POLITECNICO DI TORINO
Department of Electronics and Telecommunications
M.Sc in Communications and Computer Networks Engineering

Master Thesis

Beam Management for 5G NR

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December, 2019

A mis padres y mi tía Ana,
por su apoyo incondicional e inmenso cariño.

Abstract

5G New Radio (NR) is the first cellular standard addressing carrier frequencies above 6 GHz, covering millimeter-wave (mmWave) frequencies among others. mmWave transmissions suffer from stronger propagation losses that render communication challenging at higher frequencies. Highly directional transmissions over multiple transmit (TX) and receive (RX) antennas – i.e. beamforming – are essential to compensate for those losses. Beam Management (BM) is a collection of procedures thought to guarantee beamformed connection establishment and maintenance. Guidelines on their implementation are embedded into the current 3GPP standards release for 5G NR in its first phase, named Release 15 (Rel-15). This thesis will first focus on compiling an interpretation of each BM procedure within 3GPP Rel-15. Then, an Initial Access (IA) scheme in the context of Initial Beam Establishment (IBE) will be proposed. It includes beam sweeping schemes for Synchronization Signal Block (SSB) transmission and reception, and a 3GPP-compliant, Physical-Random-Access-Channel(PRACH)-occasion-aware beam pair selection algorithm taking place before Random Access (RA) preamble transmission. This algorithm considers configurable priorities of latency and power for connection establishment. The configurability allows the algorithm to not only contain the two most common IA beam search schemes present in literature, namely exhaustive search and fast search, but also combine those two corner cases according to quality of service (QoS) requirements. Moreover, a simulation environment to test the beam pair selection algorithm under different configurations and radio channel conditions, will be created in MATLAB. Results show, among others, that fast-search-like algorithm configurations may be recommended over exhaustive-search-like algorithm configurations depending on available antenna codebooks and system capabilities. Configurations of beam pair selection closer to fast search achieve connections in significantly less time with almost the same power levels as for exhaustive search. Clear performance enhancement at beam pair selection can be achieved by increasing beam switching capabilities, though enhancement decreases when the range between gNB and UE increases.

Keywords: 5G, NR, 3GPP, mmWave, Beam Management, Initial Access, Beam Adjustment, TCI Indication, Link Recovery, Beam Pair Selection.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Development of new technologies is enabling paths to improve quality of life beyond imagination. Expectations continuously rise and new challenges and opportunities for growth emerge. The mobile communications industry is currently taking a major leap that has a revolutionary impact not only on the phone industry, but also on automotive, manufacturing, entertainment industries, health services and much more. 5G New Radio (NR) is being conceived as a unifying radio-access technology that promises to bring enhancement directed towards a wide variety of services and better quality for all users. Its use cases can be roughly defined in three distinct service categories (Fig. 1.1): Enhanced mobile broadband (eMBB), ultra-reliable and low-latency communication (URLLC) and massive machine-type communication (mMTC) [9].

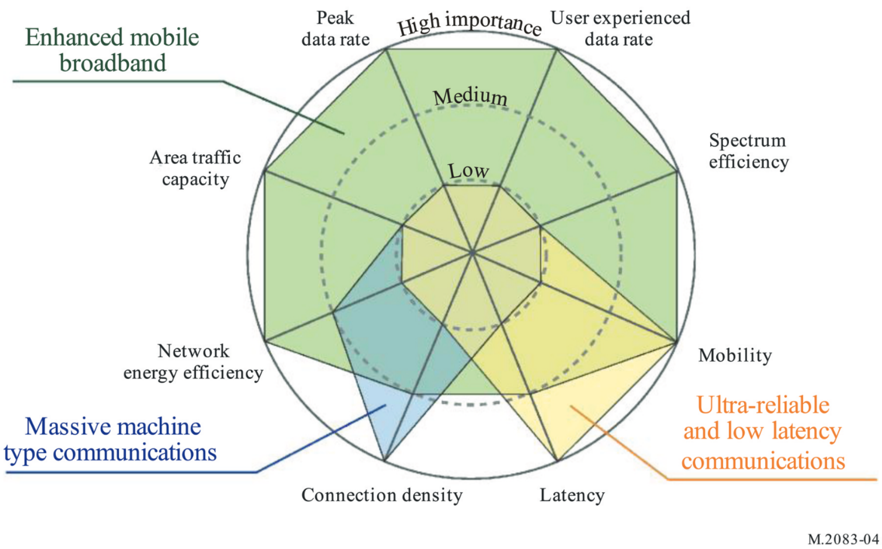


Fig. 1.1. NR Service Categories. Taken from [1]

eMBB comes in handy for servicing more densely populated environments where mobility, high data rates, high capacity and relatively small coverage areas are the main characteristics. This use case could be regarded as an evolution of the current mobile broadband services.

URLLC is thought for applications requiring very low latency and extremely high reliability, that aim to communicate critical information with high precision. Scenarios displaying these requirements can be natural disasters, military, industrial, automotive purposes and health care [10].

mMTC is characterized by support of a massive number of devices, where applications requirements shape different communication patterns in terms of connection modes, connection times, packet sizes and periodicities. This is also linked to the presence of devices not thought for human-type communication – e.g. remote sensors –, which have additional constraints on cost and power consumption. The last constraint is thought to make the devices' battery life last for several years. This leads to heterogeneous networks where new technologies that cope with a wide range of devices should be investigated.

Nevertheless, specific use cases with different requirements must be also considered. The paradigm of telecommunications then shifts to a method where use cases are first defined, requirements related to the use cases are extracted, and solutions for those requirements are conceived and developed. This requirements' (heterogeneity/diversity) that demands a flexible and more efficient radio-access technology is the motivation for the new features developed in 5G NR. The main drivers of 5G NR are currently eMBB and URLLC.

The 3rd Generation Partnership Project (3GPP), a project that unites seven telecommunications standard development organizations, provides with an environment to work towards global agreements on technology standards. The intrinsic interoperability resulting from these efforts has been essential for the success of mobile communications on a global scale. 3GPP structures the standards as releases, where numerous available-on-the-web, free-of-charge documents are compiled and extensively revised. These documents aim to cover specific details on the required characteristics of a device willing to provide mobile communications service. Every new release brings new specifications that correspond to technology evolution. The project is composed by three Technical Specification Groups (TSG), each of them with its particular area of responsibility. The groups namely are Radio Access Networks (RAN), Services & Systems Aspects (SA) and Core Network and Terminals (CT). 3GPP RAN is in charge of 5G NR functionality. The first drop of NR-related specifications corresponds to Release 15, as part of the first phase of 5G deployments. This release was initially delivered in late 2017, with a more mature version come out in late 2018. The second phase of 5G deployments will be based in Release 16 and should comply with all requirements stated in the International Mobile Telecommunications-2020 (IMT-2020) standard, issued by International Telecommunication Union (ITU), Radio Communication Sector (ITU-R). Its completion is due to December 2019.

According to [3], Release 15 focused its development on eMBB and URLLC, whereas support for mMTC and additional use cases will be extended in later releases.

The resulting highlights from that development process can be summarized in five characteristics that constitute NR structural improvements with respect to LTE [3]: Utilization of higher frequency bands, ultra-lean design, forward compatibility, low latency and beam-centric design.

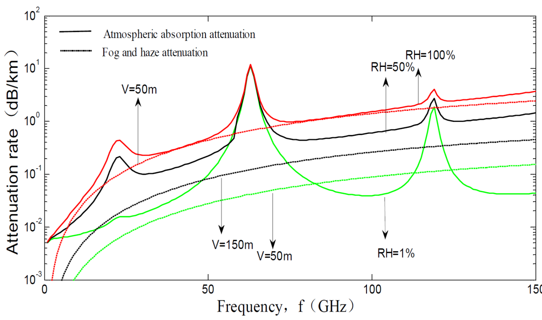
Additional utilization of higher frequency bands. The huge amount of available spectra in frequencies between 24 GHz and 100 GHz enables wider transmission bandwidth support and a subsequent increase in data rates. These frequencies are referred to as millimeter wave (mm-wave) frequencies. Joint utilization of lower and higher frequency bands might achieve great performance.

Ultra-lean design. Current mobile technologies carry out network-side transmissions on a regular basis, without being aware of present user traffic. Signals transmitted in this manner can be regarded as "always-on" signals. In very dense networks, this leads to limitations on the achievable network energy performance and interference to neighbor cells. Interference translates into worse signal quality and a corresponding data rate reduction. The ultra-lean design seeks improvement on those regards by limiting the amount of transmissions of reference and synchronization signals, with reference signals mainly being only being present when data are transmitted.

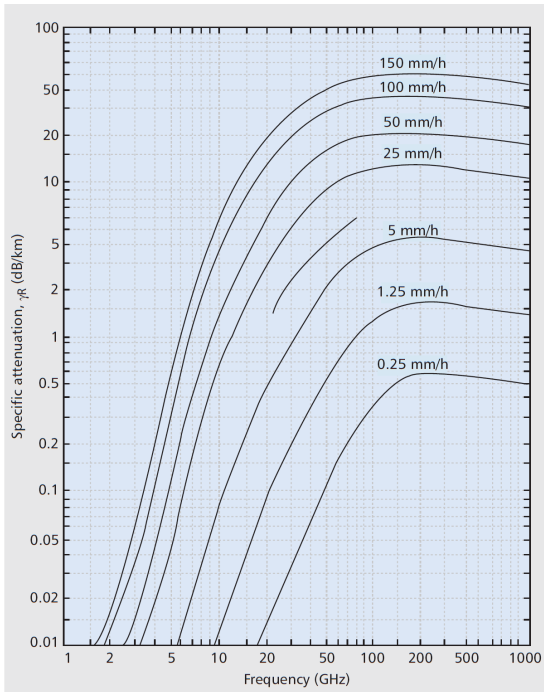
Forward compatibility. New features coming up in later NR releases shall be guaranteed the best degree of integration into the current time-frequency structure. Since services provided in the future might encompass substantially different characteristics and requirements, the goals of 3GPP Release 15 are to ensure a flexible resource allocation, minimize transmission of "always-on" signals – as in line with the Ultra-lean design paradigm – and allow reservation of resources – blank resources in the time-frequency grid – for later use. These goals aim to avoid unnecessary blocking of future key resources to enable a new feature.

Low latency. Extensive changes have been made to the physical, MAC and RLC layer design, always motivated by the tight requirements imposed by mission-critical use cases that heavily rely on fast communication. Using "front-loaded" reference signals and control signaling, enabling "mini-slot" transmissions and higher-layer headers that allow processing without knowing the amount of data to transmit are examples of the efforts carried out to minimize time delays.

Beam-centric design. Mm-wave transmissions can provide significant data rate increases thanks to wider transmission bandwidths, as previously mentioned. However, mm-wave transmissions also suffer from propagation losses that are stronger at higher frequencies. A combination of effects cause them, namely water vapor absorption, oxygen absorption, fog/haze attenuation (Fig. 1.2a), precipitation attenuation (Fig. 1.2b), foliage blockage, scattering and diffraction [11]. Since the losses limit network coverage, it is fundamental to compensate for by beamformed transmission and reception schemes using massive arrays of antenna elements. Thanks to the very small wavelength associated to mm-wave frequencies, large antenna arrays can be achieved in small, appropriate dimensions for portability. For lower frequencies, multi-antenna schemes can still be exploited for diversity or spatial multiplexing purposes.



(a) Atmospheric (oxygen and vapor absorption) and fog attenuation. Figure from [12].



(b) Rain attenuation (dB/km) at different rainfall rates. Figure from [13].

Fig. 1.2. Attenuation effects at different frequencies.

The beam centric-design is a key feature of NR, present in all NR channels and signals. Signals for synchronization and control are designed to fully support beamforming. Channel-state information (CSI) intrinsically considers beamforming as well when operating with massive multi-antenna schemes. The support offered by the NR framework enables the possibility to develop procedures that integrate beamforming when establishing first connection between a device and the network, when maintaining that connection and when recovering from connection failure. They are referred to as Beam Management (BM) procedures. Initial Beam Establishment (IBE) serves as the procedure to establish first beamformed connection. Beam Adjustment (BA) sustains the connection established by IBE. Link Recovery (LR) re-establishes connection when BA is not able to sustain the current connection. There are guidelines and requirements on BM procedures made explicit in the 3GPP specifications to ensure interoperability. At the same time, they allow differentiation among implementations thought for various devices and use cases. The purposes of this thesis are thus, to investigate on the guidelines and requirements for all three BM procedures, propose an implementation flowchart for IBE, simulate different configurations for IBE parameters and analyze the impact of parameter changes on the IBE implementation proposal performance.

The thesis is organized as follows: Chapter 2 provides an overview of fundamental aspects on NR's frame structure, more insights on the beam-centric design and beam management procedures. Chapter 3,4 and 5 investigate on IBE, BA and LR, respectively. Chapter 6 presents a novel mechanism for setting first connection between device and network in the context of IBE, after giving a motivation for its design. Chapter 7 introduces the simulation environment to deliver measurements that serve as an input to the proposed algorithm for IBE. Chapter 8 shows the obtained simulation results. Finally, chapter 9 draws conclusions on research, results and future scope.

Chapter 2

Insights on 5G for Beam Management

2.1 Introduction and basic terminology

The flexibility present in 5G is fundamental to integrate a huge amount of services into the technology, with resource planning in advance for services that have not even been conceived yet. This chapter will be devoted to introduce aspects of 5G that are relevant to understand what Beam Management (BM) refers to, as well as their intrinsic flexibility. The start relates to the operative frequency ranges envisioned for communication and the organization of resources conveying information. Then, the beamforming concept is introduced along with the concepts of antenna ports, physical antennas, reference signals, quasi co-location (QCL) and beam correspondence. All of them are interconnected towards beamformed communication. After having reviewed the necessary background on beamformed communication, the procedures that allow beamformed communication, in the Beam Management (BM) framework, are briefly described. For Initial Beam Establishment (IBE), one of the BM procedures, the state of the art of its implementations is reviewed. This serves as a justification for the conception of a new implementation proposal thought for IBE.

Some terms and concepts have been added or changed since LTE, they will be properly mentioned to convey clarity herein. A device is regarded, as in LTE, as a User Equipment (UE) and it establishes connection with a Base Station (BS), also called Next Generation Evolved Node B (gNB) in 5G NR. When the flow of information goes from a gNB to a UE, the transmission is regarded as a Downlink (DL) transmission. Information flow from a UE to a gNB is referred to as an Uplink (UL) transmission.

2.2 Mm-wave frequencies for 3GPP Release 15

As mentioned in Chapter 1, mm-wave frequency bands are additionally considered for 5G NR, in contrast with LTE. Hence, there is a delimitation of frequency ranges (FR) arranged as shown in Table 2.1. The frequency range number 2 (FR2) corresponds to the operating mm-wave frequency range in Release 15. For the purposes of this thesis, we will stick to mm-wave frequencies and thus, to the FR2 group.

Table 2.2 shows the operating bands in FR2.

