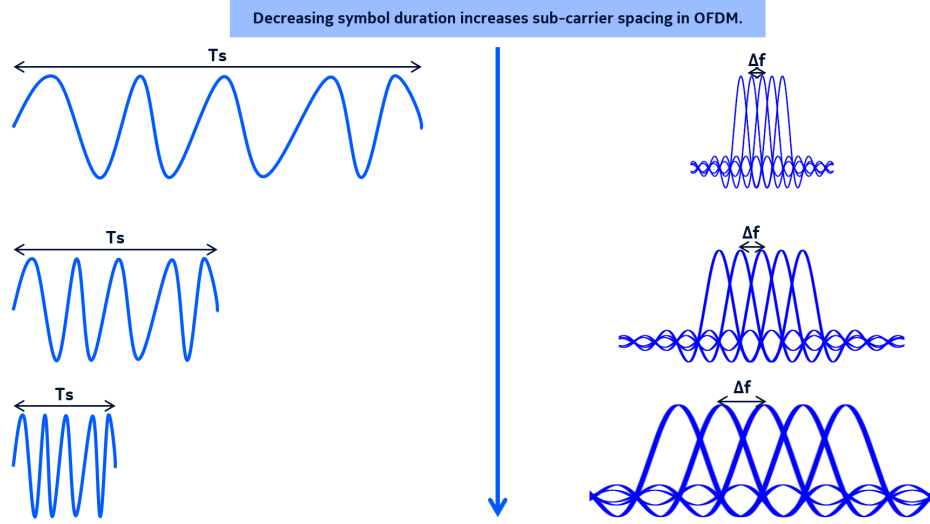


Figure 2.2: OFDM symbol duration is inversely proportional to the sub-carrier spacing used. $T_S = 1/\Delta f$.

Therefore, these bigger SCS options are used on FR2 scenarios where cell bandwidths can be higher and delay-spread may not be as big, given that multi-path in these frequencies is not as likely as on lower bands. In fact, high data transmission without LoS on these frequencies is quite difficult. What is more, higher frequencies show wider doppler-spread values and thus benefit from wider sub-carriers.

Changing the numerology of the OFDM waveform changes the symbol duration $T_S = 1/\Delta f$. Consequently, the general frame structure must adapt to these varying values. This is represented visually on Fig. 2.2.

A frame is defined having 10 ms duration, and it is divided in 10 sub-frames (SF) that each lasts always 1 ms. A time slot is comprised of 14 OFDM symbols and therefore the amount of time slots on each sub-frame and the duration of each time slot will both depend on μ just as the symbol duration varies with this same parameter. Table 2.1 shows how physical layer parameters and general frame structure configure are dependant on the setting of μ numerology. This is also presented graphically on Fig. 2.3.

On FDD the frame structure does not vary in the slot type in the sense that all defined slots carry DL and UL information, on different DL and UL frequencies

Chapter 2. NR Radio Interface

Table 2.1: NR Physical Layer parameters dependance on μ .

μ	Δf	sym. dur.	slot dur.	slots/sf	FR
0	$\Delta f = 15 \text{ kHz}$	$66.67 \mu\text{s}$	$1000 \mu\text{s}$	1	FR1
1	$\Delta f = 30 \text{ kHz}$	$33.33 \mu\text{s}$	$500 \mu\text{s}$	2	FR1
2	$\Delta f = 60 \text{ kHz}$	$16.67 \mu\text{s}$	$250 \mu\text{s}$	4	FR1 or FR2
3	$\Delta f = 120 \text{ kHz}$	$8.33 \mu\text{s}$	$125 \mu\text{s}$	8	FR2
4	$\Delta f = 240 \text{ kHz}$	$4.17 \mu\text{s}$	$62.5 \mu\text{s}$	16	FR2

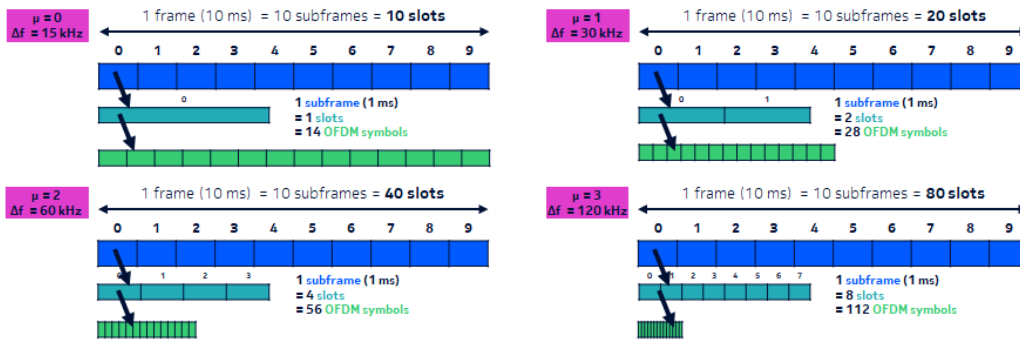


Figure 2.3: Slots and OFDM symbols on different configurations of SCS.

respectively.

In contrast, TDD frame structure is configured on a frame-basis. A slot pattern is used to define what kinds of slots are used on each moment, varying the slot content with either DL, UL, or guard symbols. Fig. 2.4 shows examples of frame structures used in 5G networks.



Figure 2.4: Examples of different possible frame structures. Slots are numbered from 0 to 19, showing a whole frame on 30 kHz SCS. D slots are used for Downlink, U for Uplink and S slots, sometimes called "Special" slots are used for transition between D and U.

Whichever slot format and slot pattern is chosen, it must account for the wave propagation speed and maximum cell radius. The switch from Downlink (DL) sym-

2.2. Physical Channels and Reference Signals

bols to Uplink (UL) symbols must have a guard time in-between which accounts for the longest possible Round Trip Time (RTT) possible on the cell service area.

In TDD as the same band range is used for DL and UL, interference from a DL transmission being received on near-by UL listening cells should be avoided. Guard times allow for the cell propagation to reduce the power before it is received on neighbour cells.

This general configuration setup allows for a very flexible air interface. Be that as it may, in practice operators within a common region sharing the same band (not the same frequency, but the same band) need to coordinate this frame structure to avoid inter-operator interference between DL and UL symbols. Thus, while the standard gives the possibility to have a very flexible air interface, this is somewhat limited in practice to whichever agreement can be reached between operators using that same band, either on NR or on other technologies (e.g. LTE, WiMax).

Such an agreement can be more flexible on high bands like 20 GHz or 30 GHz as the propagation can be more easily confined to certain spaces and thus avoid interference between different base stations and operators.

2.2 Physical Channels and Reference Signals

The OFDMA structure allows for a grid-based resource assignment process, with time on one axis and frequency (OFDM sub-carriers) on the other. Each subcarrier resource over a single OFDM symbol is called a Resource Element (RE). On each time slot subcarriers are grouped in blocks of 12 sub-carriers called Physical Resource Blocks (PRBs). Each PRB consists therefore of 14 OFDM symbols on the time domain and 12 sub-carriers on the frequency domain, which is then 168 REs. These PRBs are the base of resource assignments on NR air interface. Within each time slot, users are assigned groups of PRBs, and the amount of available PRBs to assign depends on the carrier bandwidth.

Physical channels are defined with each carrying different types of data. On the DL, the Physical Downlink Control Channel (PDCCH) is used to convey the resource assignment information towards the users. On the other hand, the Physical Downlink Shared Channel (PDSCH) is used to carry user data and user signaling from higher layers. Each user is assigned a Radio Network Temporary Identifier (RNTI) when it connects to the 5G cell and this number is used to indicate the resource assignment on the PDCCH indicating which PRBs, if any, are assigned for the user on PDSCH. The allocations are sent on Downlink Control Information (DCI) messages. But not only user data and signaling are sent over the PDSCH, System Information Broadcast (SIB) messages and paging messages are also sent through PDSCH and have special RNTI values assigned for such purposes.

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The PDCCH is sent over one, two, or three OFDM symbols at the start of the time slot. The amount of symbols assigned for PDCCH depends on the cell load. PDSCH is used on the rest of the available resources, which are often the other OFDM symbols within the time slot but it may optionally be on the very same OFDM symbols that were used for PDCCH. Fig. 2.5 represents how PDSCH and PDCCH channels are transmitted over available REs within a PRB.

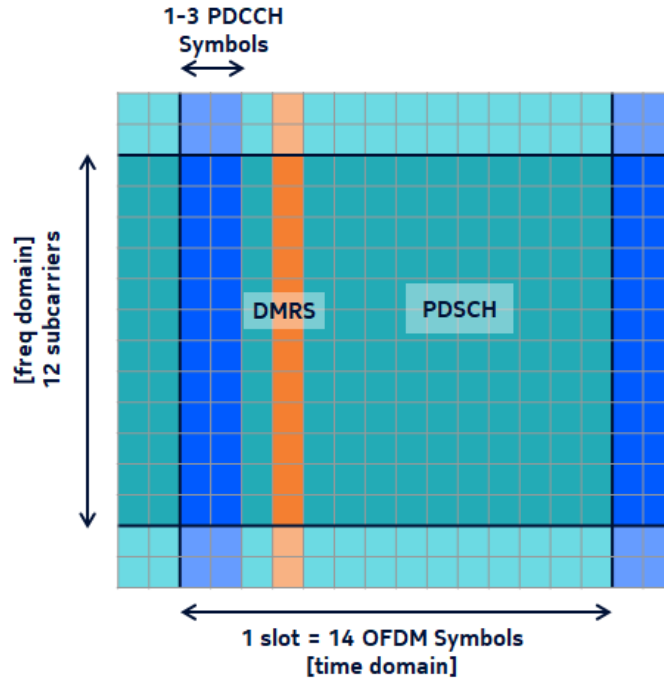


Figure 2.5: Depiction of the resources assigned to DL channels PDSCH and PDCCH, and the reference signal DMRS. The PRB is comprised of 12 subcarriers on the frequency domain and 14 OFDM symbols in the time domain, which make up a time slot. The PDCCH is sent over 1 to 3 OFDM symbols at the start of the DL slot with low layer signaling and resource assignments. 1 or 2 OFDM symbols, one at the start and an optional second one, can be used for the demodulation reference signal DMRS. The rest of the available OFDM symbols, and optionally also free REs from PDCCH symbols, are used for PDSCH which carries the actual user traffic and signaling from higher layers.

Furthermore, every 20 ms basic broadcast information is sent over some of the subcarriers over a channel that is called Physical Broadcast Channel (PBCH). This broadcast information has the minimum needed cell and network configuration information for the user to be able to start listening on the PDCCH and in this way get the rest of the broadcast information from the SIBs on PDSCH. This broadcast information is sent along with Synchronization Signals (SS) and together they occupy 20 PRBs on the frequency domain and 4 OFDM symbols. This broadcast and sync signals make up a Synchronization Signal Block (SSB) which may be sent over more than once depending on the beamforming applied to the broadcast, across what is called a SS Burst. Fig. 2.6 represents this periodic broadcast being

2.2. Physical Channels and Reference Signals

sent. More information on the beamforming and broadcast processes is given in Section 3.1.

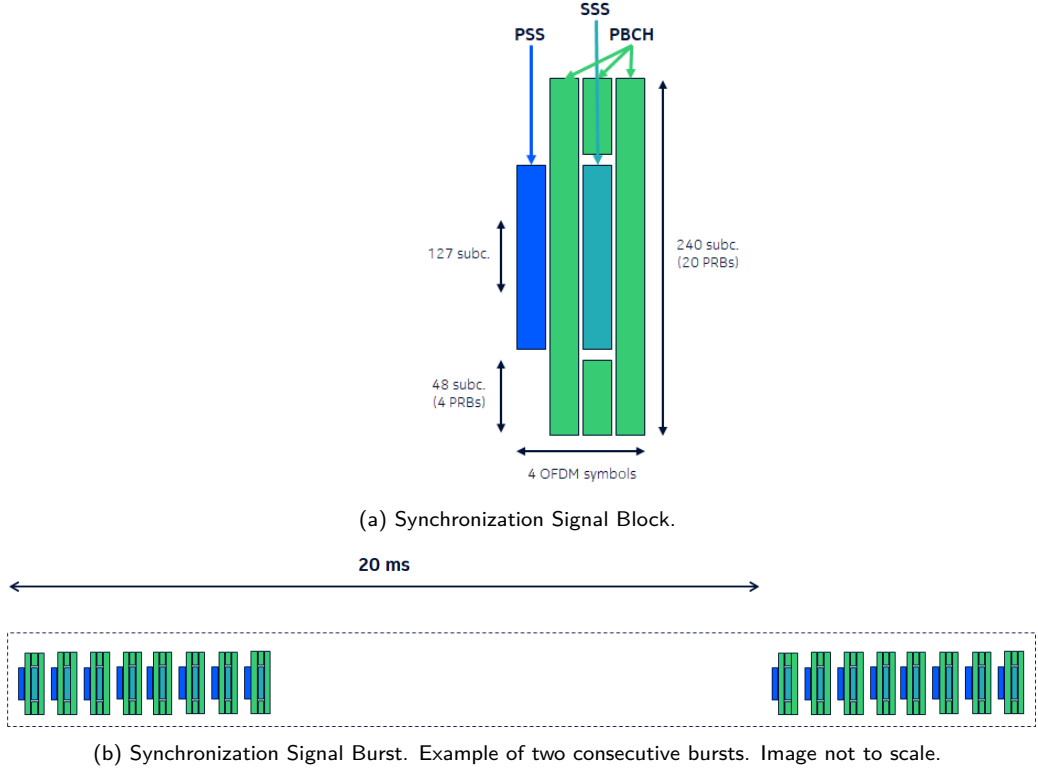


Figure 2.6: SSB can be sent more than once through different broadcast beams. A burst is formed of this set of SSBs. These bursts must be sent periodically, for instance every 20 ms.

On the UL side, the Physical Uplink Shared Channel (PUCCH) is used by the user to send the Uplink Control Information (UCI). The UCI carries Channel Status Information (CSI) which gives information on the DL radio conditions. The CSI is comprised on reports from Channel Quality Information (CQI) which is a number from 1 to 15 which ranks the DL radio conditions. It also carries the Rank Index (RI) and Precoding Matrix Indicator (PMI) which are further discussed on Section 2.3. The PUCCH is also used to indicate if the user wants to request some UL resources, with a Scheduling Request (SR) message, and also to carry HARQ ACK/NACKs. The HARQ process is also introduced and discussed on Section 2.3.

Every user connected to the cell is periodically assigned PUCCH resources, in order to always be able to send a SR if it needs to, and to keep the 5G node updated on the channel state conditions. Therefore, the amount of resources in terms of OFDM symbols and/or PRBs that are reserved for PUCCH determine a limit to the amount of users that can be connected to the cell on a given time.

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The PUCCH can either be configured as Short PUCCH, which lasts 1 or 2 OFDM symbols over a set of PRBs, or as Long PUCCH which occupies from 4 to 14 OFDM symbols over a set of less PRBs when compared to Short PUCCH.

Furthermore, the Physical Uplink Shared Channel (PUSCH) is used to send user data and signaling from higher layers. The PUSCH resources are also signaled through the PDCCH. The PUSCH may also optionally carry the UCI if the user has some information to send and is assigned UL resources on the PUSCH.

Finally, the Physical Random Access Channel (PRACH) is used for when the user first wants to connect to the cell. Whether it comes from an idle cell or from another cell to which it was connected, the user is not synchronized to the target cell on the UL. The PRACH serves to reserve some UL resources on which the user can send a random preamble chosen from a set of possible preambles that are broadcasted on the cell SIBs. This message can be used to estimate how far away the user is and therefore with how much anticipation it must send its UL messages to the 5G node in order for it to be synchronized with the UL slots. This anticipation is called the Timing Advance (TA). Section 3.1 also discusses how beamforming can be applied to this channel.

While on LTE the Reference Signals on the DL are sent persistently every two or three OFDM symbols, they are not persistent on NR. Synchronization Signals are sent together with the PBCH. The SS Reference Signal Received Power (SS-RSRP), the SS Reference Signal Received Quality (SS-RSRQ), and SS Signal to Interference Noise Ratio (SS-SINR) are measured by the user and they are used for cell selection and mobility purposes.

While on idle, the user will measure these signals and make decisions relying on these measurements to select the 5G cell that it will be camping on according to signal level rules communicated to it by the 5G node, which are often based on SS-RSRP values. Not only that, but also while connected to a 5G cell it will be asked to report measurements on the SS for mobility purposes.

It is important to consider the role that these Synchronization Signals have on cell selection and mobility, because even if a very specific and very high gain beamforming can be applied for DL traffic, the cell coverage is still determined based on these SS signals, because those are the ones the user measures to select the cell it will connect to. Beamforming application on broadcast information is therefore also very important.

Furthermore, the Demodulation Reference Signal (DMRS) is sent on one or two OFDM symbols by both the 5G node and the user on the allocated radio resources, and they are used as the name implies for demodulation purposes. The Channel State Information Reference Signal (CSI-RS) is used, also as the name implies, for the user to estimate the channel and make CSI reports. This CSI-RS has an

important role on Codebook-based Beamforming which is discussed on Section 4.1.

There is also the Sounding Reference Signal (SRS) which users can be configured to send either periodically or aperiodically, and independently of any radio resources assigned to them for data transmission. This UL resources can help gather information about the state of the UL radio scenario. In TDD it can also be used to estimate the DL channel assuming duality between the DL and the UL. This reference signal is very important to the beamforming process and is further discussed on Section 4.2.

2.3 Physical Layer

The physical layer processes receive the data to be transmitted on each slot from L2 and creates the actual waveform to be transmitted. It involves the processes and flow diagram presented in Fig. 2.7.

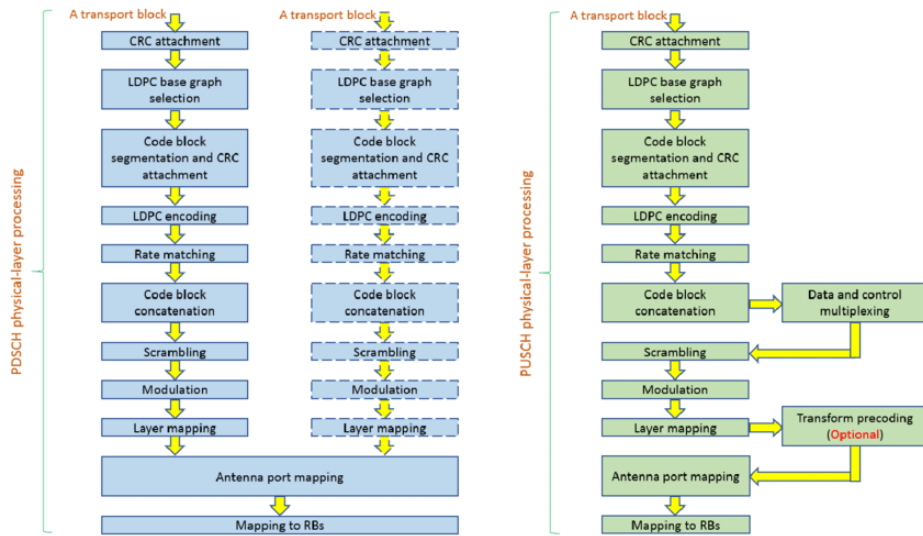


Figure 2.7: Physical layer flow diagram of the PDSCH and PUSCH traffic (source [11]).