Table 2.1: Definition of frequency ranges. Table from 3GPP 38.104 [6]

Frequency range destination	**Corresponding frequency range**
FR1	410 MHz - 7125 MHz
FR2	24250 MHz – 52600 MHz

Table 2.2: NR operating bands in FR2. Table from 3GPP 38.104 [6]

NR operating band	**Uplink (UL) and Downlink (DL) operating band** **BS transmit/receive** **UE transmit/receive** $F_{UL,low} - F_{UL,high}$ $F_{DL,low} - F_{DL,high}$	**Duplex Mode**
n257	26500 MHz – 29500 MHz	TDD
n258	24250 MHz – 27500 MHz	TDD
n260	37000 MHz – 40000 MHz	TDD
n261	27500 MHz – 28350 MHz	TDD

2.3 Time-frequency lattice structure

As also mentioned in Chapter 1, 3GPP Release 15 ensures flexible resource allocation through a combination of various strategies. The first one to remark is the numerology concept, also called subcarrier configuration μ, a number related to a set of configuration parameters that defines the frame and lattice structure of a waveform. The variety of transmission numerologies (Table 2.3) aims at providing support for devices having different transmission capabilities. The subcarrier configuration $\mu = 0$ corresponds to the subcarrier configuration mandated for LTE, with subcarrier spacing (SCS) 15 kHz, whereas further numerologies configure SCSs that are multiples of LTE's SCS by a factor 2^{μ}. Note that not all numerologies support all kinds of transmission types. Data transmissions are thus not supported for a SCS of 240 kHz, whereas synchronization transmissions are not supported for a SCS of 120 kHz.

Table 2.3: Supported transmission numerologies. Table from 3GPP 38.300 [4]

μ	$\Delta f = 2^{\mu} \cdot 15\,[kHz]$	**Cyclic Prefix**	**Supported for data**	**Supported for synch**
0	15	Normal	Yes	Yes
1	30	Normal	Yes	Yes
2	60	Normal, Extended	Yes	No
3	120	Normal	Yes	Yes
4	240	Normal	No	Yes

The numerology configurations $\mu = 0, 1, 2$ are thought for FR1, whereas $\mu = 2, 3, 4$ are available for FR2.

The time structure gets also configured by the selected numerology. Tables 2.4 and 2.5 list supported timing structures in terms of OFDM symbols and time slots, for normal and extended cyclic prefixes. The duration of a radio frame is defined as $T_f = 10ms$. A subframe for NR corresponds to a time interval that lasts $T_{sf} = 1ms$ –

i.e. 10 subframes compose a frame. The number of OFDM symbols per slot remains 14 for normal cyclic prefix in all numerologies, whereas it changes to 12 symbols for an extended cyclic prefix. It is then clear that the number of OFDM symbols per slot is doubled with respect to that of LTE. The number of slots per subframe is accordingly halved with respect to LTE, to keep up with the ratio between the duration of a frame and a subframe. For the rest of numerologies, the number of slots per subframe and frame increases by a factor 2^{μ}, the same that scaled the supported SCSs in Table 2.3.

Table 2.4: Number of OFDM symbols per slot, slots per frame, and slots per subframe for normal cyclic prefix. Table from 3GPP 38.211 [7]

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
0	14	10	1
1	14	20	2
2	14	40	4
3	14	80	8
4	14	160	16

Table 2.5: Number of OFDM symbols per slot, slots per frame, and slots per subframe for extended cyclic prefix. Table from 3GPP 38.211 [7]

μ	N_{symb}^{slot}	$N_{slot}^{frame,\mu}$	$N_{slot}^{subframe,\mu}$
2	12	40	4

On top of it, communication in both UL and DL shall be enabled. Two multiplexing schemes to switch between UL and DL are recommended for 5G, namely Frequency Division Multiplexing (FDM) and Time Division Multiplexing (TDM). FDM, as it name states, lets both gNB and UE transmit and receive simultaneously by using one frequency band for UL and another frequency band for DL. This is referred to as paired spectrum operation in Release 15. TDD, in contrast, lets gNB and UE transmit/receive at different times using the same frequency band. This is referred to as unpaired spectrum operation in Release 15. The time distribution of DL or UL opportunities is configured as a pattern in a per-symbol basis by the slot format. The slot format assigns one of 3 uses to an OFDM symbol index:

- 'D' to a symbol that shall be used for DL communication.
- 'U' to a symbol that shall be used for UL communication.
- 'F' to a symbol that has flexibility to be used for either DL or UL communication.

Notice that the slot format can be reconfigured through signaling. There are 256 slot formats present in Release 15, with 199 of them being currently reserved. For a detailed description of 5G NR slot configuration, refer to 38.213 Section 11.1 [14].

The lattice structure is conceived in such a way, that simultaneous transmission over multiple numerologies is possible. However, interference among numerologies – Inter-Numerology Interference (INI) – should be properly addressed. Extensive research is being conducted in this area [15] [16] [17] [18] [19] [20].

2.4 Beamforming

Multi-antenna schemes at transmitter and/or receiver can enhance the cellular system's performance in different fashions.

When antenna elements experience uncorrelated channels, either because of inter-element distance or uncorrelated polarization among elements, they can provide diversity against fading.

By using different antenna elements to transmit multiple streams of data – "layers" – over the same time-frequency resources, higher data rates can be achieved. This is referred to as spatial multiplexing.

If the phase, and possibly also the amplitude, of each antenna element are carefully adjusted (Fig. 2.1), constructive interference in a certain direction can be realized. This spatial filtering is equivalent to focusing the energy radiated over a transmit antenna array in a certain direction, or focusing reception of a receive antenna array in the direction of a desired signal. The adjustment is referred to as beamforming, and it increases an array's directivity, reaching higher link budget. Data rates and cell coverage are consequently improved. Interference is reduced as well, since transmission avoids radiating power into unwanted directions and reception suppresses interfering signals coming from undesired spatial locations. There are two main mechanisms to perform beamforming, namely analog beamforming and digital beamforming.

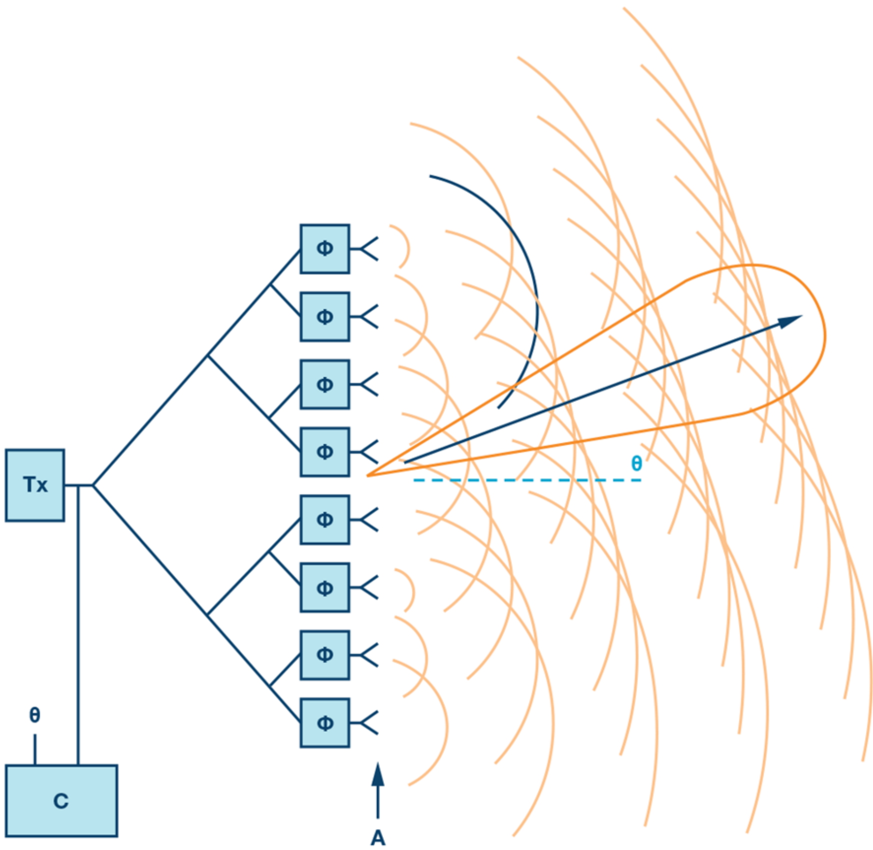


Fig. 2.1. Beamforming principle. Figure from [2]

Analog beamforming, as its name says, implements the required spatial filtering in the analog domain of the communication chain. Signal processing is therefore applied after digital-to-analog conversion (DAC) at the transmitter side, and before the analog-to-digital conversion (ADC) at the receiver side.

Digital beamforming, in contrast, performs filtering in the digital domain. Signal processing is applied before DAC at the transmitter side, and after ADC at the receiver side.

Fig. 2.2 captures the contrast between both beamforming implementations into a block diagram for a transmission chain. x_n for $n = 1 \dots N_L$ represents the n-th digital stream of symbols, where N_L is the number of transmit layers, i.e. the amount of parallel streams generated. y_m for $m = 1 \dots N_T$ represents the transmitted continuous signal from an antenna port m, where N_T is the number of antenna ports used for transmission. W represents the equivalent processing block that maps the parallel streams coming from different layers to the antenna ports used for transmission. Notice that the number of transmit layers N_L and the number of antenna ports N_T used for transmission need not be the same.

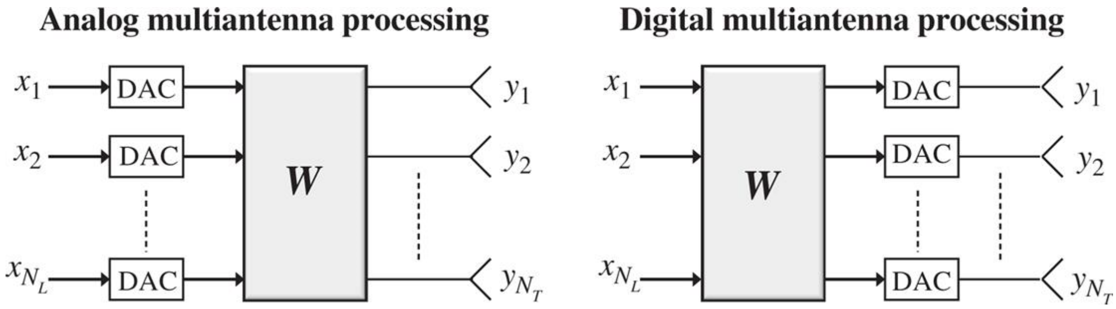


Fig. 2.2. Analog vs digital transmit multi-antenna processing. Figure from [3]

Multiple beam transmission can be realized by multiplexing over the available time-frequency resources. Time-multiplexing of multiple beams offers the possibility to transmit over one beam at a time (Fig. 2.3). This beam switching procedure is called beam sweeping, analog and digital beamforming can realize it. However, frequency-multiplexing of beams (Fig. 2.4) – i.e. simultaneous transmission of multiple beams – is only possible in the digital domain. This is one of the advantages of digital beamforming over its analog counterpart.

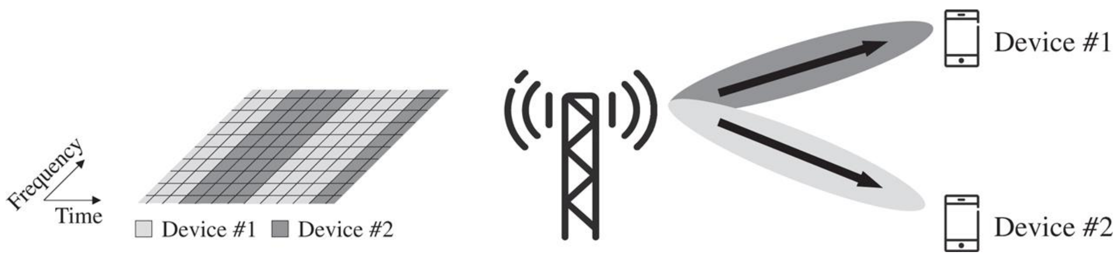


Fig. 2.3. Time-multiplexed beamforming. Figure from [3]

Moreover, digital beamforming offers better beam-switching capabilities and full control over each antenna element by associating them with entries in a so-called precoding matrix. Digital multi-antenna processing is referred to as multi-antenna precoding.

Unfortunately, digital beamforming at mm-wave frequencies faces much more challenges than the analog approach. Having fully digital baseband antenna processing requires one dedicated radio frequency (RF) chain per antenna element [21]. The interface circuits (ADCs and DACs) present per element must manage high resolutions and sampling frequencies. The aggregated consumed power by these data converters becomes prohibitively large [22]. Additionally, the cost and complexity of conceiving

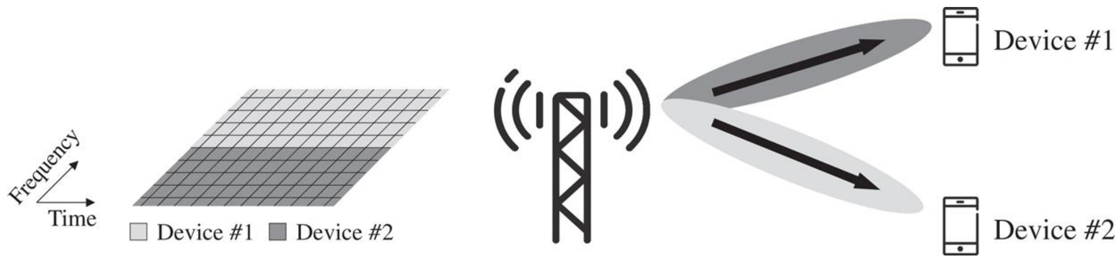


Fig. 2.4. Frequency-multiplexed beamforming. Figure from [3]

such RF chains rise too [22] [23]. Therefore, analog beamforming is a common implementation decision in the short term, whereas solutions combining the digital and analog approaches, referred to as hybrid beamforming, are topic of research [21] [24].

Beamforming can be applied at both the gNB and the UE. The resulting combination of a gNB beam and a UE beam is referred to as a beam pair. In the beam-centric design context, the concept of a beam pair is fundamental, since the perceived radio channel and the received signal power depend on the beamforming schemes applied at gNB and UE jointly. Change of only one of the beams may imply change of the radio channel conditions and the received signal power.

2.5 Antenna Ports and Reference Signals

The concept of antenna port (AP), oftentimes referred to as port, was first introduced in LTE and then reused in 5G. As Fig. 2.5 illustrates, it can be understood as a logical abstraction of a physical resource that maps to physical antennas. The antenna port (AP) indices are symbolized with the letter $y_i, i = 0, \ldots, N_T$, where N_T is the number of antenna ports used for transmission. N_E corresponds to the number of physical antenna elements available, which is not necessarily equal to N_T. Every antenna port takes a resource grid as input. The resource grids may be different between each other, meaning there may be different information transmitted over different antenna ports. After passing physical layer resources to the antenna ports, information can be transmitted over the selected physical antennas.

An antenna port may map to more than one physical antenna, meaning that the resource grid on top of the antenna port is distributed among the physical antennas mapped to the antenna port. Additionally, a physical antenna may be mapped to multiple antenna ports, meaning that resource grids coming from different antenna ports may be added at a physical antenna.

According to 38.211 Section 4.4.1 [7], "an antenna port is defined such that the channel over which a symbol on the antenna port is conveyed can be inferred from the channel over which another symbol on the same antenna port is conveyed". Put in other words, given a fixed beamforming, every symbol transmitted on the same antenna port would experience the same radio channel and the latter can be inferred from estimations previously carried out.

Notice that the radio channel evolves over time and different beamformers applied on top of an antenna port will furthermore derive different experienced channels. Hence, channel estimations performed relatively long ago and/or with different beamformers might not accurately capture the current channel response.

The estimations are calculated based on reference signals, namely on Demodulation Reference Signals (DM-RS). The DM-RS are specifically associated with one of the following physical channels:

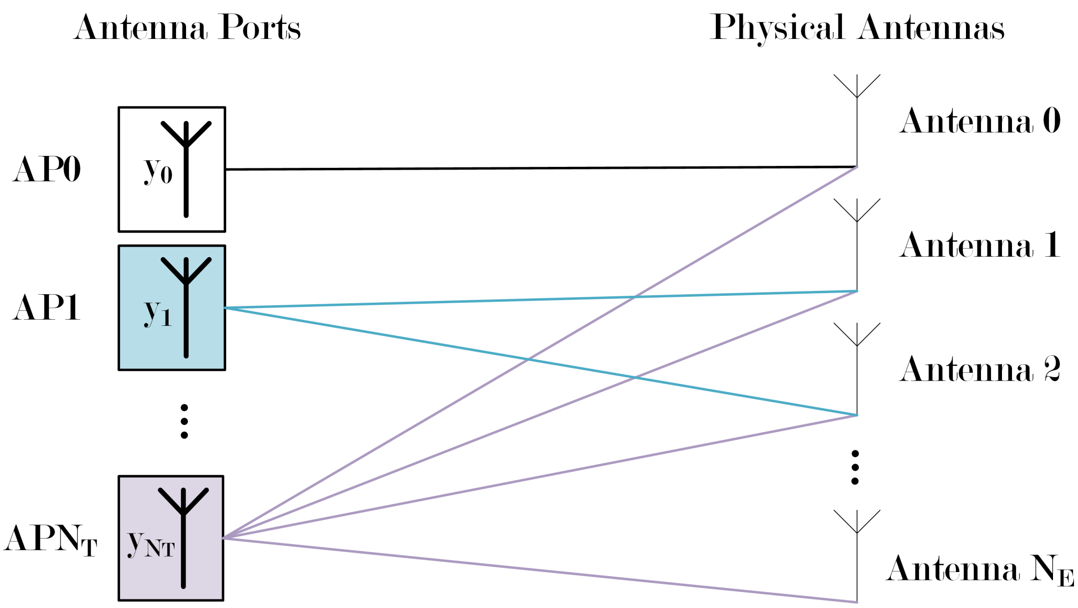


Fig. 2.5. Antenna ports and physical antennas.

- **Physical Downlink Shared Channel (PDSCH)**. Channel inference on the same antenna port is only possible if both DM-RS and PDSCH symbols are within the same scheduled resource, slot and Precoding Resource Block Group (PRG).
- **Physical Downlink Control Channel (PDCCH)**. Channel inference on the same antenna port is only possible if both DM-RS and PDCCH symbols are within resources where the same precoding may be assumed.
- **Physical Broadcast Channel (PBCH)**. Channel inference on the same antenna port is only possible if both DM-RS and PBCH symbols are within a Synchronization Signal Block (SSB) transmitted in the same slot with the same block index.

For more information on physical channels, refer to 38.211 Section 7.1.1 [7] and 38.300 Sections 5.2.2, 5.2.3 and 5.2.4 [4]. For details on channel inference according to physical channels, refer to 38.211 Section 4.1.1 [7].

2.6 Quasi Co-Location (QCL)

According to 38.211 Section 4.4.1 [7], "two antenna ports are said to be quasi co-located if the large-scale properties of the channel over which a symbol on one antenna port is conveyed can be inferred from the channel over which a symbol on the other antenna port is conveyed. The large-scale properties include one or more of delay spread, Doppler spread, Doppler shift, average gain, average delay, and spatial Rx parameters". Based on that information, channel estimation information from one antenna port may be used as an input for the channel estimation from another antenna port.

As seen later in Chapters 3 and 4, QCL between ports or signals transmitted on those ports can be either assumed by the UE or indicated by the gNB to the UE via a Transmission Configuration Indication (TCI) state, and is fundamental for the considerations taken in the Beam Management procedures. QCL is defined for DL communication and considered in every beamformed reception taking place after the

UE synchronized to the gNB. There are 4 types of QCL that indicate the large-scale properties considered:

- 'QCL-TypeA': Doppler shift, Doppler spread, average delay, delay spread
- 'QCL-TypeB': Doppler shift, Doppler spread
- 'QCL-TypeC': Doppler shift, average delay
- 'QCL-TypeD': Spatial Rx parameter

2.7 Beam Correspondence

As described at the beginning of this chapter, information flow between a gNB and a UE mainly has two possibilities, an UL and a DL direction. Consider a scenario where beamforming is applied to both gNB and UE for DL communication. Then, the gNB is transmitting with a certain DL TX beam and the UE is receiving with a certain DL RX beam. A certain time was required to select this beam pair for DL communication. UL communication can benefit from the beam selection performed in the DL by choosing the same beam pair to exchange information. By doing it, the necessary time to find another beam pair for UL communication can be spared. This is made under the assumption that a beam pair used for DL communication provides the same link budget when used for UL communication. The assumption is called Beam Correspondence, it is an important concept that may increase the efficiency of a communication system.

Nevertheless, beam correspondence does not hold in all cases, as there might be many impairments that prevent the gNB and the UE from using the same spatial filtering for DL and UL. Its indication is still work in progress in the 3GPP specifications, where a tolerance requirement for UEs of the handheld type is defined in 3GPP 38.101-2 Section 6.6.4.2 [25]. Side conditions for reference signals are still to be defined. To the best knowledge of the author, results of applied research in this topic are scarcely published or strongly copyrighted [26].

2.8 Beam Management

As pointed out in the Introduction, 5G NR's characteristic beam-centric design is key to operate at mm-wave frequencies. This feature is supported by Beam Management (BM), a collection of 3 fundamental procedures that aim at establishing and retaining a suitable beam pair. A suitable beam pair can be roughly understood as the combination of a transmit and receive beam that provides connectivity regarded as being "good enough" for particular target use cases.

It is worth mentioning that a suitable beam pair is not always related to a direct path between transmitter and receiver. When operating at mm-wave frequencies, the shorter wavelength associated to the signals translates into more reflections upon surfaces. There is a consequential steep decrease in transmitted power with respect to lower frequency ranges, caused by obstacles coming into the radio link path. This phenomenon is referred to as blockage. Studies show that the human body also plays a role into blockage effects for mm-wave frequencies [27], as well as the hand grip when a person is holding his/her mobile terminal [28].

2.8.1 Initial Beam Establishment

Initial Beam Establishment (IBE) is the procedure by which a UE starts connection with a gNB. Connection shall be ensured in both UL and DL; details on it will be described in Chapter 3. The mechanism relies on analog beamforming due to the digital-beamforming-associated challenges previously mentioned. Beam sweeping is therefore performed at both UE and gNB. The gNB first transmits synchronization and system information through different DL transmit (TX) beams switched in a manner dependent on the capabilities and strategies available. UE attempts to receive and decode this information by switching its DL receive (RX) beams. Notice that multiple cells are sending information simultaneously over different DL beams, as well as multiple UEs are simultaneously trying to establish connection over their available DL RX beams.

If there is success in the reception and decoding of synchronization and system information, different criteria shall be assessed in order to consider the new-found cells as allowed and suitable. One of those cells is selected and communication is set up by means of a procedure known as Initial Access or Initial Acquisition (IA). A suitable beam pair associating the suitable cell with the UE is found within IA. Then, a sub-procedure known as Random Access (RA) is carried out, where necessary information is conveyed through the suitable beam pair found. Agreement between the gNB and the UE with respect to gNB's DL TX, and potential UL RX beam is achieved through an association of every beam to an identifier and a corresponding allocated time-frequency resource. QCL assumptions are made here, since there is no possibility to indicate TCI states yet at this stage.

2.8.1.1 State of the art

Beam pair selection is mandated to be performed inside the RA procedure, according to the 3GPP specifications. There is a great deal of flexibility in its implementation, applied research is thus broad in this area. The main concern when first establishing connection between gNB and UE is the time that it takes to do so – the latency –, which is influenced by the number of beam pairs that need to be compared before taking a decision. Therefore, the focus of applied research is on latency reduction. Attempts to reduce latency impact on the connection's power strength, there is then a consequential trade-off to consider between latency and achieved power strength at IBE. The beam pair that achieves the highest power strength among all beam pairs can be regarded as the best beam pair.

A pre-Release-15 survey of Initial Access proposals for mm-wave communications [29] shows a concentrated interest in exhaustive and iterative evaluation of beam pairs before selecting a beam pair, known as exhaustive and iterative search respectively. Exhaustive search refers to a thorough evaluation of all possible beam pairs that can be jointly realized by gNB and UE. The outcome of exhaustive search would correspond to the best beam pair among all the available beam pairs. Iterative search, to the understanding of the author, can be also interpreted as a variant of the exhaustive search approach. This assertion is motivated by the fact that exhaustive evaluation of beam pairs is carried out in the first iteration with a sparser beam distribution in a relatively big spatial section, whereas subsequent iterations carry out exhaustive evaluation of beam pairs with a denser beam distribution in relatively smaller spatial sections inferred by the previous iteration outcome.

A study on IA using random beamforming [30] uses a faster evaluation of beam pairs organized in a random manner, i.e. a beam pair that is "sufficiently good" for communication is selected and the beam sweeping order is random. There is a time budget scheme that allows for dynamic IA latency reduction. The study shows that the proposed approach can substantially reduce the latency while keeping high performance.

Furthermore, Release 15 shows that the selection of a beam pair is not instantaneously agreed between gNB and UE. There are transmission occasions over which the UE can inform about the selection of a certain beam, and they are mapped for every beam, but not at the same time. This implies the latency for IA also depends on the relationship between transmission occasion structure and selected beam pair.

To the best of the author's knowledge, there are no published results of applied research that consider the transmission occasion time structure present in the 3GPP specifications. Neither there is consideration of the fact that lower power strengths can also enable communication in the published results. This is observed when looking at the Key Performance Indicators (KPIs) used for establishing a comparison framework among different approaches, namely the latency and the detection failure probability. The detection failure probability can be understood as the probability that the selected beam pair is not the best beam pair. In reality, the minimum requirement on received power for a UE, known as receiver (RX) sensitivity, is also defined by the 3GPP specifications. Values above it should increase the performance and may also enhance the throughput. If a selected beam pair is not the best beam pair, but it is above the required RX sensitivity, it should also be capable of establishing communication between gNB and UE. This means that the failure probability analyzed in publications does not necessarily match the probability that connection between gNB and UE is not realized. In light of the mentioned facts, one could rather set the latency and the received power strength as KPIs, which sets the results in the context of 3GPP guidelines. Thus, there is a need of an applied research initiative that considers such implications.

The proposal contained in this thesis consists then in a novel latency-dynamic initial access scheme that is aware of the transmission occasion time structure where the UE reports the selection to the gNB. The results analysis will additionally be aware of the requirements on RX sensitivity mandated in Release 15. Chapter 6 provides an extensive explanation of the proposal.

2.8.2 Beam Adjustment

Suppose a UE has established connection through a suitable beam pair. Several factors – e.g. movements, rotations, light blockage – can slowly deteriorate it, and there is the need to counteract them by adjusting the communication beam pair. Moreover, the TX beam sweeping structure at the gNB in IBE is relatively constant, as it will be discussed in Chapter 3. Hence, a fairly limited amount of TX beams with certain direction and width can only be selected by means of IBE. Beam Adjustment (BA) is the BM procedure in charge of adjusting the existing communication beam pair in case it needs to, and possibly refining the beam pair to achieve a better link budget. BA offers more flexibility in the number of beams to select from and their corresponding width. It overcomes the limitations of IBE and continuously adapts the existing connection to the ever-evolving wireless environment where UE and gNB are located. A complete description of the procedure can be found in Chapter 4.

2.8.3 Link Recovery

With the introduction of IBE and BA, it is possible to establish and maintain connection between the gNB and the UE. Sometimes, the radio channel conditions can change so rapidly, that BA is not able to cope and counteract such changes. In this case, a pair of procedures that can be referred to as Link Recovery (LR) procedures, are used to re-establish connection. For this purpose, the beam failure has to be first identified, and then solved. The two procedures that consecutively work on these aspects are called Beam Failure Detection (BFD) and Beam Failure Recovery (BFR), and will be described in more detail in Chapter 5.

Chapter 3

Initial Beam Establishment

3.1 Introduction

As previously addressed in Chapter 2, Initial Beam Establishment (IBE) consists of a set of procedures necessary for establishing first connection between a device and the provider network. Therefore, IBE takes place after a UE

- has been switched on – either for the first time or after being shut down,
- has turned off its airplane mode, or
- is back within an area of cellular coverage.

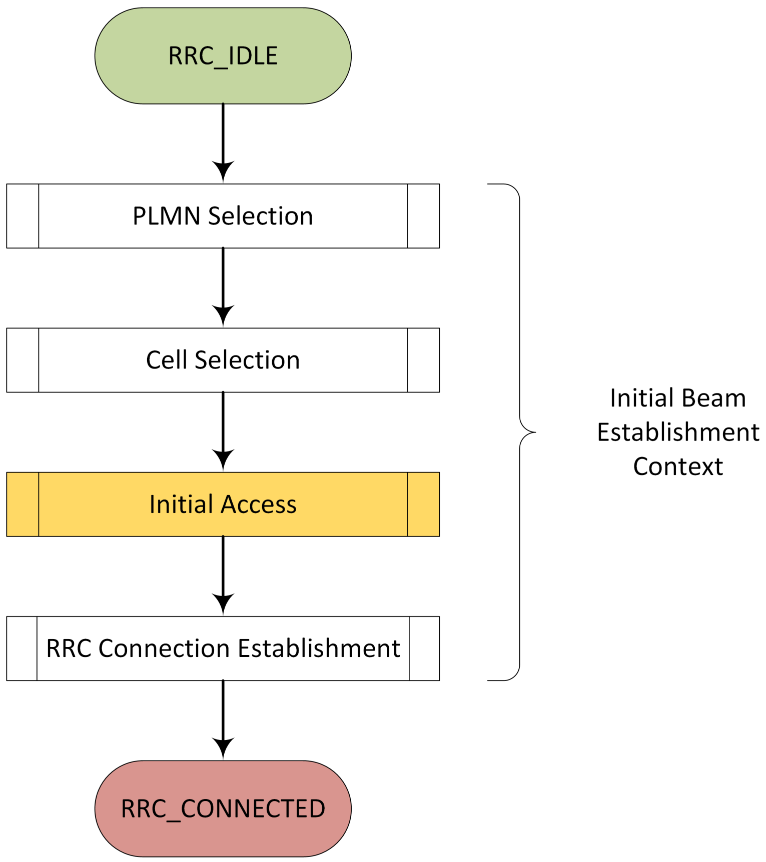


Fig. 3.1. Initial Beam Establishment overview

3GPP Release 15 establishes parts of UE's expected behavior when carrying out IBE, indicating *which* procedures shall be completed, but *how* those are completed is up to the implementation design. Fig. 3.1 shows the flow of processes present in the IBE context. PLMN Selection, Cell Selection and Initial Access (IA) perform a so-called Cell Search, where information about service provider, cell identity and system information can be inferred. The present chapter will start describing Cell Search, which is crucial for a great part of the procedures used by the UE for IBE purposes. Then, every processes involved in IBE will also be described in a sequential way as the specifications mandate for Release 15. The Initial Access stage is highlighted in yellow in Fig. 3.1. This is because there is a special reference to the contribution done in this thesis regarding an implementation proposal for Initial Access, which is described in Chapter 6.