The Modulation & Coding Scheme (MCS) sets both the modulation to be used on the data transmission for each user, and how many parity bits are going to be added to help the decoding process. This MCS takes values from 0 to 27 and is chosen by higher layers. It represents both a modulation (from QPSK to 256-QAM) and a coding rate.

Given a coding rate, the first step for the physical layer is to choose and add the corresponding parity bits. The channel coding on data channels is based on Low

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Density Parity Check codes; i.e. LDPC-codes. These LDPC-codes involve a sparse parity-check matrix, which allows for quick decoding of large transport blocks. LDPC-codes are presented as an improvement, on decoding block size, decoding speed and spectral efficiency, from turbo-codes used on LTE and HSPA, showing a better performance with BER to SINR curves closer to Shannon's limit [12] [13].

The Hybrid Automatic Repeat reQuest (HARQ) is the mechanism defined since HSPA for ACK/NACK exchange and retransmission on MAC layer. It works as IR-HARQ, where IR stands for Incremental Redundancy. This IR aspect means that if a transmission fails to be properly decoded, then the retransmission will include a different set of bits, with more parity than systematic bits, increasing the redundancy used in the decoding processes. NR maintains this mechanism and LDPC-codes allow for such algorithm to be used on the data transmission, just as turbo-codes did for HSPA and LTE.

Once the set of bits that will be transmitted is defined, they are then scrambled on a pseudo-random pattern, which allows to further robust the transmission process by avoiding a set of contiguous bits to be all lost on a fading burst during the transmission. Afterwards, bits are assembled in accordance to the amount of bits each symbol will be carrying based on the chosen modulation, from 2 bits if QPSK is chosen to 8 bits if the channel conditions allow for a 256-QAM modulation. Each set of bits is then mapped to get the actual complex symbol that will be transmitted.

Here the concept of MIMO layer is introduced. A MIMO layer is defined as an independent transmission through an ideally independent path towards the user's receiver using MIMO. In the case of Single User MIMO (SU-MIMO), the complex numbers are mapped to as many layers as the channel allows for as measured and reported by the user.

The transmitter side will have a set of transmitter ports, while the user receives from its own set of receiver antennas and ports. When pairing each transmitter to each receiver, every pair will have its own channel loss. This can be represented over a matrix of channel coefficients, in which each element of the matrix covers a pair of transmitter and receiver. Fig. 2.8 shows how channel coefficients can be represented on a channel matrix.

While each layer would ideally go through its own independent path, in practice this is hardly the case, as there is cross interference in between each pair of transmitter and receiver. Cross-polarization on the transmitter side allows to get some independance in between those signals. But SU-MIMO offers up-to 4 different MIMO layers, which require another pair of cross-polarized transmitters.

An ideal channel matrix would be a diagonal channel matrix, in which each receiver gets data from a single transmitter. While this may not occur, the channel matrix

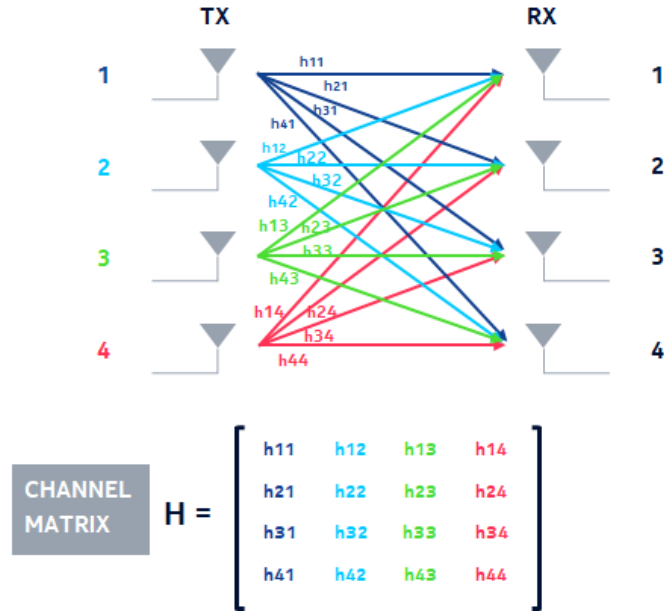


Figure 2.8: The transmitter side will send its own signal from its set of ports, while the receiver side has its own ports through which it will listen. Signal through each transmission port will reach all receiver ports, and each will see a different channel coefficient. These coefficients can be represented as a matrix.

can still be diagonalizable, and in this scenario with a pre-coding matrix applied on the transmitter side and a corresponding receiver matrix used on the receiver, then the channel can be considered diagonal and in this way allow each layer to be independently transmitted.

This whole process is depicted with Fig. 2.9. First the base station sends some reference signal through each of the transmission ports. Notably, while one of these ports transmits its reference signal, the others remain quiet. This allows for the receiver side to evaluate each channel coefficient from each transmitter independently. With this information the user can then calculate the channel matrix and evaluate if it is diagonalizable and what the rank of the matrix is.

The user then reports back to the node the Rank Index, which is a value that represents effectively what is the rank of the channel matrix it estimated. For instance, if the rank is 4 then 4 independent transmissions can be sent through the air interface, and thus it is a 4 layer or 4L transmission.

This approach is therefore based on the receiver measuring the channel and then communicating the main outcome to the transmitter side. The receiving end cannot send back to the transmitter all of the channel information, as it would be too much signaling overhead. Instead, it also reports the Precoding Matrix Indicator (PMI) that points to which precoding matrix the transmitter side should

Chapter 2. NR Radio Interface

use, based on a codebook of possible matrices that are standardized.

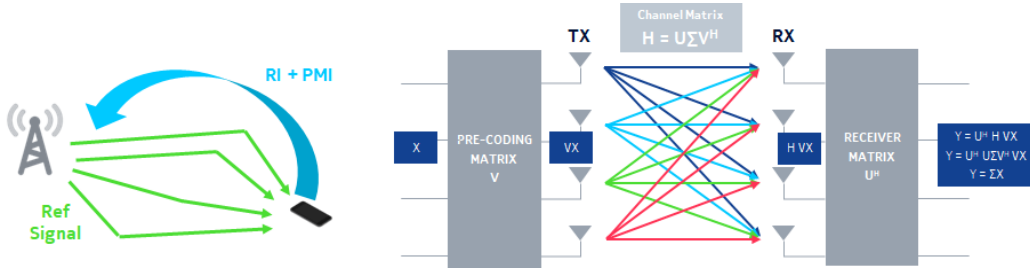


Figure 2.9: How SU-MIMO works. Base station sends reference signals to user over possible transmission paths. User then calculates rank of channel matrix and decides on best precoding matrix from available options. It then communicates this decision back to the base station. With this information base station applies precoding matrix before transmission and user can multiply at reception by corresponding receiver matrix.

2.4 Layer 2 protocols

The Service Data Adaption Protocol (SDAP) is a new protocol that allows per-flow QoS determination, as opposed to LTE's per-bearer approach. This enables a more granular management of QoS for data streams, enabling further optimization of data transfer and scheduling. It sits on top of the layer-2 protocol stack in 5G, and it is only present when the core network is 5GC (5G Core), on Stand Alone scenarios which will be further discussed on Section 2.5.

PDPC, RLC and MAC layers hold very similar tasks to the ones that were assigned on LTE. The protocol stack in the 5G air interface is shown on Fig. 2.10.

PDPC stands for Packet Data Convergence Protocol. It ensures in-sequence delivery of packets to higher layers without duplicates, and takes care of security with integrity protection and (de) ciphering. It is also in charge of header compression when appropriate, which is mostly on Voice over NR (VoNR) applications for which the RTP/UDP/IP header size is comparable to the packet content.

As opposed to LTE, PDPC layer is the only one in charge of reordering packets. This layer must hold them in a reordering window or buffer to allow enough time to receive any late packets. This allows for quicker deciphering and packets are not waiting to be resolved and reordered on RLC. It can be sent to PDPC to be deciphered as soon as it is received and it is not waiting on RLC layer for other late packets. The PDPC layer is the one in charge of accommodating traffic from/to other nodes in dual-connectivity scenario which are covered on Section 2.5.

RLC works similar to LTE only without the reordering functionality. It provides

2.4. Layer 2 protocols

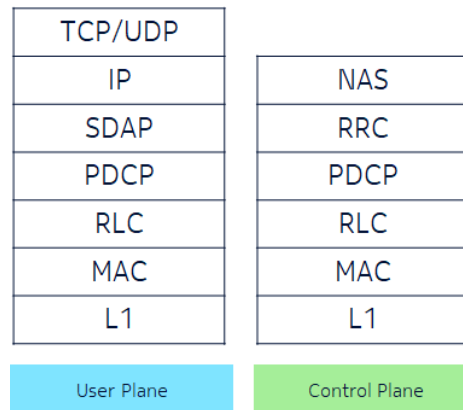


Figure 2.10: Protocol stack on the NR air interface. The SDAP is introduced in 5G to segment user traffic on different QoS flows from the same connection towards the core, as opposed to LTE which had different bearers each with its own QoS settings. On the control plane side the RRC protocol is used to exchange signaling between the user and the GNB. The NAS protocol is used for communication between the user and the CN and it is sent piggybacked with RRC.

segmentation of packets before sending them to lower layers, and does also error handling asking for retransmissions when needed. There are three operation modes which were also there on LTE: Acknowledged Mode (AM), Unacknowledged Mode (UM), Transparent Mode (TM). On TM this layer does not provide any functionality, and it is used mostly on some signaling and broadcasting. On UM there is packet segmentation but there is no check of errors and retransmissions, and it is mainly used on VoNR scenarios. AM works for general use cases and allows for error handling at RLC layer as well as segmentation.

The RLC layer is also where traffic is split for Carrier Aggregation (CA). As illustrated on Fig 2.11, CA works by allowing the user that supports it to be connected to more than one carrier at the same time, thus enabling more bandwidth to be aggregated for user data traffic. There is a Primary Cell (PCell) which handles signaling, GBR (Guaranteed BitRate) and nonGBR traffic. The user can then connect to Secondary Cells (SCells) on other frequencies to aggregate nonGBR traffic. The RLC layer is where traffic is splitted towards SCells connected to the user through CA. Each LTE carrier that the user is connected to is called a Component Carrier (CC).

Finally, the MAC layer is in charge of multiplexing data over transport blocks that will be sent over the air interface. It also does its own error correction through the HARQ processes mentioned on previous Section through ACK/NACKs being communicated over the MAC layer and sending corresponding retransmissions. The MAC layer allows also for signaling exchange regarding physical parameters such as beam information, Timing Advance (TA), Buffer Status Report (BSR), (de) activation of other carriers in CA setup, Power Head Room (PHR) reports on which user communicates available power, and coordination of Discontinuous

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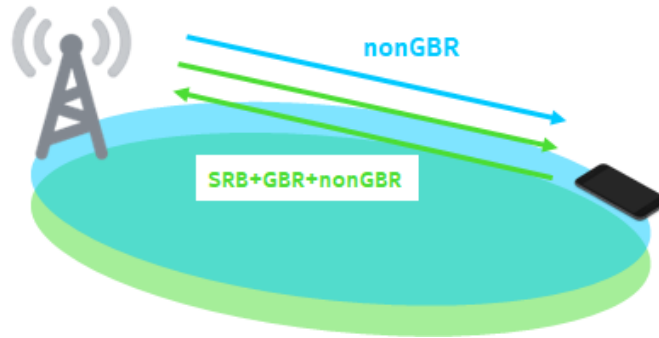


Figure 2.11: Carrier Aggregation works by enabling the user to connect to 2 or more carriers of the same technology at the same time. While signaling and GBR traffic is kept on the Primary Cell, nonGBR traffic can be offloaded to Secondary Cells.

Reception (DRX) to allow users without traffic to save some battery even while on connected state.

On top of these protocols, on the control plane side sits the Radio Resource Control (RRC) protocol, which is used for high-level signaling exchange between 5G node and the user. Non Access Stratum (NAS) signaling is exchanged between the user and the core network. On the radio interface these NAS messages are encapsulated within RRC.

2.5 Dual Connectivity

The first 5G deployments were set up as Non-Stand Alone (NSA), meaning the user relies on LTE coverage for connection towards the core network. The user is said to be on Eutra - New Radio Dual Connectivity (ENDC) which indicates the user is connected to LTE and 5G both at the same time.

On NSA the Evolved Packet Core (EPC) from LTE is used as the core network for both control and user planes. While some RRC mobility related configurations can be optionally configured to be sent straight through 5G, most of the signaling is sent through LTE's radio interface. The ENB is then responsible for routing NAS messages towards the EPC, and 5G RRC signaling towards the GNB.

Furthermore, all GBR traffic is also sent through LTE, being VoLTE the main example for GBR traffic. 5G in this ENDC scenario is used on top of LTE for nonGBR traffic only. This nonGBR traffic is split on PDCP level, with some traffic being sent through 5G and the rest, if needed, through LTE. Fig. 2.12 shows how the traffic is splitted between LTE and 5G for ENDC users.

The LTE cells that serve the user (the PCell and SCells in case of LTE CA) are

2.5. Dual Connectivity

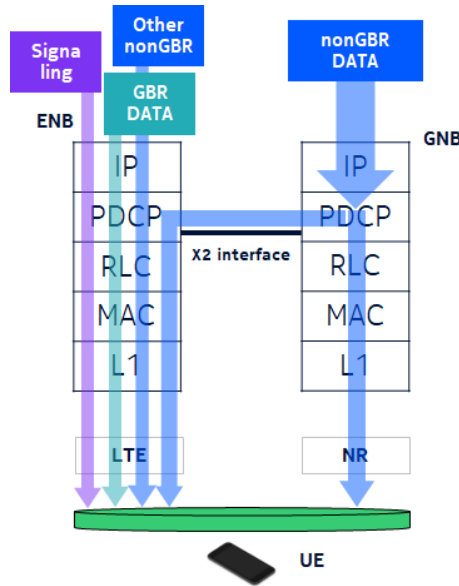


Figure 2.12: Traffic path on ENDC setup. nonGBR traffic goes through the GNB. Depending on available 5G capacity some of it may optionally be sent through LTE as well using the PDCP from the 5G protocol stack. GBR and signaling traffic are kept through LTE alone and some other nonGBR traffic can also be sent through LTE independently from 5G traffic. For instance, a VoLTE user with background data traffic will have nonGBR background data going through 5G, while SIP signaling (nonGBR) is sent through LTE alone and the RTP voice traffic is also sent over LTE.

called a Master Cell Group (MCG) and the 5G cells that serve the user form a Secondary Cell Group (SCG). Similarly, the LTE ENB to which the user is connected is called the Master ENB (MENB) and the 5G GNB the user connects to is the Secondary GNB (SGNB).

As opposed to CA, in which Uplink CA (ULCA) is optional, this DC configuration does require UL resources to be allocated on the primary cell of the SCG. This implies that while UL data could be sent over the MCG, the 5G UL should still accommodate feedback such as HARQ ACK/NACKs.

When using a mobile device on ENDC it is important to know in these deployments not only which 5G bands the equipment supports, but also which band combinations it can use. Each user will have its own sets of LTE and 5G bands that can be used together for ENDC. For instance, a user may support n78 (3600 MHz) 5G band on ENDC when connected to LTE carrier on band 3 (1800 MHz) but not if the LTE carrier it is connected to is on band 4 (2100/1800 MHz). Also, the LTE CA combinations that the user supports can be different when it is connected to ENDC than when it is not.

This ENDC allowed operators to quickly setup a 5G network without having to setup a 5G core. There is of course the option of going for a Stand Alone (SA)

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deployment in which all traffic is sent through 5G and the user connect to a 5G core, not to the EPC.

Not only that, but also if the coverage is not good enough on 5G, and this is more an issue on the UL than it is on DL, of course, then the user can rely on the help of LTE to carry out some of the traffic. Or even if the connection on 5G drops, it can still keep on trafficking through LTE.

SA is being slowly deployed on more modern networks. SA allows the operator to have a 5G network that does not depend on LTE coverage. While it did make sense at the start to speed up the 5G deployment, depending on the bands available it might not make sense to depend on LTE coverage. Take for instance T-Mobile in the US, that has 5G coverage in the 600 MHz band. It is not reasonable to have a good low band for coverage but still depend on LTE coverage to provide a 5G connection.

Furthermore, having to connect on LTE first and only then to 5G introduces a much bigger establishment delay. Not only that, but 5G introduces a new RRC inactive state in which the user context remains in the GNB, and this allows the GNB to keep some user information and do a quicker setup. This is not new, similar algorithms were in-place in 3G. But we need SA for this to work, and not rely on using LTE for control plane.

Another point to consider is that NR CA on NSA deployments is limited to DL CA only and with up to only 2 carriers on FR1. Band combinations of more NR carriers need SA deployments. Also, SA allows for better UL throughput, not only because of UL CA, but also because the mobiles can use their both transmitters to do 2x2 UL MIMO instead of using one for 5G and the other one for LTE if on dual connectivity.

The dual connectivity concept applies not only to ENDC. NRDC is a Dual Connectivity setup on SA networks that also splits nonGBR traffic. While on NR there is the possibility to do so with CA, in some scenario it might make sense to do it through a DC approach. The split traffic on RLC for CA can be more demanding on delay requirements between base stations of the PCell and SCells serving the user. While it is not always the case, CA cells are then often co-located on the same site. The split traffic being done on PDCP level for DC allows for a more flexible connectivity in the backhaul between the two nodes. FR2 and FR1 coverages are very different, and thus the deployments are different. FR2 is often used on hotspots where such wide bands are needed and can be more useful, so the user could connect to a site close to the hotspot for FR2 as SCG while having a FR1 cell as MCG from a non-co-located site.

2.6 Chapter Conclusions

This Chapter served to set up some concepts that will allow to explain beamforming properly. It also provided some context of the 5G technology, within which the beamforming is applied.