Additionally, it is worth mentioning that the description of RRC Connection Establishment, that is the last stage related to IBE, contains useful information that links IBE to the rest of the BM procedures described in Chapters 4 and 5.

The Radio Resource Control (RRC) sublayer manages functions for all the IBE stages. It is part of the control plane, and can be characterized by 3 states, namely RRC_IDLE, RRC_INACTIVE and RRC_CONNECTED. A UE trying to establish connection with a gNB is in an RRC_IDLE state. After being connected with the network the UE's RRC shall switch from state RRC_IDLE to RRC_CONNECTED. Further information on the RRC sublayer and its setting inside the control plane can be correspondingly found in 3GPP 38.300 Sections 7 and 4.4.2 [4].

3.2 Cell Search

Cell Search is a UE-side process in charge of finding cells around the UE location. This is realized thanks to the processing of so-called Synchronization Signal and PBCH Blocks (SS/PBCH block), a structure consisting of a Primary Synchronization Signal (PSS), a Secondary Synchronization Signal (SSS), a Physical Broadcast Channel (PBCH), and demodulation reference signals (DM-RS) for the PBCH. Although Release 15 refers to it as SS/PBCH block, its nomenclature is usually shortened to SSB.

An SSB is transmitted by a gNB with a configurable periodicity that ranges from 5 ms to 160 ms, and is set by default to 20 ms. Fig. 3.2 details the time and frequency structure of an SSB. Notice that time and frequency are defined in terms of OFDM symbols and subcarriers. Their scaling depends on the chosen numerology. However, not all numerologies can be chosed to transmit SSBs. As pointed out in Table 2.3, $\mu = 2$ does not offer support for synchronization.

The PSS is the first signal that must be detected by a device. Its structural design aims at ensuring detectability and device synchronization up to its periodicity once found. This allows the UE to know when to receive the SSS. The SSS provides, together with the PSS, the Physical Cell Identity (PCI) of the detected cell. The PCI is an identifier of a cell that should ideally be, from a UE's point of view, different for each detected cell. Its distribution is an important aspect to consider while planning a 5G NR network.

The DM-RS for the PBCH and the PBCH can be accordingly received, thanks to the timing synchronization and PCI knowledge jointly given by PSS and SSS. The PBCH contains information – implicitly and explicitly carried – necessary to achieve full timing synchronization and be able to receive further system information (SI).

The essential system information to initially access the network corresponds to two System Information Blocks (SIB), the Master Information Block (MIB) and the System Information Block 1 (SIB1). The MIB is contained in the PBCH as payload. Its periodicity is 80 ms, but since it is part of the SSB, repetitions are sent every SSB period.

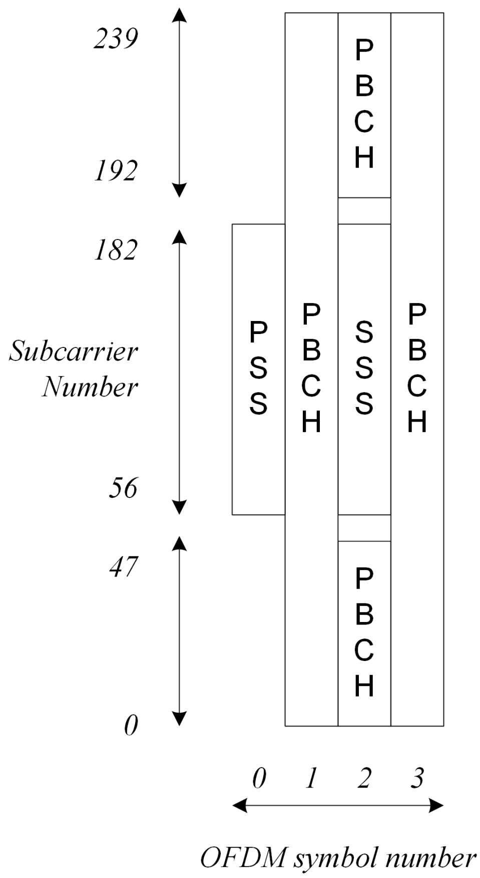


Fig. 3.2. SSB Structure. Figure from [4]

The SIB1 is sent outside the SSB context with a periodicity of 160 ms. Nevertheless, repetitions within that period are also scheduled with a configurable timing. SIB1 repetitions are carried out every 20 ms by default.

Here below, there is a description with references to the 3GPP specifications [4], [7], [31], [8], [14], [32] and [5].

- SSB acquisition
  - PSS correlation, timing offset estimation and partial Physical Cell Identity (PCI) detection (3GPP 38.211-f50 Section 7.4, 3GPP 38.213-f50 Section 4.1)
  - SSS correlation and full PCI detection (3GPP 38.211-f50 Section 7.4, 3GPP 38.213-f50 Section 4.1). Synchronization Signal Reference Signal Received Power (SS-RSRP) measurement (3GPP 38.215-f40 Section 5.1.1)
  - DM-RS correlation and extraction of half-frame bit and 2 or 3 LSBs of the SS/PBCH block index (3GPP 38.211-f50 Section 7.4.1.4). Channel State Information (CSI) computation, necessary for PBCH reception
  - PBCH reception. Extraction of timing information from 3 sources. Physical-layer model of the BCH (i.e. PBCH) can be found in 3GPP 38.202-f40 Section 5.2.2, whereas 3GPP 38.212-f50 Section 7.1 specifies payload generation, scrambling, transport block CRC attachment, channel coding and rate matching for the BCH.
    * Scrambling structure (3GPP 38.211-f50 Section 7.3.3.1)

  * PBCH payload (3GPP 38.331-f51 Section 6.2.1, BCCH-BCH-Message), which contains the Master Information Block (MIB, 3GPP 38.331-f51 Section 6.2.2) and *messageClassExtension* (guess is a way to say the message could extend its content). Actions upon MIB reception can be found in 3GPP 38.331-f51 Section 5.2
  * PBCH additional payload bits (3GPP 38.212-f50 Section 7.1.1)

- SIB1 acquisition (3GPP 38.331-f51 Sections 5.2 and 6.2.2). SIB1 includes, among others, PLMN information in the information element *CellAccessRelatedInfo*.

An overview of System Information (SI) handling can also be found in 3GPP 38.300-f50 Section 7.3.

MIB and – later – SIB1 information is parsed and partly analyzed at RRC. If both messages are shown to be valid, barring status and available resource support is correspondingly checked for MIB and SIB1. When successful, information contained in the SIB1 is forwarded to higher layers.

3.2.1 SSB index and SS-RSRP

The gNB is broadcasting periodical SSBs over different DL TX beams that are switched in time. However, from the perspective of a UE that is not synchronized to the gNB, there is no way to distinguish among beams unless an identifier associated to them is attached to the transmission. This identifier is called an SSB index – or SS/PBCH block index in 3GPP specifications – and its association with the DL TX beams serves two purposes. On one hand, it differentiates SSBs transmitted over different gNB TX beams. On the other hand, it indicates the resources to use for UL transmission to the Random Access (RA) Procedure, as it will be discussed in Section 3.5.1.

Exploiting analog beamforming and SSB indexing, it is possible for the gNB to broadcast SSBs in burst, as shown in Fig. 3.3. This multi-SSB structure is referred to as an SS burst set or SS burst, and it is confined within half a radio frame, i.e. 5 ms. The half of the radio frame the SS burst was transmitted on is indicated by a bit sent over the DM-RS and the PBCH, called the half-frame bit. The SS burst timing structure perfectly fits the SSB minimum periodicity described above, which shall be rather called SS burst periodicity.

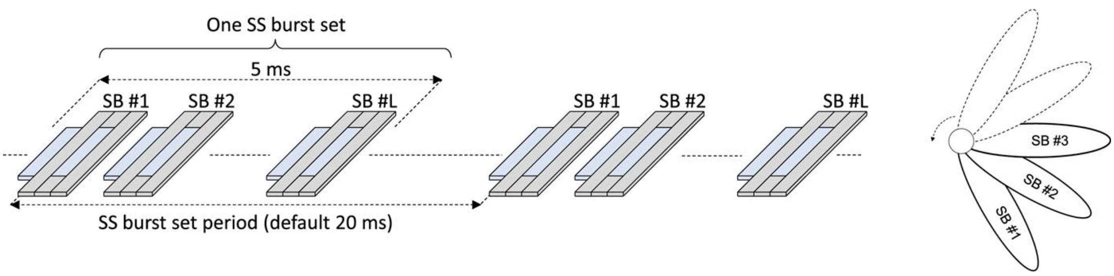


Fig. 3.3. SS burst periodicity and SS-RSRP. Figure from [3]

Depending on the frequency range, there is a limit on the number of SSBs that can be enclosed into an SS burst. Hence, there is a limitation on the number of DL TX beams the gNB can select for SSB transmission. For FR1 below 3 GHz, there can be up to 4 SSBs within an SS burst. For FR1 above 3 GHz a maximum of 8 SSBs can be adjacently transmitted, whereas for FR2 the upper boundary increases up to 64 SSBs enclosed into an SS burst. Nevertheless, the gNB decides *how many* SSBs will be within an SS burst – clearly within the indicated limits – and *how* to distribute the DL TX beams across the available SSBs.

Every gNB DL TX beam received by the UE will arrive with different perceived power values, and their power also vary when the UE sweeps its DL RX beams. Hence, metrics that realize beam pair comparison are essential for establishing a suitable connection. The Synchronization Signal Reference Signal Received Power (SS-RSRP) is one of the fundamental metrics used for IBE. It is defined by 3GPP 38.215 Section 5.1.1 as the "the linear average over the power contributions (in [W]) of the resource elements that carry secondary synchronization signals" [32]. In Fig. 3.3, there is an example of the resource elements the SS-RSRP for SSB #1 may be extracted from. Resources that carry the SSS are highlighted in red, their power contributions might be part of the averaging process.

3.3 PLMN Selection

The first stage of IBE takes place during the selection of a Public Land Mobile Network (PLMN), basically a mobile network that provides service for land-based – i.e. earth-based – communication purposes. Every cell in a 5G NR network is associated to at least one PLMN, its identifier is transmitted in the SIB1. Therefore, it is necessary to carry out cell search from the UE side to find the PLMN identities associated to a cell. When there is no available stored information about previous measurements – e.g. UE in NSA mode being switched on for the very first time –, "the UE shall scan all RF channels in the NR bands according to its capabilities to find available PLMNs. On each carrier, the UE shall search for the strongest cell and read its system information, in order to find out which PLMN(s) the cell belongs to" [33]. Otherwise, the UE may optimize the search by using that information.

When PLMN identities have been read from the strongest cell at a certain RF carrier, they are reported to the Non-Access Stratum (NAS) layer. The NAS layer selects one PLMN, reports it back to the RRC sublayer, and the cell selection stage can take place. Details on PLMN selection can be found in 3GPP 38.304 Section 5.1 [33].

3.4 Cell Selection

After having selected a PLMN in the previous stage, a suitable cell that belongs to that PLMN shall be selected. To accomplish it, the UE shall scan – as for PLMN selection – all RF channels in the NR bands belonging to the selected PLMN according to its capabilities. Since the strongest cell was previously read its system information to extract the PLMN, the UE only needs to search for the strongest cell in each RF channel to evaluate its suitability. Once a cell is found suitable, it is selected and the second is considered finished. An overview flowchart is shown in Fig. 3.4.

In the same way as for PLMN selection, cell selection can be carried out with help of previously stored information when available, shortening the search time by doing so. In that sense, one can distinguish between initial cell selection, carried out with no knowledge about which RF channels are NR frequencies, and cell selection by leveraging stored information. If the latter form of cell selection did not find suitable cells, initial cell selection is performed. If no suitable cells are found for initial cell selection, an acceptable cell is selected.

"An acceptable cell is one for which the measured cell attributes satisfy the *cell selection criteria* and the cell is not barred" [4]. A suitable cell is an acceptable cell whose PLMN corresponds to the list of accepted PLMNs, is not reserved or part of a tracking area in the list of "forbidden tracking areas for roaming".

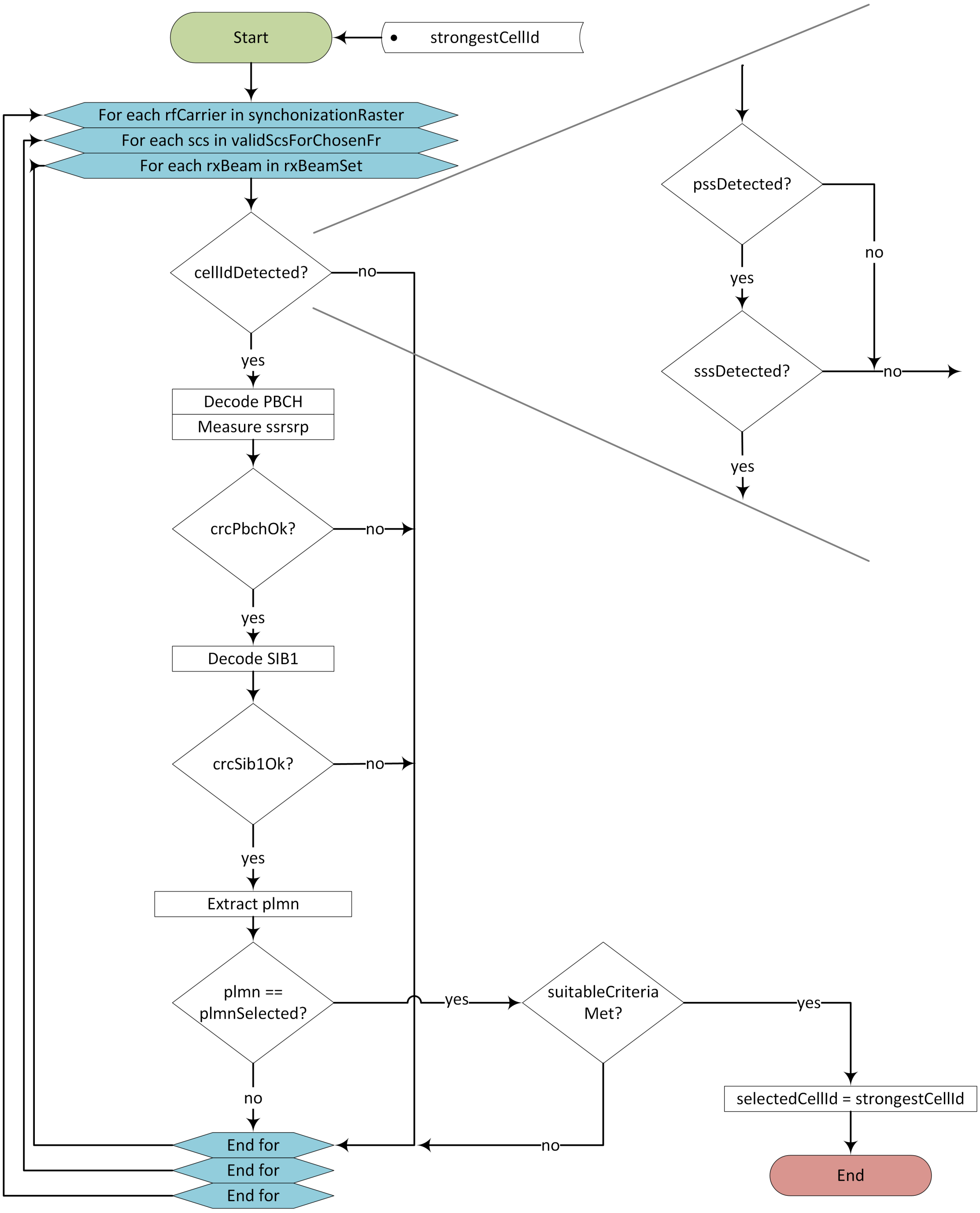


Fig. 3.4. Cell Selection flowchart.