At first, the 5G frequency ranges and bands were introduced which conveys how this technology covers a very wide variety of frequency bands, from low bands below 1 GHz that cannot use beamforming because of the antenna sizes, to very high bands above 20 GHz that could barely work without it. Midbands, between 2.6 GHz and 6 GHz are the ones used mostly for 5G beamforming as it is a sweet spot, being a range low enough to get quite decent coverage, though at the same time high enough to hold large bandwidths on available spectrum. Not only that, but also the midband has a wavelength that allows for mMIMO deployments, being short enough to install several antenna elements within the same radio equipment.

Moreover, the reference signals presented will serve as inputs for channel estimation, which is the basis for the beamforming process. Also, the frame structure and the channels presented set the stage for the frequency and time domain resource assignments of the different exchanges between the user and the node.

Take the broadcast and SS signals on SSB for instance. This is the most basic information that should arrive to the whole cell coverage area and all of the users camping while on idle or with an active connection to the node. This SSB presents to those users the reference signals that will be used to select the 5G cell they will be connecting to. However good the beamforming for user traffic is, it is still important to have a proper SSB coverage. It will be a problem if the users are not being reached on the SSB or if the users cannot select the best cell from SSB measurements (for instance too much of an overlap between SSB coverage between neighbour cells). Applying beamforming on the broadcast is a very good option to improve cell coverage. That is where the SS bursts come in, allowing the SSB to be swept across broadcast beams that cover the whole cell coverage area.

On another example, in case the SRS-based beamforming is used, which is presented on Chapter 4.2, users need to be allocated periodically SRS resources. This, evidently, can only be done on UL resources. Therefore it is relevant to know where this SRS can be configured in both frequency and time domains, and thus which frame structure and slot formats are being used. Moreover, SRS can only be applied if the users has UL resources, which is not the case on secondary cells when CA is in use.

Furthermore, the ENDC concept was also introduced and it is very important to understand the scope of the beamforming on 5G when on NSA setups. It is particularly interesting in these cases that when the UL coverage is not good

Chapter 2. NR Radio Interface

enough on the SCG, which are the 5G cells, then LTE can make up for that and help to carry the UL traffic. This in effect allows to increase the 5G coverage and therefore the benefits of DL beamforming can be further exploited. Users can be expected to stay connected and demand resources at greater distances.

Next Chapter intends to cover the main concepts and ideas behind beamforming and how they relate to 5G. It will then be complemented on Chapter 4 with more detail on the application of beamforming to traffic channels.

Chapter 3

Beamforming Theory and Methods

This chapter intends to cover the main concepts related to beamforming on mobile communications. Beamforming is a whole study topic in and of itself, and would be too ambitious to pretend to cover the whole topic within a single chapter. Instead, this tries to focus first on the main idea behind beamforming to get a basic sense on how it is working behind the scenes. Both analog and digital beamforming mechanisms, with their benefits and drawbacks, are discussed as they both are used on 5G.

Section 3.1 discusses how the beamforming is used on the NR air interface, specially how it is employed on the broadcast and random access during which there is no channel knowledge. It also serves as preface to Chapter 4, which covers the main beamforming mechanisms applied in 5G.

The use of beamforming and focusing the power towards a certain direction leads to changes on the scheduling algorithms, mostly to consider MU-MIMO. This is discussed on Section 3.2. Finally, Section 3.3 looks at how location algorithms can exploit channel knowledge related to each user to improve positioning information.

Beamforming uses several transceivers (TRX) to customize the gain towards some specific location. With several transmitters and antenna elements combined radiated power can be focused towards an intended direction. This allows to improve the radio link quality by focusing the power where it is actually needed, and also avoiding interference towards unintended directions. This is often referred to as Massive MIMO (mMIMO), given the large number of transceivers and antenna elements used on the transmitter side.

It is all about superposition of waves, to try and direct the wavefront to its coverage objective. By shifting the phase on each transmitter we can manipulate the wavefront direction and thus the beam direction. This is shown on Fig. 3.1, intro-

Chapter 3. Beamforming Theory and Methods

ducing different delays along each of the transmission lines changes the direction of the wavefront.

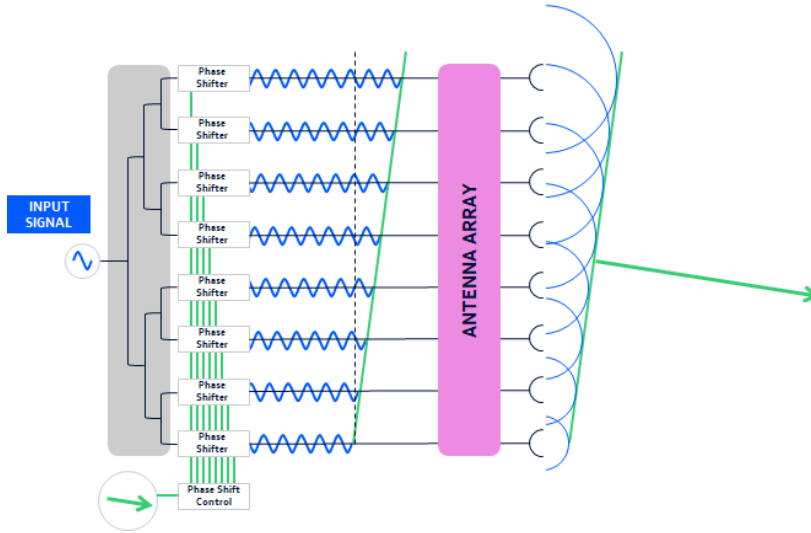


Figure 3.1: The main idea behind beamforming is to impose a phase and amplitude shift of the main signal before it reaches the antenna element. In this way the wavefront direction can be changed to match the direction of the signal target.

It is easier to think of this superposition from the transmitter side, but one should remember that from antenna theory there is a reciprocity between transmitting and receiving, so this beam that can be formed for transmission can also be used to increase reception gain on that same direction.

This superposition can be achieved on more than one way or better said more than one domain: analog or digital. In Analog Beamforming these phase differences are set in hardware. The input signal is split towards different paths, and so each antenna element is fed through a different path length and as a consequence a difference phase shift is applied. This must be set in hardware beforehand and cannot be customized on the fly. Alternative paths can be set but they need to be accounted for before deployment during the radio development stage. This kind of approach allows a set of pre-defined beams the base station can choose from, but it is restricted to that predefined set. Fig. 3.2 presents an example of a patch antenna array connected to an 8x8 Butler matrix taken from [14], which shows how stimulating each port independently leads to a different transmission direction.

However, applying different phases, can be thought of as applying different complex weights in the digital domain. In this way, instead of one single signal being split and sent over different paths, several signals are sent on several TRXs on the radio side. Each signal is multiplied beforehand by a different complex weight in the digital domain, thus resulting in a phase shift. This is exemplified with Fig. 3.3, the phase shift is introduced on the digital domain with a complex weight. As

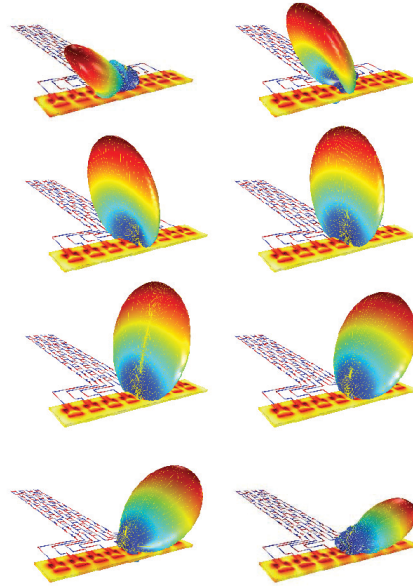


Figure 3.2: With Analog beamforming the phase shifts are set in hardware. In this example a Butler Matrix is used to take the signal from each of the possible transmission ports to take different paths to reach the transmission ends. Each path will have a different length and thus a different phase shift when it arrives to the end of the line. The analog beamforming works therefore by deciding which port is going to be stimulated, and so which phase shifts will be applied to the signal before reaching each of the transmission antennas (source [14]).

opposed to analog beamforming, this allows to customize the phase shifting in any desired direction without being limited to hardware configurations.

The main issue with digital beamforming is its higher baseband processing and power consumption requirements for calculating and applying the complex weight on each signal. Also, having to handle several different signals means increasing the amount of TRX on the radios side, thus increasing demands on power amplifiers, as well as higher traffic demand on the fronthaul, the link between the baseband and the radio modules.

Advancements in more powerful and energy-efficient chips allow for optimized calculation of beamforming weights. More intelligent radios can reduce demand on the fronthaul, allowing complex weights to be applied on the radio rather than on the baseband side. These more intelligent radios are often called Adaptive Antennas. As opposed to traditional antennas, these kinds of equipment are active rather than passive; they receive the signal in the digital domain, apply some of the L1 processing and only then radiate them on its antenna elements on the analog domain.

In the end, digital beamforming enables a more flexible approach towards beamforming, which is essential towards freedom of beam synthesizing and being able to adapt to the expected diverse scenario on the radio side.

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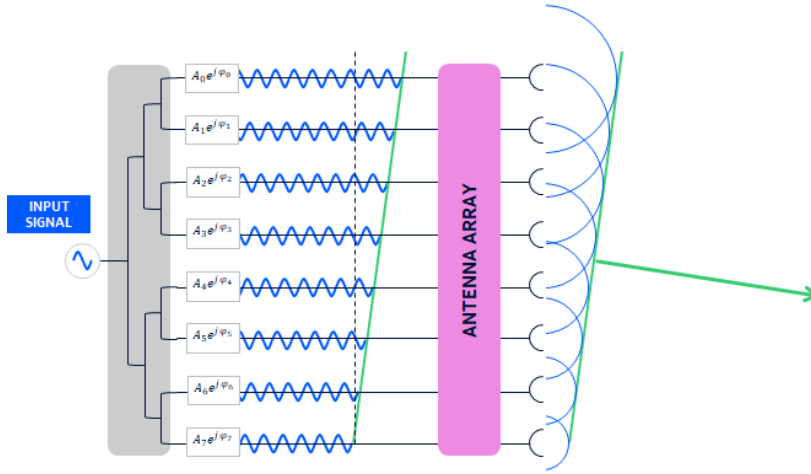


Figure 3.3: Digital beamforming works by applying a set of complex weights on the digital side. This leads to a different signal fed to each TRX. The phase of each signal will depend on the applied complex weight which imposes a phase shift. This allows a single hardware to transmit a varied set of digitally applied phase and amplitude shifts.

This amount of transceivers and power amplifiers needed, though, can be expensive to accommodate for; specially on mmWave bands. A hybrid approach, in which some of the phase shifting is applied in the analog domain can offer a mixed approach, more feasible and cost-friendly, but with a good range of flexibility towards beam customization. That is called, unsurprisingly-so, hybrid-beamforming.

This is a good moment to differentiate between Antenna Elements (AE) and Transceivers (TRX). Each TRX consists of a different power amplifier and different signal being generated from the digital domain towards the analog domain. On the other hand, AEs are the actual antennas that radiate the power. There could be one TRX for each AE, and that could be better for a more flexible approach on beam generation, but it would be too costly. Rather than reducing AEs as well as TRX, vendors choose to decrease only on the amount of TRX while not reducing amount of AEs. This enables to get a better coverage from each TRX as its AEs work jointly just as they do in any traditional passive antenna.

We can then summarize how these two variables influence the radio interface. Increasing AEs allows to get better coverage and more dBi on the beam gains. Meanwhile, more TRXs allow for better flexibility on beam definition as beam generation can be more precise. Further, the bigger the ratio of AEs per TRX the less optimal steering range as each TRX will have more AEs associated with it. Renowned radio vendors, such as Nokia and Ericsson, offer Massive MIMO radios with either 32 or 64 TRX, with each controlling from 3 to 6 AEs [15] [16].

3.1 Beamforming applied to 5G

On 5G the beamforming is applied mostly on the GNB side, where the mMIMO antenna arrays can be easier to implement as there is more space available. The beamforming methods discussed on this document are therefore related to beamforming being performed on the base station mMIMO radios. Beamforming on the user side could be considered in the future, specially on FR2 where antenna sizes are smaller and coverage is very limited, and when used for Fixed Wireless Access (FWA) given that in those cases the user is not moving.

There are two types of approaches towards defining the beams to be used on 5G NR. The Grid of Beams (GoB) approach uses a pre-defined number of beams to choose from. The other option is to just synthesize the beam on real time, and for each new transmission the optimal beam is calculated and set for that transmission. Evidently, the latter seems more promising, but each option has its use and advantages.

During broadcast and random access processes the GNB does not know where the UE is. It cannot define a specific beam for the UE to hear the broadcast on, neither can it know which one it would be best to hear the random access on the Random Access Channel (RACH). The GNB and UE need to exchange some information before being able to calculate the optimal beamforming weights for that specific UE, and that information is not exchanged until some signaling connection is setup.

3GPP allows up to 8 Synchronization Signal Blocks (SSB) to be sent within the broadcast periodicity on FR1, and up to 64 on FR2. Each SSB carries Synchronization Signals and same basic broadcast information. These enable the GNB to effectively send each SSB on a different beam. Considering FR1 scenario, up to 8 different beams could be used. These are often called SSB-beams or broadcast beams. These beams must cover the whole sector coverage area and are thus more coarse and wider in comparison to a traffic beam used for one particular UE. Nonetheless this option allows to have some beamforming gain on broadcast channels. The SSBs carry also the Synchronization Signal (SS) which is not only used for synchronization purposes, it serves also as signal reference at the UE for cell selection, cell re-selection, and handover procedures. The sending of SSB information over broadcast beams is shown on Fig. 3.4.

RACH should also be accounted for and each broadcast beam will have an associated RACH occasion. The UE then has to send its preamble message on the appropriate RACH occasion, in accordance to the best beam it is detecting. Then it is also important to have some beamforming gain on RACH occasions, effectively improving RACH coverage.

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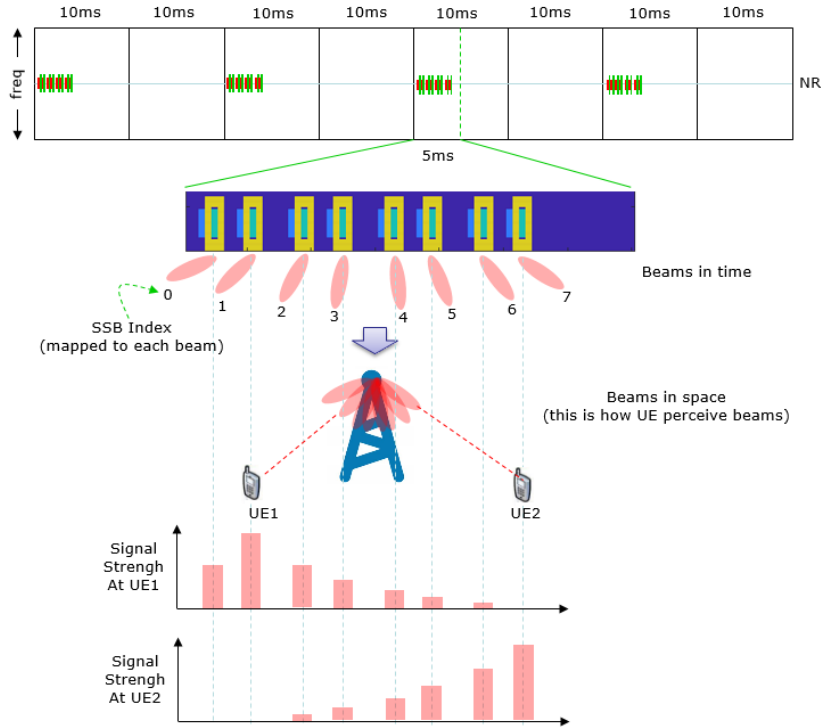


Figure 3.4: Beamsweeping on SSB-blocks. GNB sends (not concurrently) broadcast information over all pre-configured broadcast beams. User then must select the best one in order to perform initial access and other processes during which UE location is not known (source [17]).

UEs cannot be connected to the GNB at all times, as it would be very costly from a processing perspective to handle that many UE contexts on the GNB. Also, UE's battery would be quickly drained if it were kept in connected state. Thus, UEs will have to frequently rely on broadcast channels to assess coverage and RACH occasions to get back to connected state.

Once in connected state the GNB can exchange channel information with the UE in order to choose the optimal beam to be used for following transmissions. Therefore, a GoB approach on the broadcast channels and RACH occasions allows to account for a beamforming gain on these control channels.

Of course, having several beams in the broadcast implies having to send the same broadcast information on different beams and allowing for either more RACH occasions. This leads to higher overhead from broadcast and RACH that has to be accounted for, if the operator wants to improve coverage on idle.

When it comes to deciding which beams should be used for carrying traffic, there are a couple of ways to exchange channel information between the GNB and the UE to use for beam generation. The following Chapter 4 covers those two possibilities, which vary depending on who sends the reference signals and who chooses the

3.2. Spatially-aware Scheduling

beam to be used. The GNB could send a reference signal towards the UE and let it decide which best beam should be used, and this is covered on Section 4.1. Another option is that the UE itself could send a reference signal and let the GNB decide what beam to use once it has all the channel information, this is presented on Section 4.2.

It is important to note that beamforming is not exclusive to 5G. LTE already employs beamforming under certain scenarios but it is not as widely used as on 5G, and did not consider it from the beginning of the standardization.

For example, beamforming on broadcast channels is present on the first releases of 5G and not on LTE. Codebook-based beamforming, which is presented on Section 4.1, is allowed on LTE but requires user support which is not very popular. SRS-based beamforming, covered on Section 4.2 is available on TDD LTE but TDD was not widely adopted and was of somewhat limited implementation. 5G also allows to work on higher frequency resources which enable better radio implementations as the antenna size decreases as frequency increases. The 3.5 GHz frequency band, which is widely used on 5G, serves as a sweet spot in that regard. Also, FR2 frequencies introduced in 5G need beamforming in order to be actually usable, without beamforming it would not be possible to give some reasonable cell coverage on such high frequencies.

3.2 Spatially-aware Scheduling

The implementation of beamforming on mobile networks brings a whole new dimension to the scheduling process with Multi-User MIMO. The following subsections cover how the scheduler needs to adapt to be mindful of the channel information of each user, particularly the spatial distribution of the users that it is serving.

3.2.1 Multi User MIMO

The use of beamforming techniques to send traffic across users served by the cell can help boost coverage by focusing its power on the user's direction. This allows for better channel conditions in terms of modulation and coding scheme employed, and thus a higher spectral efficiency for this traffic.

Not only that, but having the power concentrated on the direction where it is needed implies that it will not be sent on other directions. This allows to reduce inter-cell interference, as opposed to the legacy approach in which no matter where the user was, the downlink power was spread across the whole cell's coverage area.