Complete information about cell selection can be found in 3GPP 38.300 Section 9.2.1.1 [4] and 38.304 Section 5.2 [33]. More details on the different cell categories – e.g. acceptable, suitable cells – can be found in 3GPP 38.304 Section 4.5. The *cell selection criteria* are defined by 3GPP 38.304 Section 5.2.3.2.

3.5 Initial Access

The previous processes were in charge of selecting a PLMN and a cell that guarantees service to the UE trying to connect to the 5G NR network. Following that, the UE attempts to establish connection with the selected cell belonging to the selected PLMN. Based on the beam-centric design from 5G NR, connection shall be established by means of beamformed operation, i.e. by selecting a suitable beam pair after switching among a set of beams. The task is taken over by the Initial Access (IA) stage – also called Initial Acquisition –, where beam switching may be carried out at the gNB and/or the UE. A procedure to gain access to the gNB, known as Random Access (RA), is used by the UE in the IA context to establish communication with it. The measurements carried out in IA are strictly not part of the RA procedure, but the RA procedure thought for IBE would not take place without them. Therefore, the beam pair measurements will be included into the stage flow interpretation of RA for IBE purposes.

3.5.1 Random Access Procedure

The progression of the Random Access (RA) procedure is managed by the Medium Access Control (MAC) sublayer, and can be triggered by a Physical Downlink Control Channel (PDCCH) order, by the MAC entity itself, or by the RRC. The RRC is the entity that triggers the RA procedure for IBE purposes. In its general sense, RA serves as a procedure used as part of

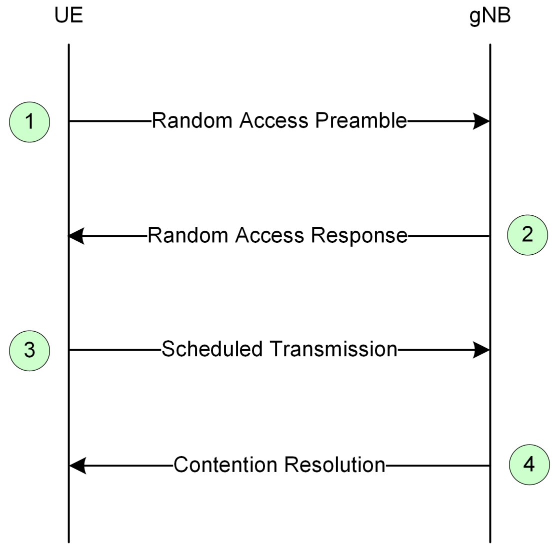
- Initial Beam Establishment (IBE),
- handover,
- UL synchronization reestablishment
- UL scheduling request, in case no resource has been previously configured, or
- Link Recovery (LR).

RA can take two forms, as shown in Fig. 3.5. From the UE point of view, both of them require the UE to transmit a preamble and receive a corresponding response from the gNB. This is done as a "probing" mechanism, analog to a situation where a person could be calling out somebody in order to start a conversation. Once the called person answers to the call the conversation can proceed.

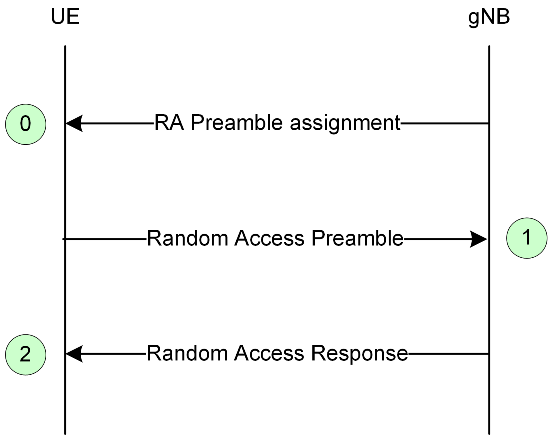
The difference between the RA variations lies in the assumption about multiple simultaneous UE-side preamble transmissions. Contention-Based Random Access (CBRA) (Fig. 3.5a) is meant when no resource assignment is given to any UE in specific. This implies that multiple UEs may be sending the same messages over the same time-frequency resources and might contend for access to the gNB. These messages are called Random Access Preambles, as seen in Fig. 3.5a stage 1. The gNB only grants access for one UE at a time, so that communication does not crash for all the parts involved. Therefore a contention resolution mechanism is present for CBRA. Therefore, stage 2 of Fig. 3.5a corresponds to the UE replying to the single or multiple random-access requests, whereas stages 3 and 4 try to solve potential collisions between the messages exchanged between the gNB and potential multiple UEs.

On the other hand, Contention-Free Random Access (CFRA) (Fig. 3.5b) applies when the network assigned specific resources to transmit over to a specific UE, as seen in stage 0 of Fig. 3.5b. This ensures that no other access-interested contender will be performing transmission in the same time-frequency occasion, so there is no need of a resolution mechanism for CFRA. Therefore, a random access preamble transmission asking for connection request (Fig. 3.5b stage 1) and a random-access response accepting the request are sufficient to establish connection between gNB and UE.

In the IBE context, UEs are not connected to the network yet, so they are not able to receive any resource assignment by the gNB. Therefore, CBRA is the form the



(a) Contention-Based



(b) Contention-Free

Fig. 3.5. Random Access Procedures. Figure from [4].

RA procedure takes when IBE is carried out. Fig. 3.6 shows the flowchart for CBRA oriented to IBE purposes. Notice that only CBRA will be explained in the remaining sections of this chapter. Therefore, referring to RA procedure in this chapter intends a reference to the CBRA for IBE purposes. CFRA will be rather described in Chapter 5, where it is triggered by the RRC in the context of Link Recovery.

The following subsections summarize all steps contained within the RA procedure when IBE is carried out. Information was gathered from [7], [14] and [34], where further details can be found. The logical flow mainly comes from 3GPP 38.321 Section 5.1. Additional pieces from one of the other sources cited above will be explicitly referenced.

3.5.1.1 Initialization

During initialization, variables and constants are configured by the RRC. Two of them are worth describing, as they will be important for later subsections.

prach-ConfigurationIndex. Configurable index that maps into an available set of Physical Random Access Channel (PRACH) occasions for RA preamble transmission. The Random Access Channel (RACH) is the channel where a configurable subset of slots, called RACH slots, can be allocated for UL transmission. Within a RACH slot, there may be multiple time and frequency-multiplexed subsets of resources called PRACH occasions. The transmission taking place within a PRACH occasion is called a PRACH or a RA preamble transmission.

Each PRACH occasion is associated to an SSB index. By transmitting a preamble in the ocassion for the SSB index associated to a certain DL TX beam, the UE is able to report to the gNB that it selected that DL TX beam for establishing connection. Nevertheless, this mechanism is transparent to the UE, since the UE receives and conveys information linked to an SSB index but has no knowledge of the TX beam the gNB carried out SSB transmission over.

The PRACH occasions repeat themselves with a periodicity called RACH configuration period or association period, that can range from 10 ms up to 160 ms. Every PRACH occasion is given a configurable amount of Contention-Based (CB) preambles, that means, one or several sequences orthogonal to each other. Preamble indices, that

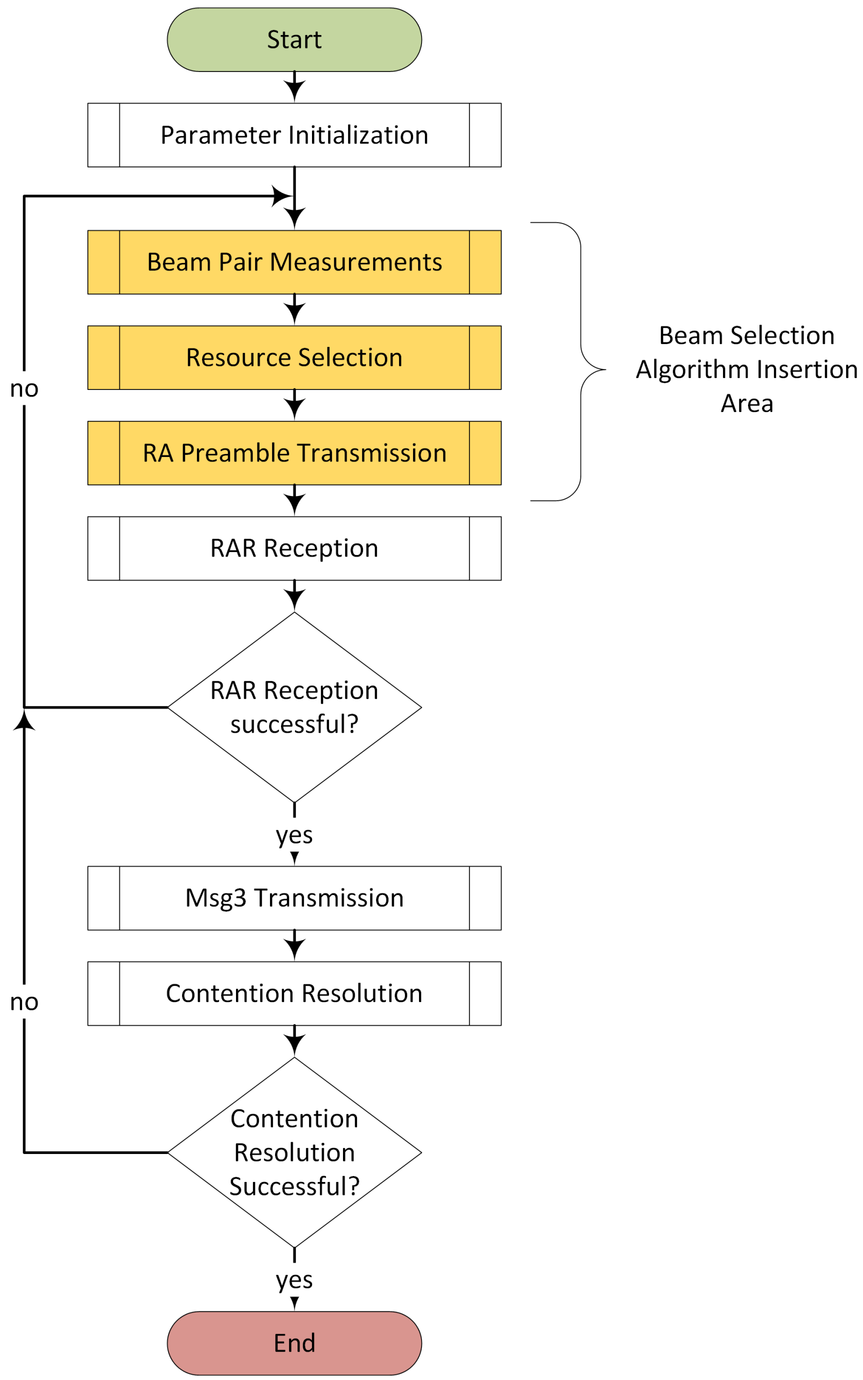


Fig. 3.6. Overview CBRA for IBE.

act as root indices for each sequence, are assigned to each PRACH occasion. This sequence design enables an initial contention management procedure at the gNB side when multiple UEs are trying to access the network simultaneously.

rsrp-ThresholdSSB. It corresponds to the threshold that checks suitability of a beam pair when an SSB is correctly received over it. If the measured SS-RSRP of an SSB is above the threshold, the beam pair related to the SSB is suitable and can be thus selected.

As an important observation, 3GPP 38.321 Section 5.1.2 in its note states that, "when the UE determines if there is an SSB with SS-RSRP above rsrp-ThresholdSSB ..., the UE uses the latest unfiltered L1-RSRP measurement". Here, L1-RSRP is referred to either an SS-RSRP or a Channel State Information RSRP (CSI-RSRP) that will be later discussed. Hence, no averaging shall be considered when checking beam pair suitability based on the SS-RSRP threshold.

3.5.1.2 Beam Pair Measurements

SS-RSRP measurements from diverse received SSBs are collected here for further analysis at the resource selection stage. Measurements are extracted according to Section 3.2.1. The amount of measurements performed here or whether to average measurements is not defined by the specifications and is thus, up to the implementation. Averaging is not mandated as well, nonetheless the latest SS-RSRP measurement shall be considered when comparing against the SS-RSRP threshold. The beam pair measurement stage is not part of the RA procedure according to Release 15. Therefore, this stage can be seen as a component of IA that intertwines with the sub-stages of the RA procedure.

3.5.1.3 Resource Selection

Resource selection decides on which SSB to select out of all the received ones. Since an SSB relates to a certain DL TX beam, and the UE can receive the mentioned SSB with multiple DL RX beams, resource selection ultimately selects a beam pair. The SSB is identified by the SSB index, which is mapped to a configurable set of PRACH occasions. Thus, a PRACH occasion to transmit the RA preamble will be determined once a beam pair is selected and a preamble index will be assigned to the transmission configuration. When a beam pair is selected, configurations on information about the transmit beam to be used by the network are set.

A flow-oriented summary of resource selection according to the specifications goes as follows.

- Select an SSB with SS-RSRP bigger than the configured *rsrp-ThresholdSSB*. If no such SSB exists, select any SSB from the available ones.
- Select the RA preamble group and set PREAMBLE_INDEX.
- Determine the next available PRACH ocassion from a list.
- Move forward to RA Preamble Transmission.

Notice that there are no indications on *how* to select an SSB when there are many with SS-RSRP above the configured SS-RSRP threshold. Neither there are indications on *how* to select an SSB when there are no SSBs with SS-RSRP above the threshold. Decision on these aspects is also left to the implementation design. The flexibility that resource selection provides becomes the main motivation for proposing different approaches unified into one implementation proposal for IA, described later in Chapter 6.

3.5.1.4 RA Preamble Transmission

The preamble transmission stage takes the parameters set by the resource selection stage, sets a transmission power by making use of the so-called power ramping feature and tags the transmission with an identifier called Random Access Radio Network Temporary Identifier (RA-RNTI).

The power ramping feature plays an important role when the RA preamble transmission gets attenuated too strongly and does not reach the gNB. The next stage, called

Random Access Response (RAR) reception is basically waiting for a response from the gNB based on the preamble transmission done here. If there is no response from the gNB, the UE, assumes the transmission power was too low and increments it by a configurable factor until either there is a RAR response from the gNB or a configured threshold is reached. The threshold can be either a maximum number of successive transmission attempts or a maximum transmission power.

The RA-RNTI is fundamental to correctly address the UE – or UEs – trying to access the network through a certain PRACH occasion. The UE computes the RA-RNTI based on the time-frequency location of the selected PRACH occasion and the UL carrier on which preamble transmission is executed.

A flow-oriented summary of RA preamble transmission according to the specifications is shown below.

- Set the target transmission power.
- Compute RA-RNTI associated with the PRACH occasion.
- Instruct the PRACH transmission to the physical layer, using
  - PRACH occasion.
  - RA-RNTI.
  - PREAMBLE_INDEX.
  - PREAMBLE_RECEIVED_TARGET_POWER.
- Move forward to RAR reception.

Depending on the number of PRACH transmission attempts, the target power will be configured by the power ramping feature. For more details on power ramping, refer to 3GPP 38.213 Section 7.4.

Information on physical layer triggering and configuration can be found in 3GPP 38.213 Section 8.1. Information on PRACH structure can be found in 3GPP 38.211 Section 6.3.3. Information on its baseband signal generation can be found in 3GPP 38.211 Section 5.3.2. Modulation and upconversion details can be found in 3GPP 38.211 Section 5.4.

3.5.1.5 RAR Reception

Random Access Response (RAR) reception starts after having transmitted a RA preamble. The MAC sublayer starts a timer called the RA response window, within which an incoming message is expected at the physical layer on the Physical Downlink Control Channel (PDCCH) and passes to MAC processing once received. If the identifier contained in the message, referred to as RA preamble ID (RAPID), matches the RA-RNTI set for preamble transmission, RAR reception becomes successful and the next stage is called. If there is no success, RA preamble transmission is called again, where power ramping is carried out.

A flow-oriented summary of RAR reception according to the specifications is shown below.

- Start ra-ResponseWindow (given in number of slots) at the first PDCCH occasion after PRACH transmission.
- Physical layer detection of a DCI 1_0 with CRC scrambled by RA-RNTI, the first symbol of CORESET to receive PDCCH for Type1-PDCCH-CSS set (3GPP 38.213-f50 Section 8.2).

- If a transport block (TB) is detected, pass it to higher layers, i.e. MAC sublayer (3GPP 38.213-f50 Section 8.2).
- When MAC sub-layer successfully decodes the TB, configure back-off and check that the received RA Preamble ID (RAPID) matches the RA-RNTI to consider RAR reception as successful.
- If RAR reception is successful, move forward to Msg3 Transmission.

3.5.1.6 Msg3 Transmission

Message 3 (Msg3) transmission can be considered as the first step towards contention resolution. The contention issue arose when multiple UEs tried to contact the gNB using the same PRACH occasion – e.g. because they selected the same DL TX beam in the resource selection stage –, and received a RAR addressed to the same RA-RNTI. The gNB additionally sent an identifier called Temporary Cell RNTI (TC-RNTI) and a UL grant as part of the RAR. The TC-RNTI is a temporary identity that shall be implicitly sent back into the UL data transmission, also known as Physical Uplink Shared Channel (PUSCH). It acknowledges UE reception and might be used as a unique identifier of the device requesting access. The UL grant is a way for the gNB to tell the UE which resources have been reserved for it to send a message in UL direction. There are two options to solve contention from this point.

The first option considers the possibility that the UE was previously connected to the network. In that case, the UE was given a unique identity, called the Cell RNTI (C-RNTI), which should have been stored for later use. In this case, C-RNTI works again as a unique identifier for the UE, and is sent into a MAC packet as a Control Element (CE). The gNB will recognize the C-RNTI, accept the connection and carry out further necessary steps.

The second option considers the UE has not been assigned a unique identity before. Since no C-RNTI exists yet for it, the UE generates an unambiguous identifier called the UE contention resolution identity, which is submitted from upper layers in the form of a Common Control Channel (CCCH) Service Data Unit (SDU). Since each UE generates its own contention resolution identity, the contention issue can be clearly solved by the gNB.

The timing and power of the message to be transmitted are adjusted by the UE, which follows instructions of the gNB and employs the power ramping feature previously explained. A flow-oriented summary of Msg3 transmission according to the specifications is shown below.

- Process Timing Advance Command, i.e. execute time alignment.
- Indicate power ramping parameters to lower layers – to the physical layer.
- Process received UL grant and indicate it to lower layers – physical layer. To know more about the content of an UL grant, go to 3GPP 38.213-f50 Section 8.2.
- Set the variable TEMPORARY_C-RNTI (from here simply called TC-RNTI) to the received TC-RNTI in the RAR.
- Include a C-RNTI MAC CE for the UL transmission. Otherwise, only include CCCH SDU submitted from upper layer and associated with the UE contention resolution identity (3GPP 38.321-f50 Section 3.1).
- Store the MAC PDU to be transmitted into the Msg3 buffer.

- PUSCH transmission – at the physical layer – based on RAR UL grant. Possible retransmissions scheduled by a DCI 0_0 with CRC scrambled by a TC-RNTI provided by the RAR (3GPP 38.213-f50 Section 8.3).

- Move forward to Contention Resolution.

3.5.1.7 Contention Resolution

In fact, when the gNB receives the PUSCH transmission from one or multiple UEs, it receives a message containing either a unique identifier registered at the network – the C-RNTI – or an unambiguous identity that solves the contention issue. Therefore, the gNB sends a control transmission, known as the Physical Downlink Control Channel (PDCCH), where either the C-RNTI or the UE contention resolution identity are indicated. The TC-RNTI was still implicitly sent along with the control message.

Therefore, when such transmission arrives at the UE, contention resolution is successful if it received either a C-RNTI that matches its C-RNTI, or a UE contention resolution identity that matches the one sent by the UE. If the latter case applies, the UE takes the TC-RNTI generated by the gNB as the C-RNTI to register to the network. Otherwise, as stated before, the C-RNTI the UE has stored previously keeps being valid for registration.

A flow-oriented summary of contention resolution according to the specifications is shown below.

- Start contention resolution timer and monitor for a PDCCH transmission.
  - If C-RNTI MAC CE was included in Msg3 and the PDCCH is addressed to the C-RNTI: Consider Contention Resolution successful, stop the timer *ra_ContentionResolutionTimer*, discard TC-RNTI and consider RA successful.
  - If CCCH SDU was included in Msg3 and the PDCCH is addressed to the TC-RNTI: When MAC PDU is successfully decoded and the UE contention resolution identity MAC CE matches the CCCH SDU, consider Contention Resolution successful, set C-RNTI to TC-RNTI, discard TC-RNTI and consider RA procedure successful.

If the contention resolution timer expires or the UE contention resolution identity MAC CE does not match CCCH SDU, a RA problem is indicated to higher layers, so the resource selection stage is carried out once more.

3.5.1.8 Completion of RA Procedure

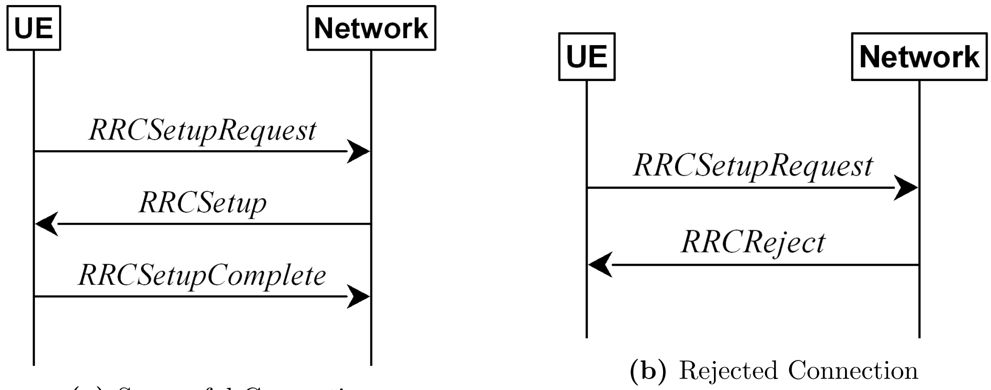
The Msg3 the UE sent to the gNB contained the UE contention resolution identity. Its storage was necessary to compare and check with the UE contention resolution identity the gNB sent. As the RA procedure is successfully completed, there is no need to keep this message in the buffer. Thus, Msg3 is deleted from memory.

A flow-oriented summary of RA completion according to the specifications is shown below.

- Flush the Msg3 buffer used for MAC PDU transmission.

3.6 RRC Connection Establishment

The completion of the RA procedure leaves the device registered under the provider network with a unique identity that allows unambiguous information exchange. The last step concerning IBE is the one that configures the UE's RRC and changes its state from RRC_IDLE to RRC_CONNECTED. The procedure involves Signaling Radio Bearer 1 (SRB1) establishment and transfer of initial NAS dedicated information from the UE to the network. Detailed information about this stage can be found in 38.331 Section 5.3.3 [5]. Valid and up-to-date essential system information is required to be acquired before initiating RRC connection establishment.



(a) Successful Connection

(b) Rejected Connection

Fig. 3.7. RRC Connection Establishment Message Sequence. Figure from [5].

As seen in Fig. 3.7, there are two possibilities when the UE sends a setup request via an *RRCSetupRequest* message. If the network rejects the connection request, the gNB lets the UE know about this decision via an *RRCReject* message. Then, the UE declares a failure to higher layers, does not switch to RRC_CONNECTED and returns to the Cell Selection Procedure.

If the network accepts the connection request, the gNB lets the UE know about this decision via an *RRCSetup* message, that configures a great deal of key parameters to configure full information exchange. The two main components of *RRCSetup* are the radioBearerConfig and the masterCellGroup information elements (IE), of types *RadioBearerConfig* and *CellGroupConfig* respectively. Full content description about the messages and IEs mentioned here can be found in 38.331 Pages 153-156, 197-200, 319-321 [5].

3.6.1 Configuration for Beam Adjustment

Two remarkable configurations that will impact the Beam Adjustment (BA) procedure – discussed in Chapter 4 – are received by the UE via the *RRCSetup* message. They are measurement and report configurations related to Channel-State Information (CSI), referred to as *CSI-MeasConfig* and *CSI-ReportConfig*. *CSI-ReportConfig* is contained within the *CSI-MeasConfig* IE. The following hierarchy flow shows how the CSI-MeasConfig is embedded into the DL-CCCH-Message. The names without parenthesis refer to the message or IE type, whereas the names with parenthesis refer to the specific name given into the RRC message:

1. DL-CCCH-Message → DL-CCCH-MessageType (message) → RRCSetup (rrcSetup) → CellGroupConfig (masterCellGroup) → ServingCellConfig (spCellConfigDedicated) → CSI-MeasConfig (csi-MeasConfig)

(a) CSI-MeasConfig → CSI-ReportConfig (csi-ReportConfigToAddModList)

The *DL-CCCH-Message* class is the set of RRC messages that may be sent from the Network to the UE on the DL Common Control Channel (CCCH), a logical channel in the RRC layer. The CCCH maps to the DL Shared Channel (DL-SCH), a transport channel in the MAC layer. The DL-SCH maps in turn to the PDSCH physical layer channel. Concluding, the CSI measurement and reporting configurations are sent from the gNB to the UE via a PDSCH message.

3.6.2 Configuration for Link Recovery

In a similar manner as for Beam Adjustment (BA), three remarkable configurations that will impact Link Recovery (LR) – discussed in Chapter 5 – are received by the UE via the *RRCSetup* message.

The first one corresponds to the configuration for monitoring the radio link, i.e. to check the connection quality over time. The configuration includes parameters to add/remove resources to/from a list of physical resources used to monitor the radio link. Those parameters are referred to as *failureDetectionResourcesToAddModList* and*failureDetectionResourcesToReleaseList*, and can be found within the *RadioLinkMonitoringConfig* IE.

The second one corresponds to the configuration for recovering after beam failure has happened, which includes a list of physical resources associated to candidate beams to reestablish connection. This parameter is referred to as *candidateBeamRSList*, and is contained within the *BeamFailureRecoveryConfig* IE.

The third one corresponds to an optional configuration of thresholds to determine when a UE is in-sync or out-of-sync. They serve two purposes, namely determining when connection failure is happening and when a candidate beam can reestablish connection. Both thresholds can be found within the parameter *rlmInSyncOutOfSyncThreshold*.

Similar to the configurations related to BA, the configurations for LR are embedded into the DL-CCCH-Message. The following hierarchy flow shows how *RadioLinkMonitoringConfig*, *BeamFailureRecoveryConfig* and *rlmInSyncOutOfSyncThreshold* are embedded into the DL-CCCH-Message. The names without parenthesis refer to the message or IE type, whereas the names with parenthesis refer to the specific name given into the RRC message:

1. DL-CCCH-Message → DL-CCCH-MessageType (message) → RRCSetup (rrcSetup) → CellGroupConfig (masterCellGroup) → ServingCellConfig (spCellConfigDedicated) → BWP-DownlinkDedicated (initialDownlinkBWP) → RadioLinkMonitoringConfig (radioLinkMonitoringConfig)

2. DL-CCCH-Message → DL-CCCH-MessageType (message) → RRCSetup (rrcSetup) → CellGroupConfig (masterCellGroup) → ServingCellConfig (spCellConfigDedicated) → BWP-UplinkDedicated (initialUplinkBWP) → BeamFailureRecoveryConfig (beamFailureRecoveryConfig)

3. DL-CCCH-Message → DL-CCCH-MessageType (message) → RRCSetup (rrcSetup) → CellGroupConfig (masterCellGroup) → (rlmInSyncOutOfSyncThreshold)

It is clear then that both configurations can also be found within the *DL-CCCH-Message* class, as with configurations for BA. Thus, it can also be concluded that the necessary configurations to indicate resources for LR are sent from the gNB to the UE via a PDSCH message.

Chapter 4

Beam Adjustment

4.1 Introduction

The procedures described in Chapter 3, when used in an IBE context, provided the UE with essential parameters to successfully connect to the gNB, switching the RRC state from RRC_IDLE to RRC_CONNECTED. Additional system information exchange might come after IBE to extend functionality, but basic communication between device and network is already enabled. This chapter will start by introducing DL control transmission carried out by the gNB, better known as PDCCH transmission, and how upcoming data or reference signals (RS) transmissions are scheduled. This is important to understand parts of beam indication in the subsequent section. Beam indication refers to how beamformed communication between gNB and UE is supported throughout time. After explaining on beam indication, aspects of the Channel State Information Reference Signal (CSI-RS) related to Beam Adjustment (BA) will be also explained. Understanding of beam indication and CSI-RS will finally help understand how BA works, which is explained at the end of this chapter. Basically, the BA procedures by which the beams used for beamformed communication are selected will be described.

In principle, Beam Adjustment (BA) continuously adapts the direction and width of the transmit and receive beams used at the gNB and UE side for UL and DL communication. For instance, one can talk – among other possibilities – about beam refinement (beams get narrower), beam tracking (beams change direction) or a combination of them. Beams might also widen if needed, e.g. if a gNB has to cover multiple UEs with the same DL TX beam. The basic structure of BA consists of:

- Resource scheduling from the gNB side to send reference signals.
- Reference signals reception and measurement computation. It could be performed at the gNB or the UE side, depending on the type of BA carried out.
- Measurement reporting. This step is optional depending on the type of BA carried out.
- Beam adaptation

Measurements and reporting can be carried out on a periodic, semi-periodic or aperiodic basis. As BA does not happen simultaneously at gNB and UE, one beam per procedure – identified by their index – is the outcome that may be used for UL or DL communication. The gNB may use information and recommendations from the UE to enhance BA. Transmission of control signaling and data may benefit from the beams selected in the process, as BA aims at improving the link quality based on ever-changing radio channel conditions. The gNB is in charge of deciding which UL RX and DL TX beams it is going to use and indicating the UE about them. If the UE does not receive any indication, it assumes them based on the configuration provided by IBE. Upon knowing or assuming the beams the gNB is using, the UE is able to select their own UL TX and DL RX beams. More on beam indication or assumption will be explained later in Section 4.3.