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Therefore coverage gain and reduced interference are clear advantages of beamforming. But there is more to it. If the GNB can focus its power on a certain direction, then a spatially distant user within the same cell area will not be as interfered by this traffic. This enables the GNB to send traffic to that spatially distant user at the same time and on the same frequency resources.

Traditionally, resources allocated on the radio interface use frequency, time or code division to separate radio resources among users. OFDMA, used on LTE and 5G, assigns blocks of subcarriers over specified times to allocate radio resources.

Given a set of spatially distant users the GNB can schedule them at the same time and on the same frequency resources. Users should be chosen such that the beams that each one of them would be assigned are uncorrelated between each other, meaning that mixed-interference generated by each beam on each other is such that it will not affect the channel performance and there is low-correlation between the users sharing the resources.

This is the idea behind Multi-User MIMO (MU-MIMO). Multiple layers, each carrying different traffic, are sent at the same time and frequency resources, but across uncorrelated beams, as depicted on Fig. 3.5. Each user will receive between one to four of these layers across one or two distinct beams. Depending on the GNB's capacity, it can send several layers (for instance 8L or 16L) at the same time across many users, albeit at the expense of more stringent channel conditions. If the GNB can use a large amount of layers at once like 16L, then it can either send 4L to four users each, or send 2L to eight simultaneous users.

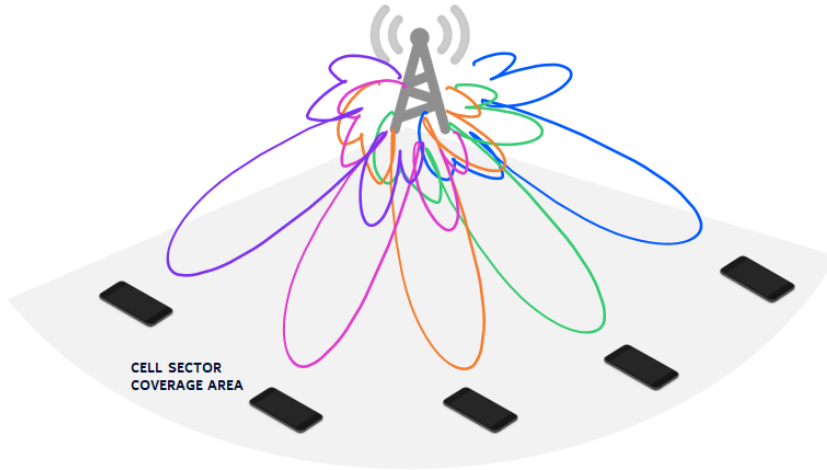


Figure 3.5: Depiction of MU-MIMO showing five users within the same cell coverage area, being each served by different low-correlated beams while sharing the same time and frequency resources.

Evidently, even when users are far apart, getting all these users to receive completely uncorrelated beams is quite difficult. Nonetheless, having these users some-

3.2. Spatially-aware Scheduling

what uncorrelated between each other can be feasible. They will inevitably interfere with each other, but keeping this interference to a minimum is enough to gain on cell capacity.

Choosing users is not straightforward. Channel information should be readily available to make a proper decision. Likewise, these users should be demanding traffic at the same time in order for them to be jointly eligible. It helps to have a somewhat loaded cell scenario in which there are many users spread across the whole cell coverage area demanding radio resources. In this way there can be plenty of users to choose from and the probability of finding jointly eligible users increases.

At the end of the day the whole point is to increase the cell's capacity and spectral efficiency. The MU-MIMO pairing needs not to be perfect, but needs to be good enough so as to be able to reliably provide downlink data at a higher bitrate from the cell's perspective, higher than it would be without it. It goes without saying that the more uncorrelated and traffic hungry users the GNB has, the better the MU-MIMO scenario can be achieved.

MU-MIMO also carries an interesting discussion in which the GNB could choose for instance, if limited to 16L for MU-MIMO (16 independent transmissions), either four users with four layers each or eight users with two layers each. Which one would be best? In general 4L usage within the same user with high MCS requires a very robust radio scenario with the user being able to receive from two cross-polarized beams at the same time. Added to a real sort of MU-MIMO scenario in which interference, while minimized, is still present, then it is challenging to get the best MCS out of a 4L transmission to that user. A simplified scenario is illustrated on Fig. 3.6 with a 8L setup that can be shared 4L+4L between two users or 2L+2L+2L+2L between four users.

Eight users with 2L each could be a more interesting use case than four users carrying 4L each. These users will not be able to get the best peak-traffic as they will be limited to 2L instead of 4L, but in the end on average this can help better increase cell capacity and therefore performance across all users in the cell. Not only that, but also from a latency point of view, if more users are scheduled at the same time, then they may each start receiving their data faster. It will not be easy to get eight uncorrelated users within the same time slot but, having said that, peak user throughput can be sacrificed in favor of higher cell throughput and spectral efficiency in this scenario.

In the case of beam synthesizing the GNB can take advantage of the channel information of the user to create a particular beam to be used for that connection. This allows to focus power on a very particular direction and thus avoid sending power towards another user's direction. This is covered in Section 4.2.2. What is more, the GNB can potentially have the channel information from both users to be

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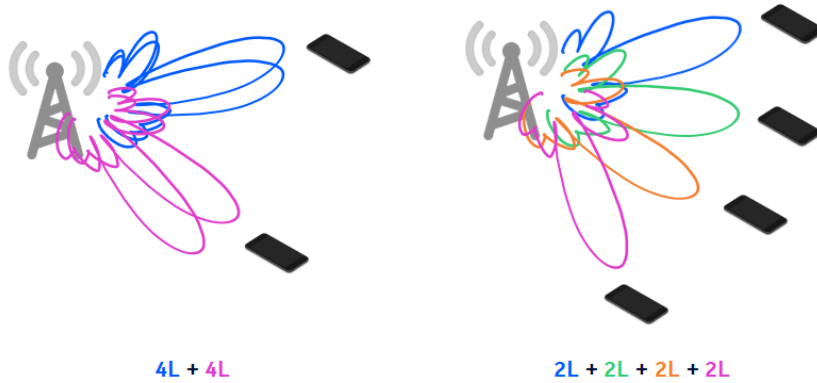


Figure 3.6: MU-MIMO Layer sharing between users. In this example the radio is configured for up-to 8 layers. They can either be shared between two users with 4L each, or between four users with 2L each. While 4L provides peak throughput, it may be interesting to favour sharing the same total layers across more users if they are uncorrelated between each other. Dividing the amount of layers between more users may improve average SINR and lower delay as some users will not have to wait for next scheduling opportunity.

served on MU-MIMO. It can then take advantage of this information and not only choose for each user its intended beam, but also set a null-gain on crossed-direction, in such a way that the interference from user A towards user B is minimized by setting a null gain on A's beam towards B's direction, and also on the other way round.

This can help potentially improve MU-MIMO performance as crossed interference is reduced and higher-order modulation and better coding rate can be used for data transmission. These sort of techniques are referenced as Zero Forcing (ZF) beamforming. Other approaches like Block Diagonalization (BD) have also been proposed. Paper by Chen et al. [18] and Zhao et al. [19] propose a BD approach to MU-MIMO and the former compares these type of algorithms with ZF.

The use of MU-MIMO also implies changes to the scheduler. With MU-MIMO, the scheduler has to be spatially-aware, in order to exploit the air interface and get as many bits as possible over each radio resource by knowing which users are uncorrelated between each other.

Traditional schedulers often implement some variant of the Proportional Fair (PF) scheduler. This scheduler calculates a metric for each user needing radio resources, with which they can rank the users. The metric of the PF scheduler is based on a ratio between a numerator proportional to channel state and a denominator proportional to past throughput. The numerator tries to favor users which have good channel conditions to try to serve those which can use the channel most efficiently. Meanwhile, the denominator tries to penalize those which have received

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good throughput values in the past, in order to add some fairness to the scheduler. With this ranking the scheduler prioritizes those users with highest metrics to allocate them the resources they need.

Introducing MU-MIMO in this scenario involves bringing spatial information to the scheduler. MU-MIMO looks to serve two different users on the same radio resources through un-correlated beams. Therefore, the scheduler must not only hold information about those PF-like metrics, but also the cross-correlation between the users.

For instance, as depicted in Fig. 3.7, it may happen that an uncorrelated user may have a very low PF metric when compared to other users, but it still can and should be scheduled at the same time over the same resources by exploiting the low correlation between the users. Another possible scenario is that two uncorrelated users both have a high metric, then we should prioritize assigning resources to both users separating them in the spatial domain instead of frequency domain, to try and exploit spatial diversity without having to rely on more frequency resources instead.

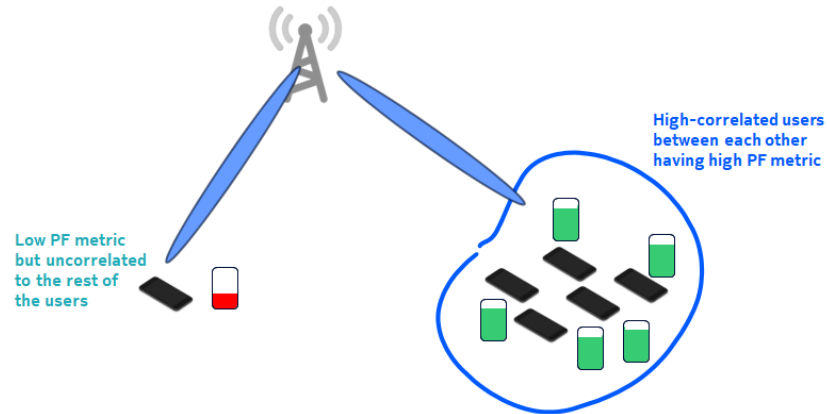


Figure 3.7: MU-MIMO scheduler should be aware of spatial information of each user when allocating resources. A user may have for instance low PF metric but if uncorrelated to the rest of scheduled users may still be a good candidate to assign resources to.

A good scheduler will not only be spatially-aware at the moment of setting up the resources, but also when choosing the appropriate Modulation and Coding Scheme (MCS) which sets the modulation and the coding rate for the transmission. Assigning the same frequency and time resources on MU-MIMO between two mostly uncorrelated users will increase the intra-cell interference between the beams of those two users. While the scheduler should choose users that will not interfere much with each other, there is still some interference present. Not only that, the transmission power will also have to be shared between the two. That implies a reduction in the radio link quality between the node and the user, that should be accounted for on the scheduling process. The scheduler, therefore, should estimate a MCS value based on the cross-correlation conditions of the chosen users. This

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MCS will of course be lower than in SU-MIMO scenario, as depicted in Fig. 3.8. But as a whole the scheduling decision should make sure that the spectral efficiency obtained offers an improvement on MU-MIMO over SU-MIMO when cell level throughput is considered.



Figure 3.8: MU-MIMO scheduler will have to adapt MCS according to cross-correlation knowledge between the users sharing the same radio resources. In this example on the left side each SU-MIMO transmission is used with MCS 23 or 24. When MU-MIMO is applied with all four users sharing the same radio resources then MCS is lowered when sharing resources with each other, but as a whole the cell capacity is increased.

There is room for optimization and study of a proper scheduling algorithm, that relies on channel information and user metrics to make the best resource assignment decisions. For instance, how loaded should the cell be when starting a spatially-aware scheduling process? Should that be done even on low load scenarios or should we avoid multiplexing resources on the spatial domain if it is not really necessary in terms of available and needed resources?

Seyama et al. [20] looks to account for fast channel changing conditions on scheduler metric. Taking into account that a fast changing environment could lead to inaccuracies on channel estimation, their proposed scheduler prioritizes users with varying SINR conditions looking to minimize the delay between the channel estimation and the data transmission.

Machine Learning (ML) approaches have been used for scheduling purposes on MU-MIMO. [21] takes the scheduling process as an optimization problem and proposes a Reinforcement Learning (RL) algorithm to solve it, with an improvement over conventional algorithms they considered.

As mentioned before, there are many factors to account for in the scheduling process. A scheduler should not only be spatially-aware and keep a notion of

3.2. Spatially-aware Scheduling

fairness, but it also cannot be too complex. Timing is evidently an issue given that there are new scheduling decisions on every time slot. With that into consideration, Chen et al. [22] propose a Deep Reinforcement Learning (DRL) algorithm for resource allocation decisions, with which they look to develop a high capacity scheduler with reduced complexity.

Bottom-line, it is important that the scheduler has spatial information of its users, and the scheduler will have to evolve to optimize the radio resources now on a spatial plane with cross-correlation information between the potential traffic beams of each user.

3.2.2 Multi-Cell Algorithms

There are also some other aspects that beamforming can take advantage of when exploiting spatial diversity. Back on LTE Enhanced Inter-Cell Interference Coordination (EICIC) and Coordinated Multi-Point operation (COMP) looked for information exchange and coordination between neighbour cells in order to either reduce inter-cell interference or exploit spatial diversity.

On EICIC neighbour cells coordinate between each other when to allocate resources to cell-edge users, avoiding full power on some scheduled subframes. On the other hand, COMP involves neighbour cells working jointly for improving transmission. On joint transmission (DL COMP) both cells would send the same information to exploit DL channel diversity. This, though, was not very widely adopted as it can raise interference on the network from increased transmission power for the same traffic. On the other hand, joint reception (UL COMP) has the neighbour cell listening to radio resources of users from the actual serving cell. As opposed to DL COMP, this has been used in some cases because in UL COMP the network is not asking for a second transmission, it just requires more processing on the neighbour cell from trying to decode the signal of a neighbour user which radiates power over its often omni antenna. It does not increase network interference though it does increase processing requirements.

Fig. 3.9 taken from [23] serves as a summary of these options applied to 5G. The principles are the same, coordination between neighbour cells to either exploit diversity or reduce interference. However, beamforming can help a lot in these scenarios by limiting interference.

Interference coordination between neighbour cells can be much more precise with spatial information and exchange of beam information between neighbour cells, so as not to direct the power towards the same location at the same time and frequency resources.

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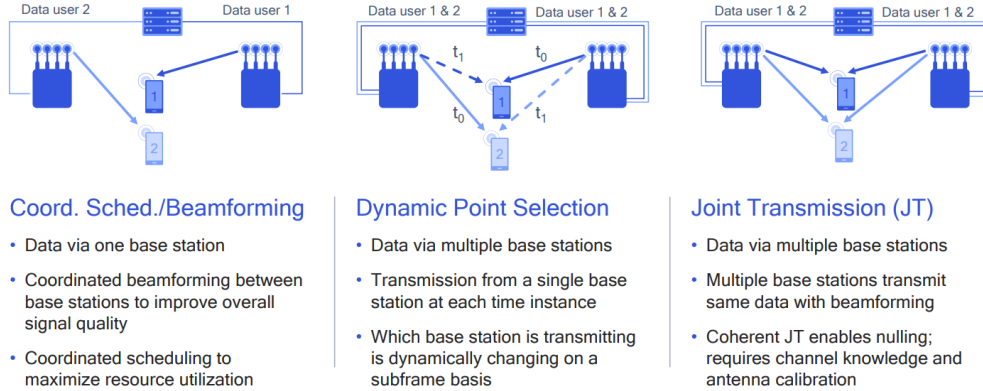


Figure 3.9: A summary of different COMP techniques that can be applied (source [23]).

Joint reception can also be improved by more precise beam gain. But the most important aspect is that joint transmission becomes feasible. Joint transmission without beamforming involves a big increase on network interference. Without beamforming the power is sent everywhere and not only on the desired location. Beamforming allows to exploit the spatial knowledge to focus the power on the desired location and thus avoiding interference towards other areas. Joint transmission is then more reasonable to implement.

Another relevant aspect on this topic is how the coordination is done between the different radiating points. In this regard Cloud RAN may play an interesting role. On a classical GNB deployment each GNB is distributed across the area. This implies that the aforementioned features would need a strong coordination between the GNBs involved. Conversely, on a Cloud RAN type of deployment, with a single GNB covering a somewhat wider area with its radio units distributed across it, there is no need for coordination between different elements as that single GNB will be in charge of all decision making.

3.3 Positioning with beamforming

Another important aspect that can be improved with beamforming is positioning. Location-Based Services (LBS) offer the possibility of taking some action on the user based on its location. There are several positioning methods that can be used on the radio network [24].

GPS-based mechanisms like Assisted Global Navigation Satellite Systems (AGNSS) are limited to open areas and may not be suitable for dense urban areas or indoor scenarios. They are used very often but they are sometimes not accurate enough when visibility towards the sky is not good.

OTDOA stands for Observed Time Difference of Arrival. It allows estimation of the user's location based on the delay measured from different cells that the user can receive signals from. It can either be on the downlink, with user estimating delay from positioning reference signals sent from the cells, or on the uplink, based on reference signals from the user. This was introduced as an alternative to GPS-based systems, trying to improve user location detection by not relying on satellite signals and detecting it based on cellular signals instead.

Some other more robust options involve just knowing the ECID, which is the cell identification information, and just knowing which cell the user is connected to. The Timing Advance (TA) of the user, which indicates when a user should send its uplink transmission so as to have it reach the BTS synchronized with the uplink frame, can also be used as a reference for distance and thus complement the ECID information. Distance and cell ID are not good enough estimates, but incorporating Angle of Arrival (AoA) through beamforming information can improve the estimation. Even better, we could rely on an UL signal sent from the user that allows AoA estimation from different neighbour cells close to the user.

Evidently, not all bands support beamforming so it will not be an easy process because the operator would have to move the user to a beamforming-capable band. Still, it could be an interesting alternative for LBS.

3.4 Chapter Conclusions

This chapter covered the main aspects of beamforming theory giving a big picture of how the beams are created from an array of antennas either on the analog or digital domains, by means of controlling the signal wavefront thanks to superposition principles.

It was also addressed how beamforming is specifically applied on 5G. While the two main beamforming techniques for traffic beams on 5G are covered on the following Chapter 4, these previous pages served to indicate how beamforming can be used when channel knowledge is limited such as during broadcast and RACH processes. Both broadcast and RACH have a big role on communication towards users during cell selection and cell access.

Applying beamforming on user traffic enables using different beams across shared time and frequency resources towards two different users. The concept of MU-MIMO was explained on this Chapter and how the base station scheduler needs to be upgraded to handle a new scheduling dimension, handling not just frequency and time resource, but also becoming spatially aware of the users it intends to serve. Not only that, but it also enables enhancements on COMP and EICIC which allow coordinated transmissions and receptions across installed base stations which

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can help improving radio connectivity.

Moreover, this Chapter mentioned how beamforming can also be used towards improving positioning algorithms that can reliably locate the user based on channel knowledge. The concept of Angle of Arrival is introduced as a means to complement Timing Advance and in this way know not only how far the user is, but also where its signal is coming from.

Chapter 4

Beamforming Algorithms in 5G

The traffic beam definition is arguably the most relevant aspect of the beamforming process. Before we can use any complex weights and the output signals we need to define those complex weights. There are two main forms of beam definition.

On Codebook-based Beamforming the reference signal used for channel estimation and beam definition is provided by the GNB. The user is in charge of choosing the beam to be used from a predefined codebook and then signaling back to the base station.

In contrast, SRS-based Beamforming uses a reference signal, the SRS, that is sent from the user towards the GNB. It relies on channel reciprocity principles of TDD that enable the GNB to decide on beam to send traffic towards the user, based on a reference signal sent from the user.

This Chapter explains these two beamforming techniques, their benefits and drawbacks, and on which scenarios they are most suitable.

4.1 Codebook-based Beamforming

As the name implies, codebook-based beamforming uses a codebook approach towards beam selection. Codebooks were already present in previous 3GPP releases for MIMO purposes. For instance, in LTE, the ENB sends one reference signal for each of its transmitters (generally two, often four) and the UE would then have to use this information to calculate the best precoding matrix for optimum MIMO performance. However, this precoding matrix, must be communicated to the ENB as it is the one that actually uses it. The UE sends this information

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within the Uplink Control Information (UCI) carried on either the PUCCH or PUSCH channel.

Sending all the complex values of the chosen matrix to the ENB over UL channels would mean too much overhead. Not only is it additional information but it would also imply a larger delay on sending the information to the transmitter side.

Thus, the codebook approach allows a compromise. The UE sends a reference to one of the pre-defined matrices on 3GPP standards, whichever best applies to the channel conditions, and that is the one the transmitter side uses for precoding when on SU-MIMO transmission. The compromise is, of course, that they will not be using the ideal pre-coding matrix, but the best available on codebook instead. This allows for less overhead and for quicker transmission of channel feedback to be applied on the DL transmission.

This codebook approach is extended for beamforming. In this case, the GNB transmits a reference signal called Channel State Information Reference Signal (CSI-RS) on up to 32 ports. Unlike LTE, there are two types of codebooks: Type I and Type II. The first one is similar to the one used on LTE, and chooses from a set of matrices. The latter uses a more complex approach which provides a more fine tuned selection albeit at the cost of additional overhead.

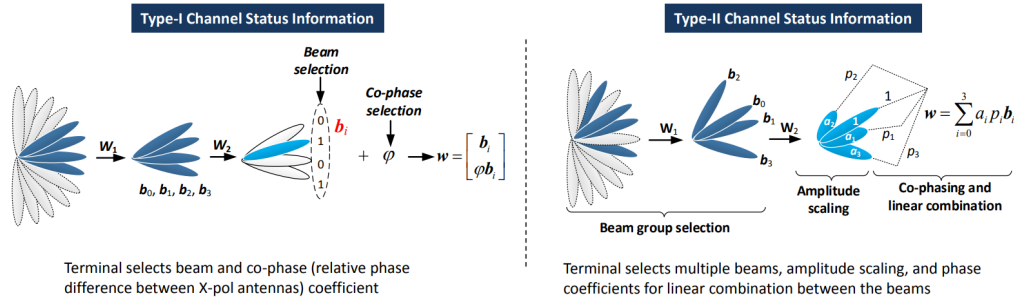


Figure 4.1: Working of Type I and Type II codebooks. User estimates channel co-efficients from reference signal input sent from node, and then decides on the best beam available (source [25]).

With this option, the UE is the one responsible for choosing which beam will the GNB use for communication. While Type II codebook provides additional flexibility towards beam selection, this option is nonetheless somewhat limited by the fact that there must be a selection on the UE side; it will not be always the ideal beamforming matrix, but it will be the best one it can choose.

On the other hand, it has its benefits. The GNB is the one that sends the reference signal used for channel estimation and beam selection. As such there is less power constraint when compared to the alternative of being the UE the one that sends the reference signal. This allows for better coverage of the CSI-RS which leads in turn to a more robust beam decision on cell-edge scenarios.

4.1. Codebook-based Beamforming

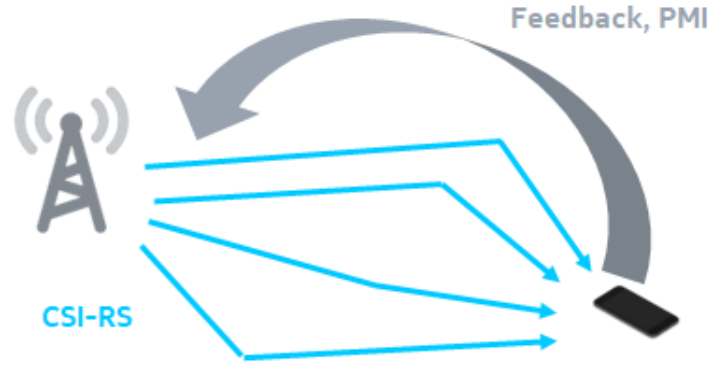


Figure 4.2: The GNB sends the reference signal CSI-RS towards the user. Based on this reference signal it determines the Precoding Matrix Indicator which indicates the matrix that should be applied on the transmitting side. It then must transmit this selection back to the GNB over signaling exchange, which is the PUCCH channel on the primary cell. Note that the primary cell in CA scenarios does not need to be the same cell that the channel is being estimated for.

Furthermore, the UE is estimating the channel based on DL transmission of the CSI-RS and choosing the more appropriate DL beam for it. Therefore there is no need for any channel reciprocity assumptions when it comes to beam selection for the DL transmission. This enables beamforming on FDD bands which cannot take advantage of channel reciprocity as TDD bands can.

What is more, in the process the UL is only used for feedback transmission with the UCI. Therefore, it is not actually used in the process of the channel estimation. This allows for algorithms based on this approach to be used for Carrier Aggregation setups on which one needs to choose a beam for a secondary cell that serves on the DL but not on the UL. There is no need for UL transmission on the carrier that is being sounded, the UCI with SCell information is sent through the PCell UL.

To summarize, a codebook-based approach to beam selection enables a robust choice of beam on diverse radio scenarios, particularly on cell-edge. This comes at the cost of less than ideal beam definition as the UE's selection is constrained by the codebook set by 3GPP. This allows for a good performance on cell-edge, while also being an enabler to beamforming on FDD bands where channel reciprocity cannot be assumed, and on CA scenarios where there are no UL resources available.

If channel reciprocity can be assumed, and the UE can send an UL transmission on the carrier (i.e. the carrier is not being used by the UE for DL only), then being the UE the one that sends the reference signal can allow for better beam definition. This is presented and discussed on Section 4.2.

4.2 SRS-based Beamforming

As opposed to codebook-based beamforming, this approach is based on the Sounding Reference Signal (SRS), which is sent by the UE in the UL. In turn, the GNB is responsible to decide based on this received signal which will be the beam used to carry traffic towards the user.

Algorithms that rely on the SRS from the UE are generally better performing on near-cell or mid-cell scenarios. The UE is the one that sends the reference signal. Therefore there is no beam selection on the UE side, it just sends the SRS that the GNB would have previously configured it to send periodically and the GNB does then all the work towards beam definition.

The GNB will not have to rely on a set of limited possible beams to choose from, restricted by 3GPP standards. It can freely define whichever beam best suites the radio scenario, and will only be limited by the processing capacity for beamforming weight calculation. Provided the SRS is properly configured, the GNB will have access to the whole channel matrix to work with, as it will use the reception of the SRS on each of its TRX to choose the best beam possible.



Figure 4.3: On SRS-based BF the user sends the reference signal that will be used for channel estimation. The channel is evaluated on the GNB side which then defines which beam will be used to carry user traffic. The beam selection is not limited to pre-existing codebook and can thus be more freely defined. The user power for SRS transmission needs to be accounted for and therefore may not be a reliable BF mechanism if used on the cell edge.

However, if the UE is the one sending the reference signal used for channel estimation it must do so with its limited power output. On cell-edge scenarios where the UE's power is limited, the SRS SINR may not be good enough for proper channel estimation and can thus lead to inaccurate beam definition.

Furthermore, all UEs have to send their own SRS so they must all be accounted for and assigned orthogonal SRS occasions, which leads to higher overhead on UL transmissions in order to avoid different UEs sharing same time-frequency SRS resources.

4.2. SRS-based Beamforming

It also should be noted that SRS-based beamforming for DL beam selection is based on channel reciprocity, as this approach chooses the DL beam based on UL signals. Therefore, it is best suited for TDD bands and does not apply to beamforming on FDD. What is more, it needs the UE to send a reference signal, so UL should be configured in this band. This implies that this is not a suitable option for Carrier Aggregation SCells in which UE cannot send its SRS.

4.2.1 Sounding Reference Signal

The SRS configuration variants are defined on 3GPP 38.211-Table 6.4.1.4.3-1 [26]. They vary depending on how many PRBs are used for each SRS transmission, and how many PRBs will be sounded in total through frequency hopping after all transmissions, before starting over.

UEs can each be periodically scheduled to transmit their SRS across the whole channel bandwidth on a single transmission instead of doing frequency hopping over several transmission occasions. This implies a very fast channel estimation, as the whole bandwidth information would be quickly available. However, this is more stringent on the UE's power, as it would have to spread it across the whole bandwidth. It would also limit the SRS scheduling capabilities on the GNB as it will not be able to multiplex more than one UE in the same SRS occasion.

The alternative is for each UE to use less bandwidth on each transmission. This helps the UE with its limited power to spread it across less PRBs thus increasing the power used on each sub-carrier. Furthermore, multiplexing UEs on frequency domain allows for far more flexibility on the GNB side for scheduling purposes, to accommodate for many connected UEs and other processes they could be having, such as measurement gaps and Discontinuous Reception (DRX).

It will depend on each vendor's algorithm how much of the bandwidth is needed for proper beam definition, and how fast the SRS periodicity should be configured. Evidently, the more bandwidth is sensed and the lower the periodicity is used, the more channel information is received and thus better channel estimation can be used for beam definition. It is therefore a balance and trade-off between the amount of available channel information and the number of UEs that can be accommodated for SRS transmission.

When the UE sends its SRS it is received on all TRX at the GNB side, it does so from a single antenna. Each SRS occasion can have configured an additional resource to send also from a second antenna. But if the GNB requires the complete channel information, then it would need the channel estimation from all the reception antennas on the UE.

Chapter 4. Beamforming Algorithms in 5G

UEs often have more reception antennas than they do for transmission. Power amplifiers demand more energy consumption and make for a more expensive hardware setup on the phone. Therefore, UEs may have one or two transmission antennas while having four reception antennas on TDD bands, which allow for up to four independent layer reception in the DL. What is more, UEs on NSA mode often dedicate one antenna for LTE and one for NR, so they only use one transmitter on NR while having four reception antennas. It should be noted that on low FDD bands UEs do not have more than two reception antennas but on TDD bands they often do.

Transmit Antenna Switching (TAS) allows for estimation of channel paths to all reception antennas, by means of switching on each SRS occasion which antenna is used to transmit the SRS. Not every UE supports it, but the ones that do can be configured to send their SRS across all of their reception antennas. The TAS support is signaled as either 1T2R, 1T4R, or 2T4R. For instance, a UE supporting 1T4R can use four SRS occasions to transmit its channel information across all reception antennas, one being used on each SRS occasion. Thus, if the GNB requires all of the channel information it can get that information at the cost of needing four times more SRS occasions for the same UE. Figure 4.4 illustrates a 2T4R TAS can be applied for a user transmission over the four receiving antennas on two SRS occasions.

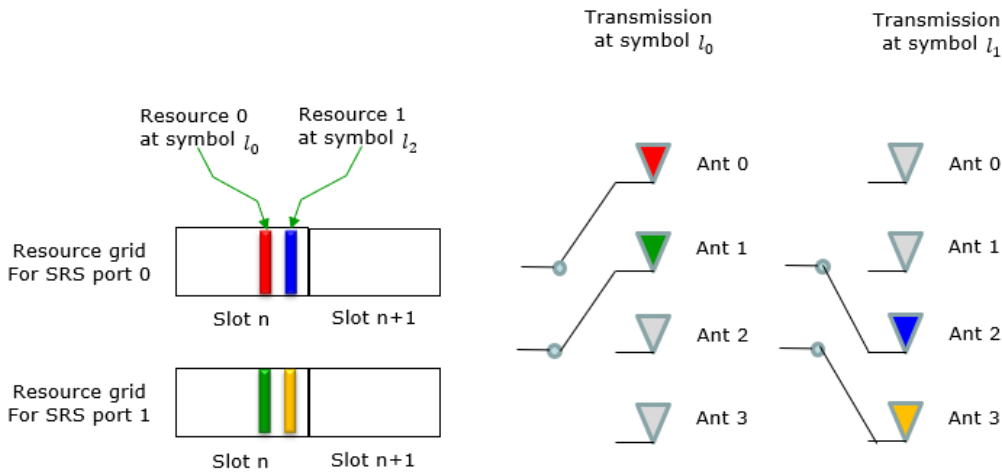


Figure 4.4: Transmit Antenna Switching (TAS) can be used to get information from all receiving user antennas, even if the users has less transmitters than available receiving antennas. On this Figure user supports 2T4R. The user first sends two SRS on the same SRS occasion using different OFDM symbols for each. It then switches the transmitting antennas towards the other two, and those are used on the next SRS occasion to transmit the SRS (source [27]).

4.2.2 Beam Synthesizing

Beam synthesizing takes full advantage of SRS-based BF approach by using the channel information gathered from reception across all of its TRX to synthesize a custom-made beam for that UE. In this scenario the GNB does not rely on a set of possible beams to choose from, but instead it synthesizes for each user a particular beam based on the channel information. This kind of approach helps produce a much better beam in terms of coverage when compared to some kind of grid-of-beam alternative. This process can sometimes be referred to as Real Time Beamforming (RT BF).

Nonetheless, this comes at the expense of higher demand on computational requirements as the GNB needs to quickly process all the information gathered to find out the best weights to be applied on the beamforming matrix. What is more, this process also demands a lot of knowledge of channel conditions; the channel response across all of its TRX. The SRS is evidently a must for this sort of algorithms to work. A codebook-based simply cannot provide this information. Thus, this can only be used on TDD bands.

Not only that, the SRS information needs to be readily available. This implies that we cannot schedule target UE to send small chunks of bandwidth on each SRS transmission, as the whole band mapping would take too long to complete on the channel information across the whole band and all TRX will not be there in time to properly synthesize the best beam.

Therefore, if UEs have to send larger bandwidths on SRS those in cell-edge will not be able to do so, as power available will be limited to surpass pathloss and provide a reliable SRS to the GNB. Not only that, but also this means GNB has less flexibility to schedule multiple UEs across the whole bandwidth within a time slot.

These drawbacks illustrate that while customizing a beam per user provides a very interesting beamforming capability to the GNB portfolio, it cannot be used for all users at all times. The use of these sorts of algorithms should mind the user's channel conditions, the amount of users in the cell and how much traffic is needed to be carried. If beam-synthesizing resources are very demanding, should the GNB use them on users with little to no traffic?. Thus, RT BF is often applied to data-hungry users on near-cell scenarios.

4.3 Chapter Conclusions

This Chapter served to illustrate how the traffic beams can be defined for each user connected, which differentiate on who sends the reference signal used for channel learning: SRS-based BF and Codebook-based BF.

SRS-based BF mechanisms allow the base station to have full knowledge of the channel, given TDD reciprocity between DL and UL. This enables the base station to have a lot of information when it comes to deciding the beam that will be used to carry the user's traffic. SRS-based BF therefore provides the best results in terms of peak throughput and channel capacity. RT BF exploits that channel knowledge to the fullest by allowing the base station to customize a beam for a specific user.

However, it has two main drawbacks. On the one side, power-limited users whose SRS can not be reliably used for channel estimation cannot be candidates for this type of channel acquisition. Furthermore, given that the user needs to transmit the SRS on the same band that is being estimated, then this is not a proper beamforming definition mechanism on CA scenarios.

Codebook-based BF, on which the GNB sends the reference signal instead of the user, is a great alternative to overcome both scenarios. It can be used on CA as the reference signal is received on the DL and then signaling feedback, being the chosen beam, sent back through the primary cell. Moreover, as the base station often has more power available than on the user side, then it can be more reliable than the SRS sent by the user.

Fig. 4.5 illustrates how there is no single beamforming technique that should be applied over the whole cell area at all times. Instead, each beamforming mechanism can be applied where and when it is most suitable.

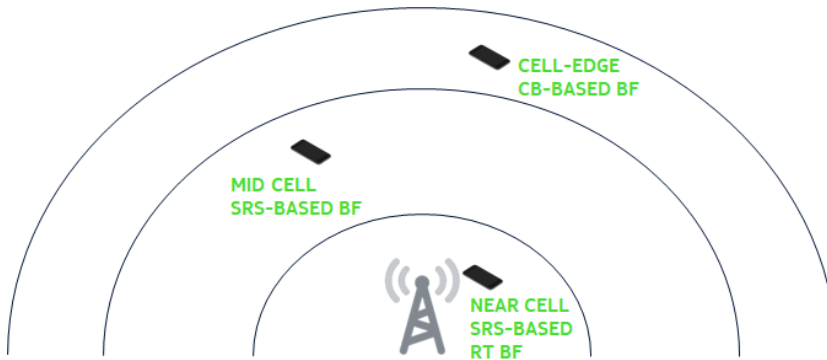


Figure 4.5: Illustration of how the different beamforming techniques can be applied over the 5G cell coverage area.

Chapter 5

Field Tests

The main objective of this chapter is to illustrate and exemplify the two main beamforming mechanisms that were presented on Chapter 4 with field tests. This allows to get a better understanding of the beamforming process using real world examples from a live commercial 5G network.

It is important to note that these tests do not intend to be a comprehensive analysis of beamforming mechanisms and performance. That would need a more extensive field test plan, one which would compare performance across different types of hardware and software on both user and GNB sides. Instead, these tests look to provide more insight on the beamforming process by means of viewing the performance of each of those in a real world scenario.

The 5G NSA network of a local operator in Uruguay was used. In this case a 32 TRX 128 AE Massive MIMO radio was installed on the base station side. Band n78 on 3500 MHz was used for 5G air interface, using a TDD 7D:1S:2U frame structure, with special slot S configured to not carry out any downlink traffic. During each of the tests instances the only change done on the GNB side is the beamforming mechanism. Table 5.1 summarizes the configuration setup.