4.2 PDCCH: Structure and scheduling of PDSCH/PUSCH

Potential control messages, called Physical Downlink Control Channel (PDCCH) candidates, are monitored in so-called search space sets. The search space sets are associated to control regions composed of time-frequency resources, called Control Resource Sets (CORESETs). The common control region shared by multiple UEs in a cell is delimited by a CORESET with index 0. The resources for the common control region are configured in the MIB and reconfigured through the *PDCCH-ConfigCommon* IE included into different RRC messages. Dedicated UE-specific control regions are delimited by CORESETs with indices different than 0.

PDCCH transmissions serve different purposes that are conveyed through the payload, which is referred to as the Downlink Control Information (DCI). Then, different DCI formats convey different purposes for the PDCCH transmission, as shown in Table 4.1.

Table 4.1: DCI formats. Table from [8]

DCI format	**Usage**
0_0	Scheduling of PUSCH in one cell
0_1	Scheduling of PUSCH in one cell
1_0	Scheduling of PDSCH in one cell
1_1	Scheduling of PDSCH in one cell
2_0	Notifying a group of UEs of the slot format
2_1	Notifying a group of UEs of the PRB(s) and OFDM symbol(s) where UE may assume no transmission is intended for the UE
2_2	Transmission of TPC commands for PUCCH and PUSCH
2_3	Transmission of a group of TPC commands for SRS transmissions by one or more UEs

The DCI formats scheduling either Physical Uplink Shared Channel (PUSCH) or Physical Downlink Shared Channel (PDSCH) transmissions are basically scheduling data transmissions. This implies, every PDSCH or PUSCH transmission is related to a PDCCH transmission. The same DCI formats may additionally schedule channel sounding reference signals in some cases, either in UL or DL.

DCI formats 0_0 and 1_0, also known as fallback formats, support a limited set of NR features and their size is relatively fixed. Their use is recommended when there is uncertainty in the device configuration or signaling overhead is to be avoided. DCI formats 0_1 and 1_1, also known as non-fallback formats, support all NR features. Their size is variable and depends on the configuration features indicated. Fields may or may not be present depending on whether certain features are enabled.

The channel sounding reference signals scheduled in DL and UL are respectively Channel-State Information Reference Signals (CSI-RS) and Sounding Reference Signals

(SRS). They are time-frequency resources that relate to different beams. Their structure will be discussed in their corresponding BA section. Both CSI-RS and SRS have identifiers that serve the same purpose as SSB indices (Section 3.2.1), i.e. selecting an index translates into selecting a gNB's TX beam.

4.3 Beam Indication

For beamformed communication, gNB and UE shall coincide on a beam pair that maintains connectivity. However, they are not always aware of the beams that the other part is using. Suppose for instance, that the gNB wants to transmit in DL with a certain TX beam. The gNB expects the UE to succeed in its reception, even though the gNB does not know whether the RX beam the UE will use is going to receive the DL transmission correctly. At most, what the gNB can do for the UE, is to provide information as to which TX beam is being utilized. Information on the gNB's DL TX beam is referred to as beam indication. Therefore, the UE is expected to associate the indicated TX beam to an RX beam known to establish suitable connection. If there is no indication, the UE shall assume a gNB's TX beam and receive with a corresponding RX beam known to establish suitable connection.

Beam indication is implicitly conveyed by the gNB through a so-called Transmission Configuration Indication (TCI) state. The TCI state establishes a QCL relation between DM-RS ports of PDSCH, a DM-RS port of PDCCH or CSI-RS port(s) of a CSI-RS resource, and one or two DL reference signals – i.e. SSB, CSI-RS –.

Coming back to Section 2.5, PDCCH and PDSCH and their DM-RS will be correspondingly transmitted over the same antenna ports with the same precoding – i.e. same beam. The same reasoning goes for the CSI-RS antenna port(s) and the CSI-RS resource. Hence, the QCL relationship can be also seen as between PDCCH, PDSCH or CSI-RS and one or two reference signals. QCL on the other hand, indicates inference between the large-scale radio channel properties experienced at two antenna ports. Thus, the properties experienced when transmitting the reference signals with a certain TX beam hold when transmitting PDCCH, PDSCH or CSI-RS with the same TX beam. Therefore, the TCI state ultimately indicates that the gNB will transmit PDCCH, PDSCH or CSI-RS with the same TX beam as it did for an indicated reference signal. Due to the described relationship, the terms beam indication and TCI state indication and the terms TCI state and DL TX beam will be onwards used interchangeably.

4.3.1 Beam Indication for PDCCH

Beam indication for a PDCCH may be conveyed by a MAC CE inside a PDSCH transmission. There are MAC CEs containing identifiers (IDs) for the serving cell, the CORESET and its TCI state. Depending on the CORESET ID, the TCI indication is extracted from different configuration parameters. Information on configuration parameters and the MAC CE for TCI state indication of a PDCCH is found in 38.321 Section 6.1.3.15 [34]. UE's MAC behavior upon receiving the MAC CE is found in 38.321 Section 5.18.5.

The gNB sets up the configuration parameters for CORESETs with index different from 0 through the *RRCSetup* message (see Section 3.6) sent at RRC Connection Establishment. If a single TCI state is provided in the RRC configuration, explicit beam indication by a MAC CE is not necessary, since the only TCI state provided is chosen. If multiple TCI states are provided, a MAC CE indicating a single TCI state out of the provided ones is necessary. In case no beam indication is carried out by the gNB, the UE assumes the DM-RS of PDCCH to be QCL-ed with the SSB identified during initial access. This implies, the UE will take the same RX beam it took for receiving the selected SSB during IBE.

For a CORESET with index 0, a MAC CE indicating the TCI state is required for beam indication. If no such indication is delivered by the gNB after the most recent RA procedure not initiated by a PDCCH order that triggers a CFRA, the UE shall assume the DM-RS of PDCCH to be QCL-ed with an SSB identified during the mentioned RA procedure. This implies, the UE will take the same RX beam it took for receiving the selected SSB during a RA procedure that, among other reasons, might have been triggered in an IBE context.

Further information on QCL for PDCCH can be found in 38.213 Section 10.1 [14].

4.3.2 Beam Indication for PDSCH

A UE can be configured with a maximum number of TCI state configurations that depends on its capabilities. The list containing them is sent within the *PDSCH-Config* message, whose structure is available in 38.331 Section 6.3.2 p281-284 [5]. A MAC CE activates and deactivates TCI states that can be selected out of the list. The MAC CE command is referred to as the activation command, transmitted on a PDSCH. Its structure can be found in 38.321 Section 6.1.13.14, as well as the UE's MAC behavior upon its reception in 38.321 Section 5.18.4 [34].

There are a maximum of 8 activated TCI states are mapped to a list of so-called codepoints. The gNB may indicate one of the activated TCI states for a PDSCH via the TCI field included in a DCI format 1_1, which is scheduling the PDSCH of concern. If the gNB chooses not to indicate any TCI state in the DCI format 1_1, it indicates to the UE's higher layers that the field is non-existent. In this case, the higher layer parameter *tci-PresentInDCI* is set as 'disabled' for the CORESET scheduling the PDSCH.

Since the DCI is sent through the PDCCH, the TCI indication can be only processed if there is enough time between PDCCH and PDSCH transmissions. A threshold called *timeDurationForQCL* is used to decide on the processing of a TCI indication contained in the PDCCH. If the time between PDCCH and PDSCH transmissions is shorter than *timeDurationForQCL*, the TCI indication used for PDCCH reception is used for PDSCH reception. This implies, the UE will receive the PDSCH with the same RX beam previously used for PDCCH reception. The same assumption on beam indication is done in case:

- the gNB chooses not to indicate any TCI state in the DCI format 1_1, or
- a DCI format 1_0 is used for scheduling the PDSCH (no TCI state present in the scheduling format).

Upon TCI state configuration, activation command reception, DCI 1_1 reception with a TCI state indication and time spacing between PDCCH and PDSCH transmissions larger than *timeDurationForQCL*, it is possible to apply the TCI state configuration indicated within the PDCCH transmission by the gNB. This implies, the UE will receive the PDSCH with the same RX beam used for reception of a reference signal indicated by the TCI state.

For more details on QCL for PDSCH, refer to 38.214 Section 5.1.5 [35].

4.3.3 Beam Indication for CSI-RS

Depending on the periodicity type configuration, beam indication for a CSI-RS is carried out in different ways. There are 3 types of periodicity applicable to a CSI-RS resource, namely periodic, semi-persistent and aperiodic. TCI state indication for each of the periodicity types is explained in Section 4.4.

4.4 CSI-RS in the Beam Adjustment context

The Channel-State Information Reference Signal (CSI-RS) is a special and versatile DL reference signal that provides with rich information about the radio channel. Received power, signal quality, interference and suggestions on precoding are among the information that can be inferred from the CSI-RS. A great deal of information regarding the CSI framework can be found in 38.214 Section 5 [35], references to it and other Technical Specifications (TS) will be made along this section.

CSI-RS transmission is scheduled on resource sets known as Non-Zero Power CSI-RS resource sets, that are configured by higher layers. The parameters that configure a CSI-RS can be found in 38.214 Section 5.2.2.3. Each resource has its own identification called *nzp-CSI-RS-ResourceId*, which is a remarkable detail for BA purposes. For interference measurements, a special type of CSI-RS resource, called CSI-IM resource, is used. The parameters that configure a CSI-IM resource can be found in 38.214 Section 5.2.2.4. Scheduling of Zero-Power CSI-RS resource sets is required to avoid collisions between PDSCH transmissions and CSI-RS that use the overlapping sets of resources. The physical signal sequence and mapping to physical resources – i.e. time-frequency grid and antenna ports – is described in 38.211 Section 7.4.1.5 [7].

Based on the measurements carried out on the CSI-RS resources, the UE can either send reports to the gNB on information about the channel conditions – i.e. Channel State Information (CSI) – or take actions at its side based on the measurements.

As already stated in Section 3.6, the gNB configures the UE to receive the CSI-RS resource through the information element (IE) *CSI-MeasConfig* (38.331 Section 6.3.2 p.216-218). If a report is also needed, the gNB configures its parameters through the IE *CSI-ReportConfig* (38.331 Section 6.3.2 p.218-224).

Inside *CSI-ReportConfig*, there are two configurable parameters that condition the whether the reporting is performed, namely *ReportQuantity* and *repetition*. When *reportQuantity* is set to "none" or *repetition* is set to "on", reporting is not carried out.

The CSI reported can be transmitted in one single instance or divided into 2 parts depending on the report purpose. For BA purposes, the reporting is set for CRI/RSRP or SSBRI/RSRP (see Section 4.5.1).

The CSI-RS resources can be allocated in three ways, namely in a periodic, semi-persistent or aperiodic basis. Similarly, the CSI reports can be allocated in a periodic, semi-persistent or aperiodic basis. Not all kinds of combinations among periodicity types for measurement and reporting are allowed, as seen in Table 4.2.

Table 4.2: Supported combinations of report type and resource type.

CSI-RS Configuration	**Periodic CSI Reporting**	**Semi-persistent CSI Reporting**	**Aperiodic CSI Reporting**
Periodic CSI-RS	Supported	Supported	Supported
Semi-persistent CSI-RS	Not supported	Supported	Supported
Aperiodic CSI-RS	Not supported	Not supported	Supported

The measurement and reporting periodicity types are configured by RRC signaling, as explained in Section 3.6.

For periodic CSI-RS transmission, the field *qcl-InfoPeriodicCSI-RS*, that is configured through the higher layer parameter *NZP-CSI-RS-Resource*, points to the TCI state configuration indication intended for the UE. The structure of the parameter *NZP-CSI-RS-Resource* is found in 38.331 Section 6.3.2 pp. 268-269 [5].

For semi-persistent CSI-RS transmission, the SP CSI-RS/CSI-IM Resource Set Activation/Deactivation MAC CE indicates each CSI-RS/CSI-IM resource set and their associated TCI states. The MAC CE structure is found in 38.321 Section 6.1.3.12, UE's MAC sublayer behavior is also specified in 38.321 Section 5.18.2 [34].

For aperiodic CSI-RS transmission, the TCI state is indicated in the same manner as for a PDSCH TCI state indication.

4.5 DL Beam Adjustment

Beam Adjustment (BA) intended for DL is based on either CSI-RS or SSBs. As stated at the beginning of this chapter, the BA workflow consists of transmission of reference signals, measurements, possible measurement reports and potential beam switching upon the measurements. DL BA can be further decomposed into 2 variants, receiver-side (RX-side) and transmitter-side (TX-side) BA.

4.5.1 DL TX-side BA

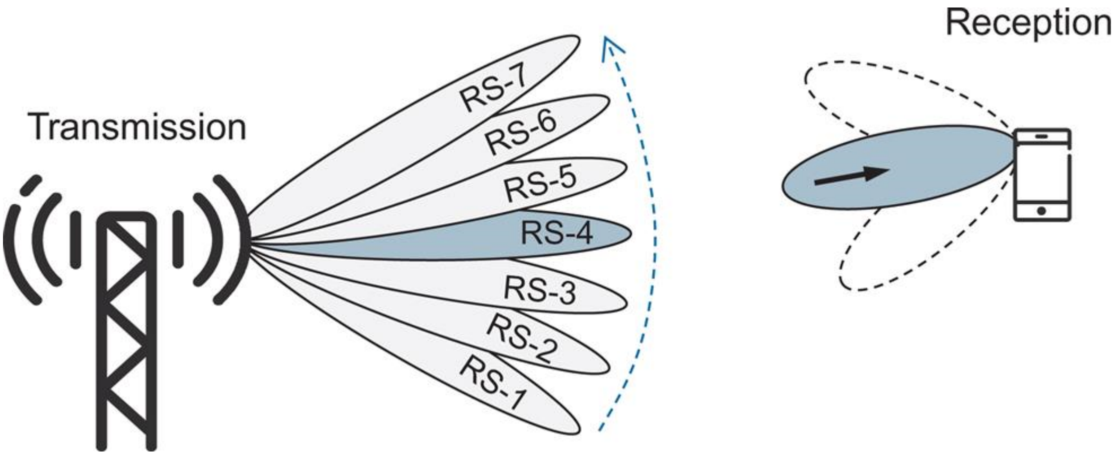


Fig. 4.1. Beam sweeping for DL TX-side BA. Figure from [3].

Referring to DL TX-side BA is referring to BA carried out at the gNB for the DL communication, i.e. the TX beam used by the gNB gets adjusted. The gNB is in charge of transmitting DL reference signals (RS), associating different RS resources to different DL TX beams. Then, the gNB is sweeping through a configurable amount of beams to transmit the RS, as shown in Fig. 4.1. This implies that measurements performed on the reference signals shall be carried out by the UE. To establish a fair comparison of gNB's TX beams, the UE shall measure all incoming RS with the same RX beam. Since the gNB does not have direct access to the measurements, the UE is responsible for sending measurement reports back to the gNB.