Table 5.1: NR network parameters as seen from logging messages.

parameter	value
band	n78 (3300 MHz - 3800 MHz range)
SCS	30 kHz
used bandwidth	273 PRBs (100 MHz)
slot pattern (10 ms)	DDDDD DDSUU DDDDD DDSUU
max DL layers	4
max modulation	256 QAM

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With this configuration the maximum achievable throughput can be estimated at around 1.4 Gbps [28], considering only traffic contribution from 5G n78 band in use. This bitrate, though, is on optimal radio conditions which are rarely achieved. The network is generally configured to accept around 10% block error rate when choosing a modulation and coding rate.

Being a NSA network, the user is connected on both LTE and 5G at the same time with ENDC and can potentially be aggregating traffic concurrently on LTE and 5G cells that it is connected to. Nonetheless, only 5G traffic is considered on the result evaluation as it is the actual band that is being tested with beamforming.

Logging was done with XCAL software from Accuver [29], which was set up on a Windows laptop connected to the mobile through USB ports. A GPS was also connected to the PC to gather location information during testing. Fig. 5.1a summarizes the connections, while 5.1b shows the actual setup on the field. It is important to note that all logs are taken at the user side, and therefore there will not be more information available than what the user can know during these tests.

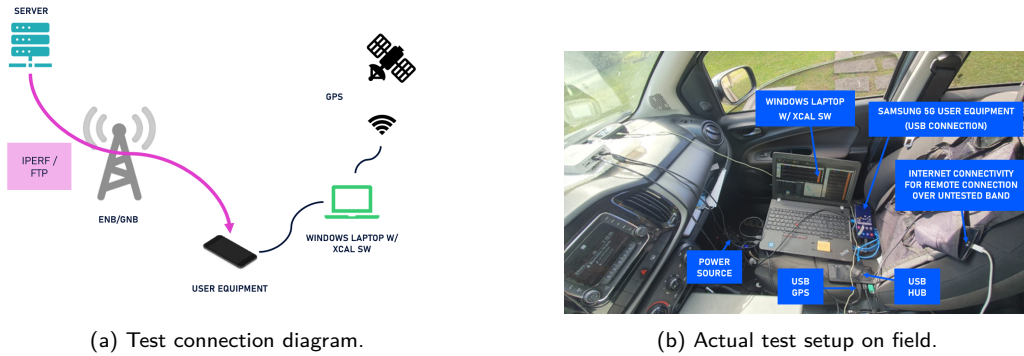


Figure 5.1: SRS-BF and Codebook-BF test setup. Windows laptop is running XCAL software to capture logging information from the UE.

Many of the charts of this chapter show different metrics graphed against SS-RSRP. This type of plots are interesting to show not just an average value, but both a scatter and average line plot across varying radio conditions. While SS-RSRP is a fairly good reference to represent the general radio conditions, it is certainly not ideal. Without beamforming being used the PDSCH received power on the user can be well correlated with the reception power on the RSRP reference. But when beamforming comes into play then the traffic beams are very much different from the broadcast beams from which the SS-RSRP is taken. Therefore, the SS-RSRP is sent over a broadcast beam which is not correlated with the traffic beam. Even so, the SS-RSRP gives a reasonable notion of the radio scenario, though it should be noted that it is far from an ideal indicator of the perceived radio performance on PDSCH traffic.

This Chapter is comprised of two Sections, each corresponding to a testing in-

5.1. SRS-based BF vs Codebook-based BF

stance. Section 5.1 covers tests that look to compare SRS-based BF against Codebook-based BF, while Section 5.2 show the results of enabling RT BF to data-hungry user on near-cell scenarios.

5.1 SRS-based BF vs Codebook-based BF

The following field tests look to provide some insight when it comes to comparing SRS-based beamforming methods against codebook-based. As mentioned on Chapter 4, Codebook-based BF provides a robust beam definition, given that it is based on reference signal sent by the GNB, which is a good beamforming mechanism to be used on the cell-edge. However, on mid and near cell setups this beamforming algorithm is limited by pre-defined weights known by both user and base station based on pre-defined codebook. SRS-based BF enables better performance across mid and near cell given that reference signal is sent by the user and then GNB has all of the channel information to decide on the best possible beam, that will not be limited to those pre-defined by the standard.

Therefore, what is expected of these tests is to get better bitrates on mid and near cell when using SRS-based BF. On the other hand, better results are expected on the cell-edge when using Codebook-based BF.

During these tests, the SRS-based beamforming is using a Grid-of-Beams approach, choosing the best beam available from a fixed set of possible beams. There was no beam synthesizing configured during these tests. One single GNB was configured at this point for testing purposes, while other GNBs in the area were not on air during these tests.

One mobile device Samsung S22+ was used on full-buffer download traffic from Linux server. Iperf3 was used as traffic generation tool. UDP was used as transport for this traffic in order to both isolate the downlink from the uplink and also avoiding TCP artifacts that may influence the actual received throughput. At the end of the day what is being tested is the air interface efficiency and capacity. Therefore, avoiding the role of TCP procedures allows to evaluate the air interface as isolated as possible.

Before comparing both beamforming mechanisms, it is interesting to view how the beamforming of the SSB is used on this setup. Fig. 5.2 shows the coverage regions of each broadcast beams. Applying beamforming on the broadcast and RACH is optional (there could be a single broadcast beam transmission instead) but it allows to increase the broadcast coverage upon which the user bases its SS-RSRP measurements which uses for cell selection and mobility.

Fig. 5.3 shows user measurements related to the broadcast information. More

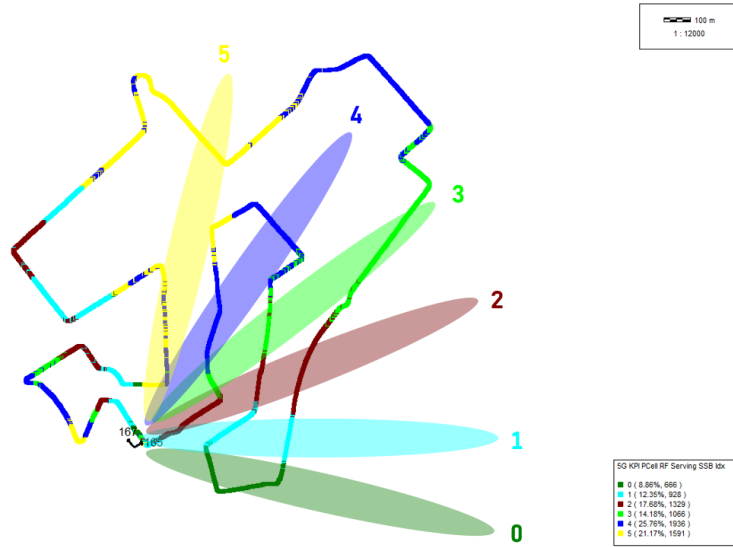


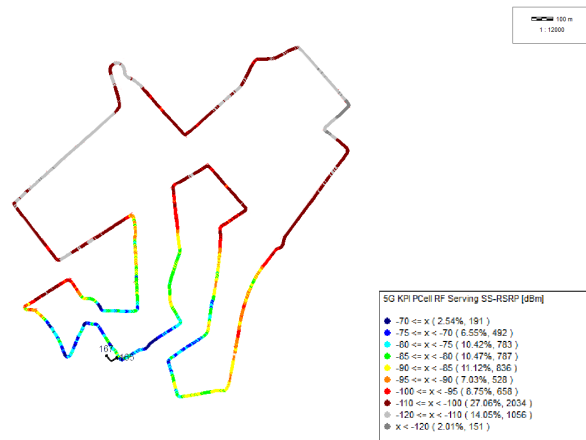
Figure 5.2: The user measures the coverage of each SSB broadcast beam sent from the GNB, providing main network configuration and serving for synchronism purposes and to take reference measurements such as SS-RSRP. Map reference was taken out of the image at the request of the base station MNO.

precisely, SS-RSRP and SS-SINR are presented, which are measurements of the synchronisation signals sent from the GNB and which are used for mobility and cell selection purposes. The Physical Cell Identity (PCI) is used to indicate which cell the user is connected to.

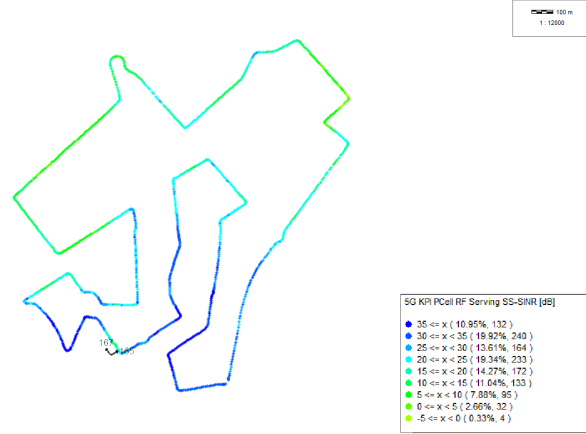
Fig. 5.4a shows an extract of the RRC reconfiguration messages during ENDC setup procedure. For codebook-based beamforming this serves to check that Type I codebook is being used. On the other hand, for SRS-based beamforming, RRC message shows that TAS is being used and SRS is set up with bSRS 2 and cSRS 63. This values serve as reference to 3GPP table 38.211-Table 6.4.1.4.3-1, on which it can be seen that this maps to the user being required to send the SRS with frequency hopping covering 272 PRBs over transmissions of 8 PRBs each.

Fig. 5.5 shows main KPIs taken from drivetest route with codebook-based beamforming configured on the GNB. Fig. 5.6 shows these same KPIs but with SRS-based beamforming configured.

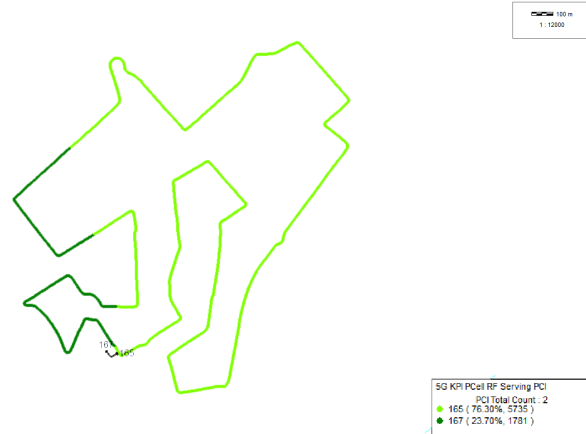
5.1. SRS-based BF vs Codebook-based BF



(a) SS-RSRP



(b) SS-SINR.



(c) PCI

Figure 5.3: Synchronisation Signal measurements from the user. Map reference was taken out of the image at the request of the base station MNO.

Chapter 5. Field Tests

```

1664 csi_RS_ResourceSetList
1665 npr_CSI_RS-SSB
1666 npr_CSI_RS_ResourceSetList[0] = 8
1667 bwp_Id = 1
1668 resourceType = periodic
1669 csi_ReportConfigToAddModList[0]
1670 reportConfigId = 0
1671 resourcesForChannelMeasurement = 0
1672 csi_IM_ResourcesForInterference = 11
1673 reportConfigType
1674 periodic
1675 reportSlotConfig
1676 slots20 = 288
1677 pucch_CSI_ResourceSetList[0]
1678 uplinkBandwidthPartId = 1
1679 pucch_Resource = 9
1680 reportQuantity
1681 cri-RI-LI-PMI-CQI
1682 reportFreqConfiguration
1683 cqi_FormatIndicator = widebandCQI
1684 pmi_FormatIndicator = widebandPMI
1685 csi_ReportingBand
1686 subbands18 11111111 11111111 11
1687 timeRestrictionForChannelMeasurements = configured
1688 timeRestrictionForInterferenceMeasurements = configured
1689 codebookConfig
1690 codebookType
1691 type1
1692 subType
1693 type1-SinglePanel
1694 nrOfAntennaPorts
1695 moreThanTwo
1696 n1_n2
1697 Four-one-Type1-SinglePanel-Restriction 11111111 11111111
1698 type1_SinglePanel_r1_Restriction 00001111
1699 codebookMode = 1
1700 groupBasedBeamReporting
1701 disabled
1702 cqi_Table = table2
1703 subbandSize = value1
1704 csi_ReportConfigToAddModList[1]
1705 reportConfigId = 2
1706 resourcesForChannelMeasurement = 10
1707 reportConfigType
1708 periodic
1709 reportSlotConfig
1710 slots20 = 288
1711 pucch_CSI_ResourceSetList[0]
1712 uplinkBandwidthPartId = 1
1713 pucch_Resource = 9
1714 reportQuantity
1715 ssb-Index-RSRP
1716 timeRestrictionForChannelMeasurements = notConfigured
1717 timeRestrictionForInterferenceMeasurements = notConfigured
1718 groupBasedBeamReporting
1719 disabled
1720 nrOfReportedRS = n2
1721 cqi_Table = table2

```

(a) Codebook-based beamforming configuration showing Type I codebook used.

```

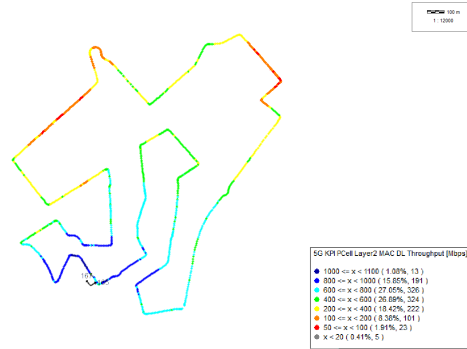
941 scaling = f1
942 tp_pi2BPSK = enabled
943 srs_Config
944 setup
945 srs_ResourceSetToAddModList[0]
946 srs_ResourceSetId = 0
947 srs_ResourceIdList[0] = 0
948 resourceType
949 periodic
950 usage = codebook
951 alpha = alpha1
952 p0 = -80
953 srs_ResourceSetToAddModList[1]
954 srs_ResourceSetId = 1
955 srs_ResourceIdList[0] = 0
956 srs_ResourceIdList[1] = 1
957 srs_ResourceIdList[2] = 2
958 srs_ResourceIdList[3] = 3
959 resourceType
960 periodic
961 usage = antennaSwitching
962 alpha = alpha1
963 p0 = -80
964 srs_ResourceToAddModList[0]
965 srs_ResourceId = 0
966 nrOfSRS_Ports = port1
967 transmissionComb
968 n2
969 combOffset_n2 = 1
970 cyclicShift_n2 = 1
971 resourceMapping
972 startPosition = 1
973 nrOfSymbols = n1
974 repetitionFactor = n1
975 freqDomainPosition = 48
976 freqDomainShift = 0
977 freqHopping
978 c_SRS = 63
979 b_SRS = 2
980 b_hop = 0
981 groupOrSequenceHopping = neither
982 resourceType
983 periodic
984 periodicityAndOffset_p
985 sl40 = 7
986 sequenceId = 165
987 srs_ResourceToAddModList[1]
988 srs_ResourceId = 1
989 nrOfSRS_Ports = port1
990 transmissionComb
991 n2
992 combOffset_n2 = 1
993 cyclicShift_n2 = 1
994 resourceMapping
995 startPosition = 1
996 nrOfSymbols = n1
997 repetitionFactor = n1
998 freqDomainPosition = 48

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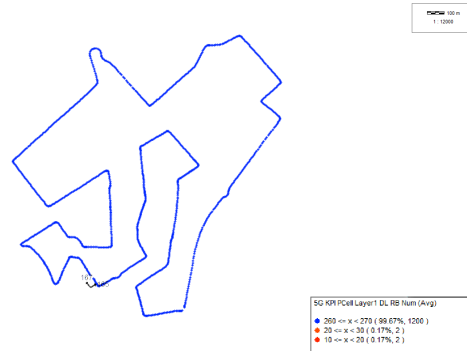
(b) SRS configured with TAS setup using cSRS 63 and bSRS 2.

Figure 5.4: Extract of RRC Reconfiguration message sent to user during ENDC setup.

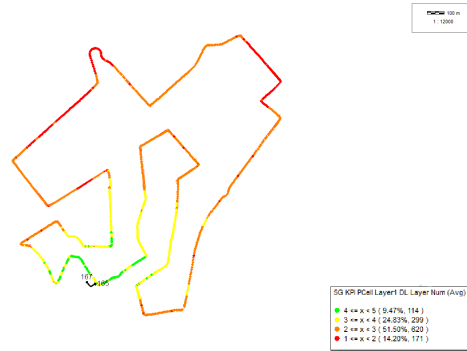
5.1. SRS-based BF vs Codebook-based BF



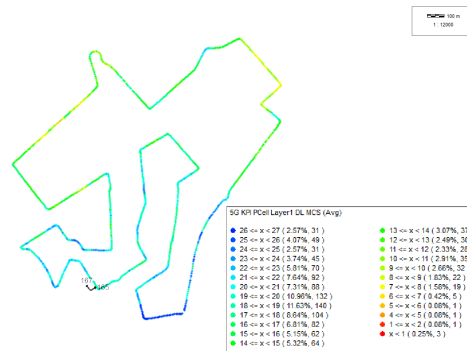
(a) DL MAC Throughput



(b) DL PRBs



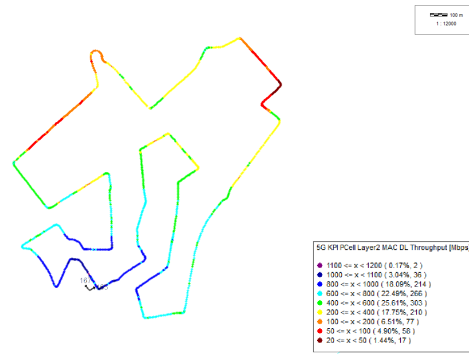
(c) DL Layers



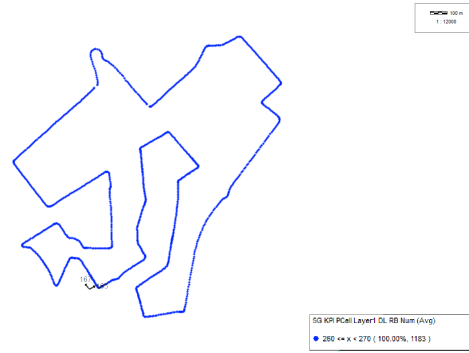
(d) DL MCS

Figure 5.5: Test results with Codebook-based beamforming configured on GNB. Map reference was taken out of the image at the request of the base station MNO.

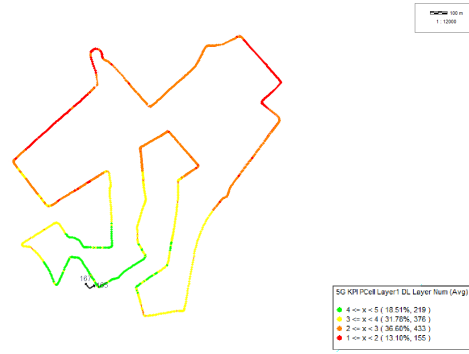
Chapter 5. Field Tests



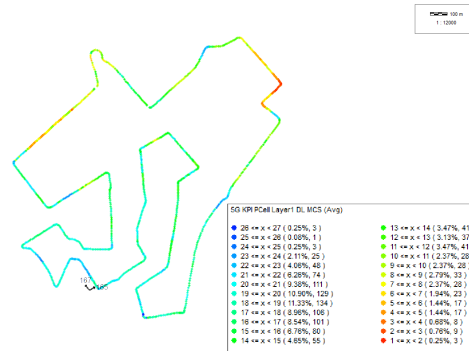
(a) DL MAC Throughput



(b) DL PRBs



(c) DL Layers



(d) DL MCS

Figure 5.6: Test results with SRS-based beamforming configured on GNB. Map reference was taken out of the image at the request of the base station MNO.

5.1. SRS-based BF vs Codebook-based BF

Throughout both tests PRBs allocated are always at near maximum of 273, as the cells do not have any other users, all radio resources are available for scheduling. In both cases DL MCS gets lower when more DL layers are used for data transmission. Therefore, while having more layers certainly leads to better throughput values, MCS needs to compensate the interference between those layers by using more robust modulation and coding rate.

SRS-based beamforming allows a clear gain on DL layers being used, there is much more usage of 3 and 4 layers during the drivetest route with SRS-based beamforming being used on near/mid cell areas. This is more clearly presented on Fig. 5.7.

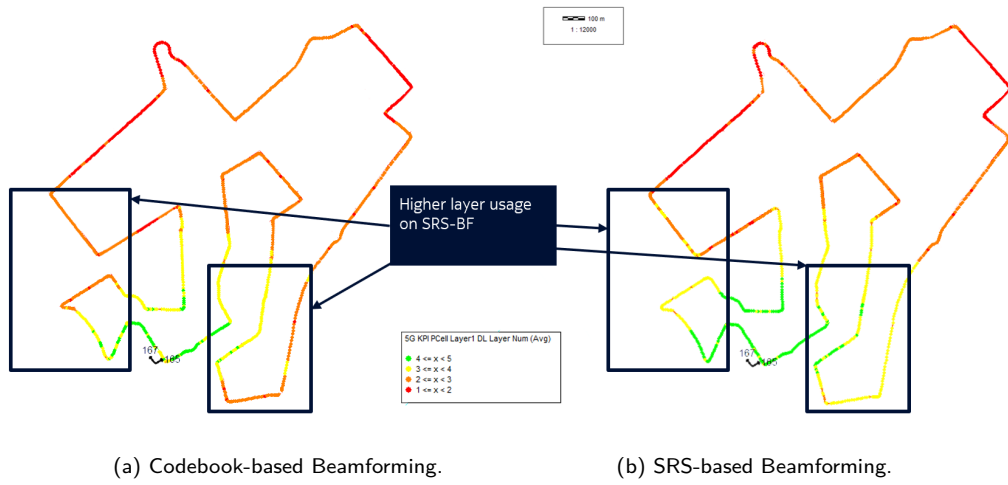


Figure 5.7: DL Layers transmitted. Each DL layer holds an independant transmission. The more layers are used the higher the potential bitrate than can be achieved on the radio interface. Codebook beamforming on the left shows in general less layer than SRS beamforming on the right. Map reference was taken out of the image at the request of the base station MNO.

This leads to better throughput values, which can be seen on Fig. 5.8. This image presents the DL MAC layer throughput obtained on each drivetest. However, upon closer inspection it is also seen that on the cell-edge codebook-based beamforming outperforms SRS-based beamforming.

These results can also be presented with plots comparing layer and throughput to SS-RSRP values, which are shown on Fig. 5.9. SS-RSRP can be seen as a reference to general radio conditions, and therefore allows to get some knowledge of how each algorithm performs on varying radio conditions. SS-RSRP values are grouped into *bins* of 5 dB length to take an average of the plotted metric on each SS-RSRP range. However, it should be considered that SS-RSRP is far from a perfect metric to evaluate the radio scenario. SS-RSRP is measured from broadcast beams and not from traffic beams. Therefore, while it gives a general

Chapter 5. Field Tests

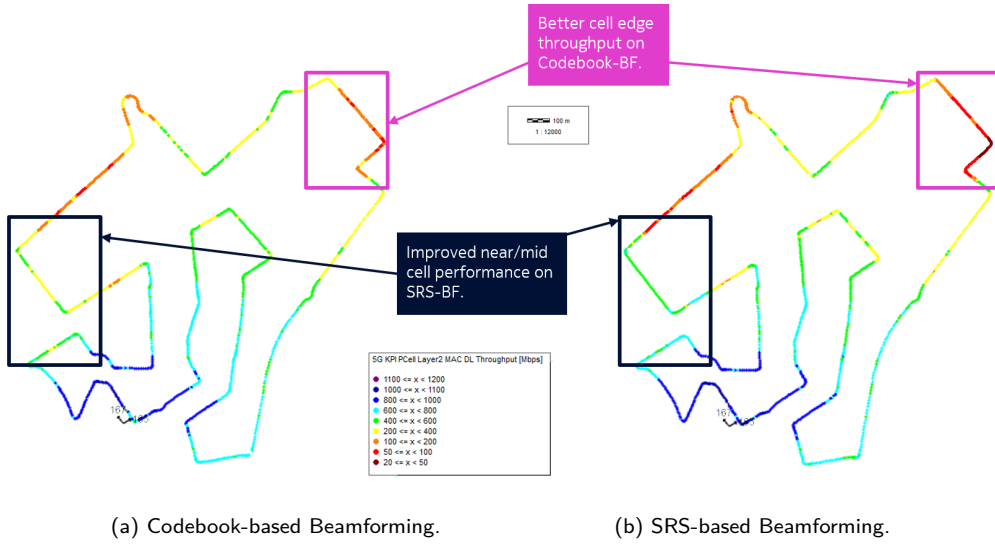


Figure 5.8: DL MAC Throughput. Codebook beamforming on the left shows lower throughput values on near/mid-cell areas when compared to SRS-based beamforming. However, on cell-edge codebook-based beamforming outperforms SRS-based. Map reference was taken out of the image at the request of the base station MNO.

idea, it is not representative of the radio conditions on traffic channels.

From Fig. 5.9 it is clear that it is much easier to reach high throughput values on near cell when using SRS-based beamforming. On the contrary, on cell-edge with SS-RSRP values lower than around -115 dBm, codebook-based beamforming gets better throughput values.

These tests serve to corroborate how each type of beamforming performs and where it is most useful. SRS-based beamforming is good for near/mid-cell scenarios, even when a GoB approach is used. Having the beam chosen at GNB side allows the network to not rely on predefined 3GPP codebook structures from which to choose the beam. The GNB can freely decide on the best beam with less constraints.

On the other hand, SRS-based beamforming needs the SRS to be sent and properly received and decoded on the GNB. Transmission power is much more limited on the UE side when compared to power from GNB transmissions. On cell-edge user power is not always enough for the SRS to reach the GNB with good enough reception power, even when SRS is being sent with frequency hopping over smaller bandwidth portions. This leads to a poor channel estimation and thus beam selection. Meanwhile, codebook-based beamforming uses a reference signal sent from the GNB, which can reach further by means of more power employed on its transmission.

SRS-based beamforming is therefore a better option for near or mid cell scenarios,

5.1. SRS-based BF vs Codebook-based BF

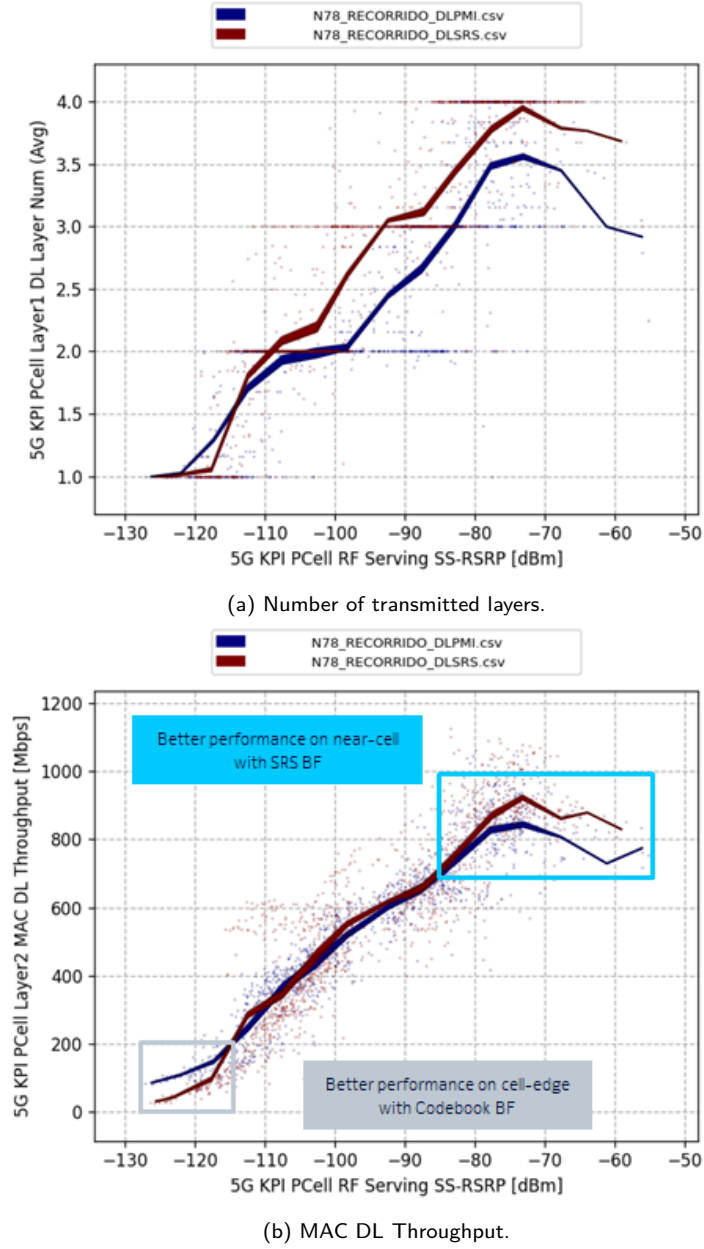


Figure 5.9: Layer and throughput plotted against SS-RSRP, representing values across varying radio conditions. Each point represents a 1-second average. Line plots 5 dB spaced bin average and its width is modulated with amount of samples available on each bin.

while it seems reasonable to use codebook-based beamforming on the cell-edge. SRS-based BF can also be enhanced with synthesizing which allows the GNB to customize a beam for a specific user. Tests of this feature are presented on Section 5.2.

5.2 Real Time Beamforming

This Section looks to exemplify the use of RT BF, presenting not only its benefits to improve the radio performance given a customized beam, but also show how it is limited to users connected near the GNB, as the power used for the reference signal is also limited.

The GNB configured a Sub-Band SRS (SB SRS) to all users, which serves as input for SRS-based BF. This SB SRS is sampling only 8 PRBs at a time, which allows many users to transmit their SRS at the same time, using different frequency resources.

In this setup the GNB will modify that configuration to those users that show a high demand of resources and for which the SB SRS is received with strong power levels. In such cases it will de-configure that SB SRS setup and will instead configure a Wide-Band SRS (WB SRS) that will cover the whole of the band on each single transmission. This allows the GNB to quickly get knowledge of the whole channel on a single SRS occasion, and therefore potentially apply RT BF.

As mentioned on Section 4.2.1, the SRS is configured using 3GPP 38.211-Table 6.4.1.4.3-1 [26]. From that table, cSRS is defined as 63 which indicates that at the end of the SRS frequency hopping 272 PRBs will have been used for SRS transmission. The bSRS parameter set on 2 indicates that each SRS occasion consists of 8 PRBs, while bSRS 0 sets a 272 PRB transmission. Therefore, the last known value exchanged of bSRS helps to determine from the user perspective whether it has SB SRS configured, or if it has WB SRS configured. While bSRS at 0 indicates the use of WB SRS, it is important to note that does not imply that the user will necessarily be receiving traffic over RT BF. Whether the user is being scheduled with a RT BF beam or not is not something that can be derived from the user perspective, as it is not signaled towards the user (and it does not need to know either).

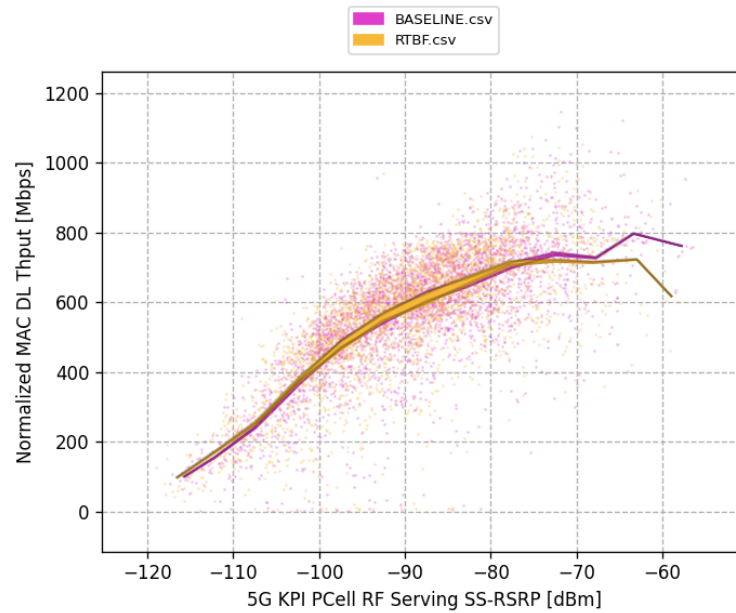
A Samsung S23 mobile was used during these tests and FTP/TCP download of a big random file (80 GB) was used instead. In this setup there were two GNBs on testing area, with other two farther away. All GNBs had the same configuration at all times. Two different configurations were used, with the enabling of RT BF being the only difference between each test.

First tests comprised a drivetest across the area. While results showed on Fig. 5.10a that bSRS can be used to check when WB-SRS is configured for the user, Fig. 5.10b shows there is no gain seen on throughput plots. There are in fact lower throughput values at good SS-RSRP, although those bins have very few samples on them and therefore cannot be relied on.

5.2. Real Time Beamforming



(a) bSRS shows where WB SRS was configured during drivetest. Map reference was taken out of the image at the request of the base station MNO.



(b) NR DL MAC Throughput with and without RT BF configured on GNB, plotted against SS-RSRP representing values across varying radio conditions. Each point represents a 1-second average. Line plots 5 dB spaced bin average and its width is modulated with amount of samples available on each bin.

Figure 5.10: Results obtained during drivetest.

While these results seem discouraging at first, the moving speed of the user is a factor that should be accounted for. During drivetest the user is moving at 45 km/h. It may be the case that radio conditions are changing too fast and beam

Chapter 5. Field Tests

customization cannot keep up. Even so, these results are interesting to note that WB SRS is used even at around 200 m away from the GNB, with some samples going as far as 300 m.

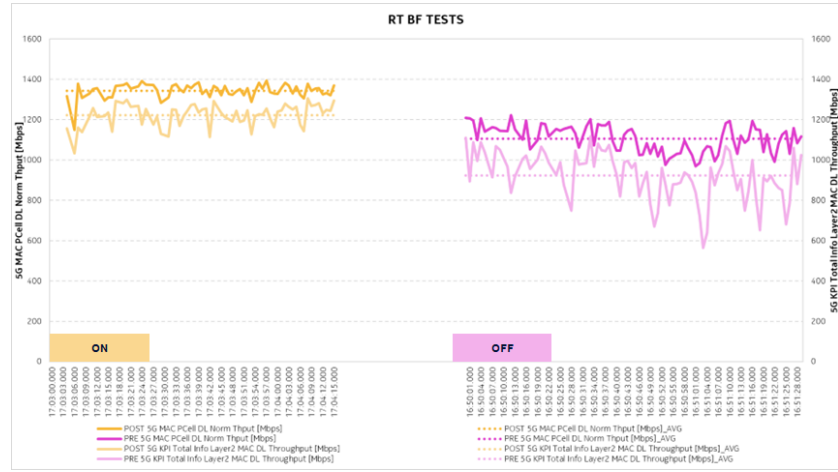
Assuming the speed is not allowing to get any gain out of RT BF, static tests were also performed on a selected point near the GNB, around 50 m away from the base station. These results are much more promising. Fig. 5.11a shows NR MAC DL Throughput increases 30% from 930 Mbps to 1220 Mbps with RT BF enabled. Seen as *normalized* throughput, which calculates what bitrate would have been if all resources were assigned to the user, increases 23% 1100 Mbps to 1350 Mbps. That is a very large increase on the bitrate.

Moreover, Fig. 5.11b shows that both with and without RT BF, the user was being scheduled with 4-layer transmissions. The main difference is that with RT BF much higher DL MCS can be achieved and thus much more traffic is sent over each radio interface resource, with much higher spectral efficiency. It should be noted as well that there were not only better results with RT BF, but they were also much more stable.

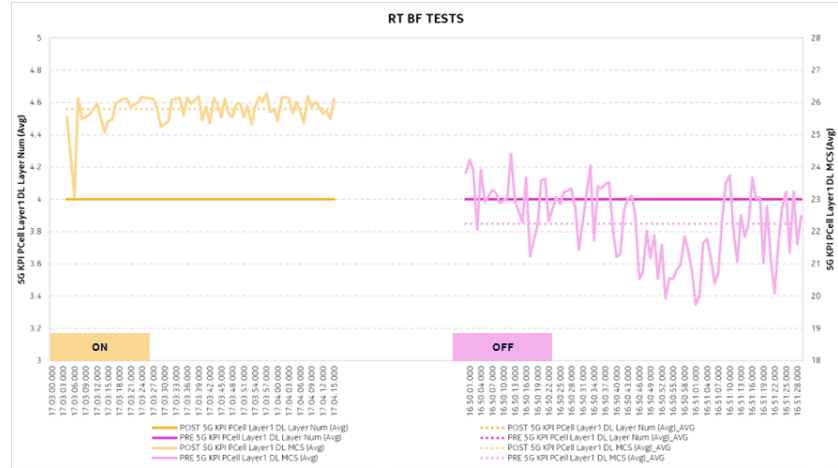
While these results are very good, they only show a single location near the GNB. To complement those results a walk test was carried out with user moving over three blocks over varying radio conditions, although staying somewhat near the GNB.

Fig. 5.12a shows that WB SRS is configured on the first two blocks, before the user turns and moves away from the GNB. Fig. 5.12b shows a clear increase in obtained bitrate when WB SRS is configured, as seen in plot showing samples with higher NR MAC DL Throughput values.

5.2. Real Time Beamforming



(a) NR MAC DL Throughput values during tests with and without RT BF configured. Normalized throughput shows bitrate that would have been obtained if all resources had been scheduled to the user. This allows to ignore differences on resource assignment between both tests.



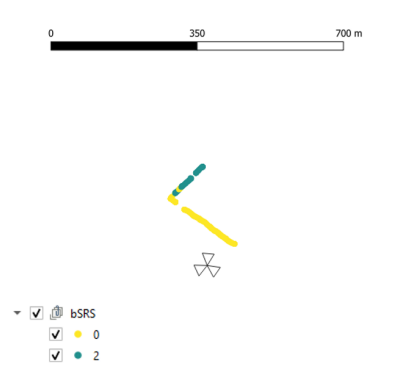
(b) NR DL Layers and DL MCS values during tests with and without RT BF configured.

Figure 5.11: Static test results with and without RT BF configured on the GNB. There are 20% gains on throughput values. Improvement is clearly seen as a consequence of much better DL MCS being assigned to the user. On both setups 4-layer transmissions were used, but with RT BF the achieved DL MCS is much higher.

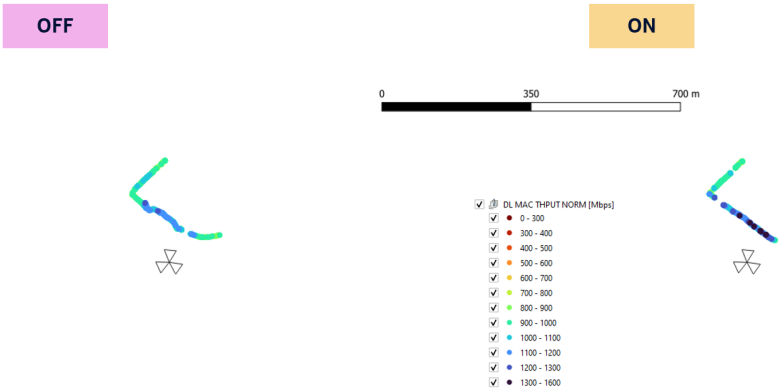
Fig. 5.13 shows the NR MAC DL normalized throughput results plotted against SS-RSRP. As opposed to what was seen on this same plot during drivetest, on walktest results there is a very big and clear improvement on throughput values. This can be seen both on the average throughput on each bin, and on the scatter points noting that there are no samples above 1.2Gbps without RT BF, while there are several above that threshold when RT BF is configured on GNB.

Fig. 5.14 shows that the improvement seen is a consequence of using higher MCS and more layers on average when RT BF is available. The use of a more spectrally

Chapter 5. Field Tests



(a) bSRS shows were WB SRS was configured during walktest.



(b) NR DL Normalized MAC Throughput with and without RT BF configured on GNBs. Each point represents a 1-second average.

Figure 5.12: Walktest results show there is a clear improvement when using RT BF and good radio scenarios. Map reference was taken out of the image at the request of the base station MNO.

efficient modulation and higher number of layers lead to higher amount of bits sent over each radio resource.

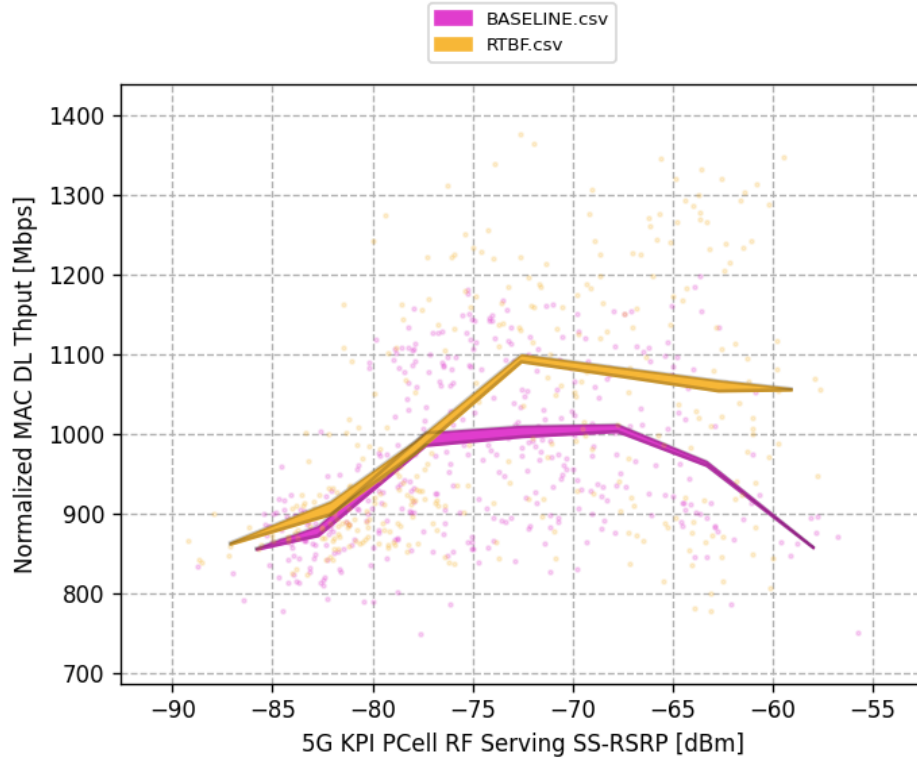


Figure 5.13: NR DL Normalized MAC Throughput with and without RT BF configured on GNB, plotted against SS-RSRP representing values across varying radio conditions. Each point represents a 1-second average. Line plots 5 dB spaced bin average and its width is modulated with amount of samples available on each bin. There are not only higher average values on line plot, but also there are samples above 1.2 Gbps with RT BF configured and none without it.

5.3 Chapter Conclusions

This Chapter provides a better insight into the beamforming mechanisms described on Chapter 4. This allows to get a better understanding of the benefits, drawbacks and limits of each beamforming mechanism.

SRS-based BF shines on near and mid cell scenarios given that there is much more flexibility and liberty on the GNB side to choose the most appropriate beam. On SRS-based BF the user sends a SRS reference signal and the GNB decides on the best possible beam based on the channel informaton taken from that reference. On the other hand, Codebook-based BF has a very limited set of beams on which the users choose from, which is therefore sub-optimal.

Conversely, Codebook-based BF is seen to outperform SRS-based BF on the cell edge just as expected. On the cell edge the power available on the user does not

Chapter 5. Field Tests

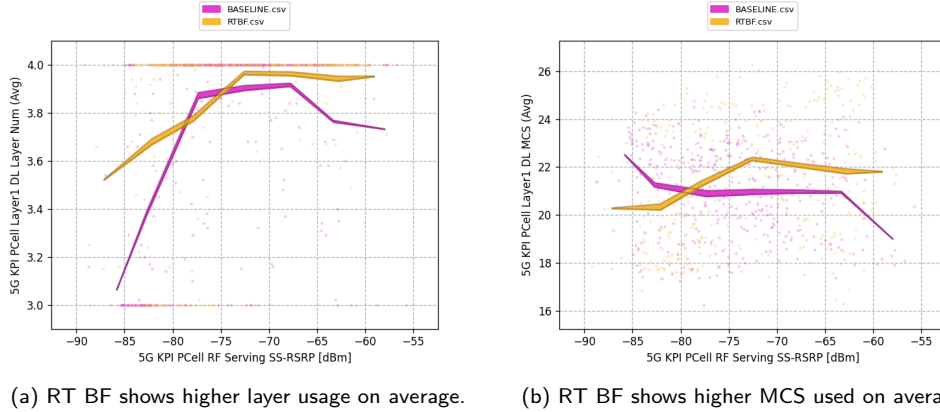


Figure 5.14: Radio related metrics during walktest plotted against SS-RSRP representing values across varying radio conditions. Each point represents a 1-second average. Line plots 5 dB spaced bin average and its width is modulated with amount of samples available on each bin.

allow for the GNB to receive the SRS with strong enough power and therefore cannot properly decide on the best beam on which to carry user traffic. In turn, Codebook-based BF relies on a reference signal sent from the GNB towards the user, which can be more reliable as there is more power available on GNB side for CSI-RS transmission.

Moreover, RT BF trial showed that there is a very big and clear improvement on results taken during both static tests and walk tests. Much higher throughput values are obtained when RT BF is configured based on the GNB, as well as a more stable transmission. The customization of the traffic beam allows for the use of higher number of layers on transmission and with a much more spectrally efficient modulation and coding rate.

It was interesting to note that such gains were not seen during drivetest. On those tests the user is moving at speeds of about 45 km/h, which may be too fast for proper beam definition in the context of a fast changing radio environment. It could be interesting to conduct further tests with varying speed setups on the UE side.

Chapter 6

Conclusions

This thesis presented a thorough account of how beamforming is applied on 5G. Beamforming is a very interesting Massive MIMO technique to exploit the radio interface to its fullest. Even though it has been used before on other technologies, the use of beamforming on 5G provides a widespread application of this technology across next generation mobile networks, enabling a much higher capacity in the context of an ever increasing demand of traffic on cellular networks.

Beamforming mechanisms based on Codebook and SRS were presented and its advantages and disadvantages were evaluated from a theoretical stand point. Furthermore, they were also confirmed on field tests that were carried out on a live commercial 5G network of a local operator. The real world case tests served to provide further insight and better understanding of the benefits and limitations of each algorithm and on which sort of scenarios they can be applied.

SRS-based BF excels on a wide cell area on mid / near cell connections. What is more, a SB SRS can be used to multiplex several users across SRS occasions, which allows this algorithm to be usable for most users. On the other hand, power limitation on the user side limits the applicability of SRS-based BF on the cell-edge due to reception power not being strong enough on reception in such cases.

Codebook-based BF can in turn provide a more reliable beamforming as it is based on user decisions taken from CSI-RS sent from the GNB which has more power available for transmission. This also allows to apply beamforming on FDD bands where channel reciprocity cannot be assumed, or even CA setups where the user has no UL to be sent over secondary cells.

Moreover, using beam synthesizing with RT BF shows great improvements on beam definition, as the user can get a customized beam which provides a higher and more stable bitrate over the air interface. However, such algorithm requires

Chapter 6. Conclusions

several SRS resources to get better and quicker channel knowledge, which limits its applicability to a handful of near-cell users. Not only that, but also during the field tests user speed seemed to be a limitation when it comes to beam definition, given that there was no improvement seen.

On top of that, beamforming on the broadcast and RACH serves to provide a better cell coverage during cell selection, mobility, and initial access. Even if the best possible beam can be found for PDSCH transmission, if the user cannot properly decide on the best cell to connect to, then the coverage will still be limited, given that all cell selection decisions are based on broadcast signals.

Bottomline, there is no single beamforming technique that should be applied at all times. Each of them has its own advantages and disadvantages, and areas of applicability.

6.1 Future Works

There are several aspects that can be further studied in relation to this topic. First of all, as mentioned before this thesis is not a thorough performance study of each beamforming method. While it did provide results that permitted better insight and improved understanding of how beamforming techniques are applied, it was a single scenario that was tested. There are many variables that are involved in the results and could be further studied, such as radio vendor, height installation, tilt, band used, number of TRX and AE, and how they are placed on the radio, etc.

6G will probably evolve towards Massive MIMO radios of higher bands and will most likely use larger number of TRX and AE, so studies of how increasing TRX and AE can improve the radio performance is in and of itself an interesting study topic. 6G spectrum is not yet defined, but the band of 7 GHz – 8 GHz looks promising [30].

COMP and EICIC mechanisms were mentioned on 3.2 as means of improving radio connection based on either joint transmission or reception, or on inter-cell coordination. While these are not new to 5G, the widespread use of beamforming can improve these scenarios and enhance their applicability. Further studies could evaluate the performance of such mechanisms when beamforming is applied.

Throughout this whole thesis the beamforming was always applied on the base station side. But it might as well be used on the user side. Further studies could relate to how that can be implemented, its applicability to mobile phones or solely for Fixed Wireless Access (FWA) type of users, what sort of reference signals are most suitable and what sort of signaling should be exchanged between the user and the base station, if any.

6.1. Future Works

During tests performed, results showed that RT BF did not provide any gain when device speed was at driving pace. Further studies could reflect on how speed affects beam definition on RT BF would be interesting, testing this method at different device speeds.

Furthermore, RT BF can also change the scheduler decision. PF metrics do consider current channel conditions, but the applicability of beam customization towards certain users can provide great results so it may be good to prioritize these users. However, if RT BF is configured only on data-hungry users, that prioritization could lead to those users unfairly hoarding resources. There might be a sweet-spot in the middle, with a higher but limited prioritization of RT BF users.

MU-MIMO was mentioned on this thesis but there could also be tests performed on how it works. Most notably, testing how far apart users need to be for it to work best, and how that changes with an increase on TRX or AE, and with the use of ZF-BF techniques.

Moreover beamforming enables the use of a spatially-aware scheduler. Further works could focus on studying best MU-MIMO scheduler practices and how spatial information should be considered when it comes to scheduler definition and user pairing over shared radio resources. The widely used PF scheduler as it does not consider correlation between the users. If a user does not have a higher PF metric, but has low correlation with other user, then it could be a great candidate for scheduling decisions. Therefore there should be changes either on scheduler decisions or on PF metric to account for that spatial awareness.

Finally, evidently Artificial Intelligence (AI) can be applied to topics of scheduling decisions and beam definitions. Therefore studies of the use of AI on beamforming related 5G topics can also be an interesting future work. Whatever algorithm is used in the end, it should have low complexity given that there will be a scheduling decision on each traffic slot and therefore there is no time to be wasted.

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Acronyms

5GC 5G Core.

AE Antenna Element.

AGNSS Assisted Global Navigation Satellite Systems.

AM Acknowledged Mode.

AoA Angle of Arrival.

AR Augmented Reality.

BD Block Diagonalization.

BF Beamforming.

BRS Buffer Status Report.

BTS Base Transceiver Station.

CA Carrier Aggregation.

CC Component Carrier.

CID Cell Identifier.

CN Core Network.

COMP Coordinated Multi Point Operation.

COTS Commercial Off The Shelf.

CP Cyclic Prefix.

CQI Channel Quality Information.

CSI Channel State Information.

CSI-RS Channel State Information Reference Signal.

Acronyms

CU Centralized Unit.

CUPS Control and User Plane Separation.

DC Dual Connectivity.

DCI Downlink Control Information.

DL Downlink.

DLCA Downlink Carrier Aggregation.

DMRS DeModulation Reference Signal.

DRX Discontinuous Reception.

DS Delay Spread.

DU Distributed Unit.

ECID Enhanced Cell Identifier.

EICIC Enhanced Inter Cell Interference Coordination.

EMBB Enhanced Mobile Broadband.

ENB Evolved Node B.

ENDC Eutra New Radio Dual Connectivity.

EPC Evolved Packet Core.

FDD Frequency Division Duplexing.

FR1 Frequency Range 1.

FR2 Frequency Range 2.

FWA Fixed Wireless Access.

GBR Guaranteed BitRate.

GNB Next Generation Node B.

GoB Grid of Beams.

GPS Global Positioning System.

HARQ Hybrid Automatic Repeat Request.

HSPA High Speed Packet Access.

IR-HARQ Incremental Redundancy - Hybrid Automatic Repeat Request.

ISP Internet Service Provider.

LBS Location Based Services.

LDPC Low Density Parity Check.

LoS Line of Sight.

LTE Long Term Evolution.

LTECA LTE Carrier Aggregation.

MAC Medium Access Control.

MCG Master Cell Group.

MCS Modulation and Coding Scheme.

MENB Master ENB.

MIMO Multiple Input Multiple Output.

mMIMO Massive Multiple Input Multiple Output.

MMTC Massive Machine Type Communications.

MNO Mobile Network Operator.

MU-MIMO Multi User - Multiple Input Multiple Output.

NAS Non Access Stratum.

nonGBR Non Guaranteed BitRate.

NR New Radio.

NRCA NR Carrier Aggregation.

NRDC New Radio Dual Connectivity.

NSA Non Stand Alone.

OFDM Orthogonal Frequency Division Multiple Access.

OFDM Orthogonal Frequency Division Multiplexing.

OTDOA Observed Time Difference of Arrival.

PBCH Physical Broadcast Channel.

PCell Primary Cell.

Acronyms

PCI Physical Cell Identifier.

PDCCH Physical Downlink Control Channel.

PDCCH Physical Random Access Channel.

PDCP Packet Data Convergence Protocol.

PDSCH Physical Downlink Shared Channel.

PF Proportional Fair.

PHR Power Headroom.

PMI Precoding Matrix Indicator.

PRB Physical Resource Block.

PUCCH Physical Uplink Control Channel.

PUSCH Physical Uplink Shared Channel.

QAM Quadrature Amplitude Modulation.

QPSK Quadrature Phase Shift Keying.

RACH Random Access Channel.

RAN Radio Access Network.

RE Resource Element.

RI Rank Index.

RLC Radio Link Control.

RNTI Radio Network Temporary Identifier.

RRC Radio Resource Control.

RT Real Time.

RT-BF Real Time Beamforming.

RTP Real Time Protocol.

RTT Round Trip Time.

SA Stand Alone.

SB SRS SubBand Sounding Reference Signal.

SCell Secondary Cell.

SCG	Secondary Cell Group.
SCS	Sub-Carrier Spacing.
SDAP	Service Data Adaptation Protocol.
SF	Subframe.
SGNB	Secondary GNB.
SIB	System Information Broadcast.
SR	Scheduling Request.
SRS	Sounding Reference Signal.
SRS-BF	SRS-based Beamforming.
SS	Synchronization Signal.
SS-RSRP	Synchronization Signal Reference Signal Received Power.
SS-RSRQ	Synchronization Signal Reference Signal Received Quality.
SS-SINR	Synchronization Signal Signal to Interference Noise Ratio.
SSB	Synchronization Signal Block.
SU-MIMO	Single User - Multiple Input Multiple Output.
TA	Timing Advance.
TAS	Transmit Antenna Switching.
TDD	Time Division Duplexing.
TM	Transparent Mode.
TRX	Transceiver.
UCI	Uplink Control Information.
UE	User Equipment.
UL	Uplink.
ULCA	Uplink Carrier Aggregation.
UM	Unacknowledged Mode.
URLLC	Ultra Reliable Low Latency Communications.
V2V	Vehicle to Vehicle.

Acronyms

V2X Virtual to Anything.

VoNR Voice over New Radio.

VR Virtual Reality.

WB SRS WideBand Sounding Reference Signal.

WCDMA Wideband Code Division Multiple Access.

ZF Zero Forcing.

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