The measurement quantity corresponds to the L1-RSRP. Either SS-RSRP (described in Section 3.2.1) or Channel-State Information Reference Signal Received Power (CSI-RSRP) can be used for L1-RSRP. According to 38.215 Section 5.1.2 – refer to it for further details –, the CSI-RSRP is defined as "the linear average over the power contributions (in [W]) of the resource elements of the antenna port(s) that carry CSI reference signals configured for RSRP measurements within the considered measurement frequency bandwidth in the configured CSI-RS occasions". Hence, CSI-RS configured for received power measurements are used for BA purposes. Their transmission is carried out using 3000-series antenna ports.

The resources associated to different beams need to be distinguished by different identifiers. For CSI-RS, the field *nzp-CSI-RS-ResourceId* is in charge of configuring a beam identity. For SSB, their identities should be mapped to identifiers used for BA, considering that there are up to 64 SSBs each with an index ranging from 0 to 63.

Table 4.3: Mapping order of CSI fields of one report for CRI/RSRP or SSBRI/RSRP reporting. Table from [8].

CSI report number	**CSI fields**
CSI report #n	CRI or SSBRI #1 as in Table 4.4, if reported
	CRI or SSBRI #2 as in Table 4.4, if reported
	CRI or SSBRI #3 as in Table 4.4, if reported
	CRI or SSBRI #4 as in Table 4.4, if reported
	RSRP #1 as in Table 4.4, if reported
	Differential RSRP #2 as in Table 4.4, if reported
	Differential RSRP #3 as in Table 4.4, if reported
	Differential RSRP #4 as in Table 4.4, if reported

Then, each measurement report transmitted by the UE contains information from 4 reference signal resources, as shown in Table 4.3. A resource identifier and its corresponding L1-RSRP are stored into the report. There is a maximum of 4 resources – potentially associated to 4 different beams – that can be stored into the report. The identifiers for CSI-RS and SSB resources are referred to as CSI-RS Resource Indicator (CRI) and SSB Resource Indicator (SSBRI), respectively. The first L1-RSRP in Table 4.3 corresponds to the highest L1-RSRP out of the up to 4 resources. The rest of the L1-RSRPs are differential RSRPs calculated with respect to the best RSRP reported. The RSRP arrangement is done to reduce overhead without reducing measurement precision. The bitwidth for each of the potential reported fields is shown in Table 4.4

Table 4.4: CRI, SSBRI, and RSRP. Table from [8].

Field	**Bitwidth**
CRI	$\lceil log_2(K_s^{CSI-RS}) \rceil$
SSBRI	$\lceil log_2(K_s^{SSB}) \rceil$
RSRP	7
Differential RSRP	4

Reporting for DL TX-side BA purposes has *reportQuantity* set to either 'cri-RSRP' or 'ssb-Index-RSRP' (38.214 Section 5.2.1.4.2). The report is contained in the UL control information on the Physical Uplink Control Channel (PUCCH). The Information Element (IE) MeasResults contains the report sent to the gNB (38.331 Section 6.3.2 p.261-264).

Notice that the gNB may receive multiple reports from different UEs distributed along the gNB's coverage area. There might be multiple ways to adjust the TX beams currently used by the gNB, such as modifying the beamwidth, beam direction and/or the beam transmission power. Therefore, the number of reports and the behavior of the gNB upon receiving the reports is left up to the implementation.

Since the UE kept its RX beam fixed to receive all the candidate TX beams considered for DL TX-side BA, it shall keep using it for DL reception when a TCI indication points at the recently-adjusted TX beam.

4.5.2 DL RX-side BA

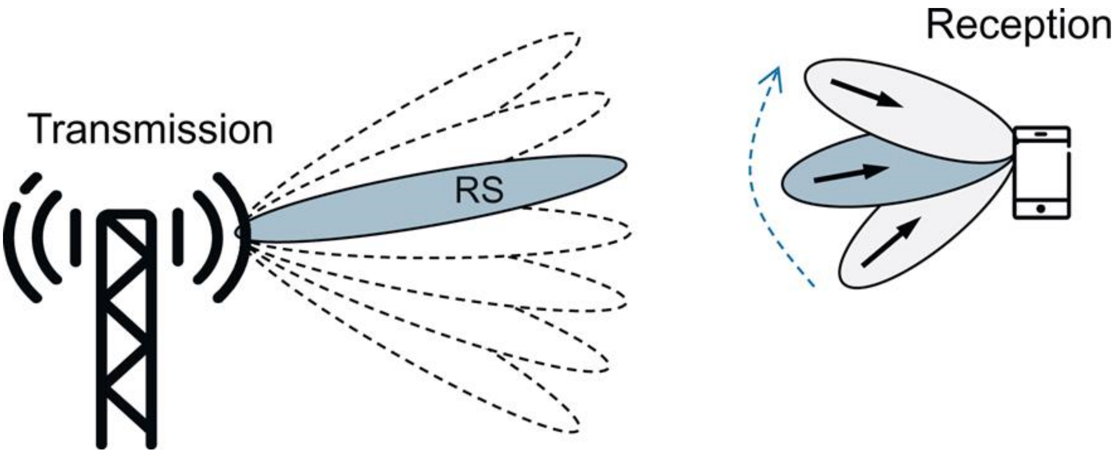


Fig. 4.2. Beam sweeping for DL RX-side BA. Figure from [3].

This variant of BA is intended for adjusting the RX beam used by the UE, clearly in DL communication. In contrast with DL TX-side BA, the gNB is sending all the RS with the same TX beam for DL RX-side BA purposes. This is needed since the UE shall sweep through its RX beams and measure the same gNB's TX beam to get a fair measurement comparison, as shown in Fig. 4.2. However, the gNB has to notify the UE whether DL BA should be carried out at the TX-side or the RX-side. As mentioned in Section 4.4, when *reportQuantity* is set to "none" or *repetition* is set to "on", reporting is not carried out. The special case when *repetition* is set to "on" is the way the gNB tells the UE that the TX beam is repeatedly associated to every NZP CSI-RS resource, so DL RX-side BA shall be performed. This also implies that reporting is not carried out by the UE for DL RX-side BA, since the UE is in charge of adjusting its own RX beam.

As well as for DL TX-side BA, the way the UE decides how to adjust its DL RX beam is left up to the implementation. Since the gNB is always sending over the same TX beam, the UE needs to update the TCI correspondence outcomes. When a TCI indication that points to the TX beam previously used for DL RX-side BA, the UE shall then use the recently-adjusted RX beam to communicate with the network.

Chapter 5

Link Recovery

5.1 Introduction

Link Recovery (LR) is the term given to a collection of two procedures used for recovering beamformed connectivity. The two procedures are called Beam Failure Detection (BFD) and Beam Failure Recovery (BFR), and may be used after connection has been established, as it was the case for Beam Adjustment (BA). They run consecutively in case BA were not able to respond quick enough to fast changes in radio channel conditions. Such sudden changes may be caused e.g. by blockage. The reference signals SSB and CSI-RS, described in previous chapters, are also used for LR. Therefore, their understanding is assumed here. The content of this chapter focuses on describing BFD, BFR and their connection to Radio Link Failure (RLF), a state where no recovery procedure was successfully completed.

5.2 Beam Failure Detection

As seen in Section 3.6.2, resources may be configured by the gNB to check if the radio link can ensure connection between the gNB and the UE. Those resources can be periodic CSI-RS resources and/or SSBs, as 38.133 states in its Section 8.5.1 [36]. They are pointed by a set $\bar{q}_0$ consisting of CSI-RS resource configuration indexes and/or SSB indexes, configured by the RRC list *failureDetectionResources*, as expressed in 38.213 Section 6 [14]. *failureDetectionResources* is a list of reference signals (RS), pointed by their indexes, used for Radio Link Monitoring (RLM) purposes. The elements in the list can be either added, modified or removed (released). The maximum number of failure detection resources that can be configured is 10 resources, according to 38.331 Section 6.4 p. 446 [5]. Notice from 38.300 Section 9.2.8 [4], that "SSB-based Beam Failure Detection is based on the SSB associated to the initial DL BWP and can only be configured for the initial DL BWPs and for DL BWPs containing the SSB associated to the initial DL BWP. For other DL BWPs, Beam Failure Detection can only be performed based on CSI-RS".

The radio link quality check can be assessed by means of thresholds. There is one parameter that lets know if the connection is becoming unreliable, namely the out-of-sync (OOS) threshold $Q_{out,LR}$. According to 38.133 Section 8.5.1 [36], "the threshold $Q_{out,LR}$ is defined as the level at which the downlink radio level link of a given resource configuration on set $\bar{q}_0$ cannot be reliably received and shall correspond to the $BLER_{out}$=10% block error rate of a hypothetical PDCCH transmission". $Q_{out,LR}$ and the parameters for its calculation vary depending on if the detection is done using SSB or CSI-RS resources. Additional details on the mentioned parameters for SSB-based and CSI-RS-based BFD can be found in 38.133 Sections 8.5.2 and 8.5.3 [36], respectively.

Beam Failure Detection (BFD) at UE's physical layer, as 38.213 Section 6 states [14], "provides an indication to higher layers when the radio link quality for all corresponding resource configurations in the set $\bar{q}_0$ that the UE uses to assess the radio link quality is worse than the threshold $Q_{out,LR}$". This indication goes up to the UE's MAC layer, where it is referred to as a beam failure instance.

The RRC configures the parameters for BFD for the MAC layer, that are contained within the information element (IE) *RadioLinkMonitoringConfig*. *RadioLinkMonitoringConfig* was sent either at RRC connection establishment in the context of IBE (Section 3.6.2) or at RRC reconfiguration when the device was already connected to the network – i.e. RRC_CONNECTED state –. *RadioLinkMonitoringConfig* may contain sets of failure detection resources to be added/modified to or released from *failureDetectionResources*. The sets are respectively called *failureDetectionResourcesToAddModList* and *failureDetectionResourcesToReleaseList*.

There are two BFD-associated parameters fundamental to understand when beam failure is detected, namely *beamFailureInstanceMaxCount* and *beamFailureDetectionTimer*. Beam failure is detected when the number of consecutive beam failure instances surpasses the configured *beamFailureInstanceMaxCount*, with a time gap between each beam failure instance not greater than *beamFailureDetectionTimer*. A counter named *BFI_COUNTER* is used to compare against *beamFailureInstanceMaxCount*. In case the mentioned parameters and/or the reference signals used for BFD are reconfigured, or *beamFailureDetectionTimer* expires in the middle of the counting process, *BFI_COUNTER* is set back to zero. This means, the beam failure instance counting process is restarted.

Since BFD and BFR are two consecutive LR procedures, the UE immediately starts a random-access (RA) procedure for BFR purposes after a beam failure is detected through BFD, as explained in Section 5.3.

For more details on the physical layer requirements for BFD, refer to 38.133 Sections 8.5.1 – 8.5.4, 8.5.7 [36]. For details on MAC guidelines related to BFD, refer to 38.321 Section 5.17 [34]. For further information on the RRC parameters described here, refer to 38.331 Section 6.3.2 pp. 328-329 describing the IE *RadioLinkMonitoringConfig* [5].

5.3 Beam Failure Recovery: Random Access for BFR

As stated at the end of Section 5.2, Beam Failure Recovery (BFR) starts right after a beam failure has been detected. Then, the UE initiates a RA procedure for BFR purposes, with the RRC configuring all parameters based on the information element (IE) *BeamFailureRecoveryConfig*. The relation between *BeamFailureRecoveryConfig* and BFR is analogous to that of *RadioLinkMonitoringConfig* and BFD. *BeamFailureRecoveryConfig* was also sent either at RRC connection establishment in the context of IBE (Section 3.6.2) or at RRC reconfiguration when the device was already connected to the network – i.e. RRC_CONNECTED state –. After the RA procedure is complete, BFR is also considered complete.

Transmission of *BeamFailureRecoveryConfig* is optional. The gNB then, may or may not provide parameters for the RA procedure, which has two implications. As already mentioned in Section 3.5.1, there are two variants of RA, namely contention-based RA (CBRA) and contention-free RA (CFRA). If the gNB provides dedicated resources to the UE for starting a RA, then the UE starts a so-called CFRA. Otherwise, the UE starts a so-called CBRA. Additionally, if the UE does not provide parameters necessary for either of the RA variants, default values will be selected by the UE for performing RA. The possibility to perform CFRA is one of the differences with respect to RA used in an Initial Beam Establishment (IBE) context.

Random access (RA) for BFR has few more differences with respect to RA for IBE. One of them is that the selection of reference signals associated to different beams is not only limited to SSBs. CSI-RSs may be also used to extract and compare RSRP measurements. Therefore, there may be measurements coming from SSBs and measurements coming from CSI-RSs, respectively called SS-RSRP and CSI-RSRP as mentioned in Chapters 3 and 4. When the measurements correspond to physical-layer measurements, they are referred to as L1-RSRP measurements. Another difference is the fact that the UE surely had been previously given an identity by the network, namely the Cell Radio Network Temporary Identifier (C-RNTI). Its C-RNTI is unique and known to the gNB, and it was generated when performing IBE. This will imply later that the UE does not need to send a Common Control Channel (CCCH) Service Data Unit (SDU) including the UE contention resolution identity to the gNB for further contention resolution, as it was the case for RA for IBE.

In the same manner as for Section 3.5.1, a significant amount of the following information will be coming from 38.321 Section 5.1 [34]. Therefore, its citation will be omitted and assumed to be the source of information unless otherwise explicitly stated. Information on the RRC parameters influencing BFR can be found in 38.331 Section 6.3.2 pp. 190-192 [5]. They are contained within the IE *BeamFailureRecoveryConfig*.

5.3.1 Initialization

Both RA variants start with a parameter configuration process performed by the RRC. The set of resources subject to selection may be provided by the gNB as a list *candidateBeamRSList* of candidate beam reference signal (RS) indexes. The resource set is symbolized in 3GPP Release 15 as $\bar{q}_1$.

SSB and CSI-RS have separate RSRP thresholds that are initialized by the RRC and used for selection, respectively *rsrp-ThresholdSSB* and *rsrp-ThresholdCSI-RS*. When the RA is initiated for BFR, both are associated to *rsrp-ThresholdSSB* in *BeamFailureRecoveryConfig* IE, according to 38.321 Section 5.1.1 [34]. The threshold ultimately indicates a level $Q_{in,LR}$ at which the downlink radio link quality can be significantly more reliably received than at the OOS level $Q_{out,LR}$. This threshold is also known as the in-sync (IS) threshold $Q_{in,LR}$, according to 38.133 Section 8.5.1 [36]. Notice that the threshold $Q_{in,LR}$ is directly applied to SSBs only. For CSI-RS resources, the RSRP threshold is applied by the UE after scaling the CSI-RS reception power with a value provided by *powerControlOffsetSS*, according to 38.213 Section 6 [14]. The value *powerControlOffsetSS* is sent along every configured NZP-CSI-RS resource by the gNB, within the IE *NZP-CSI-RS-Resource*, as seen in 38.331 Section 6.3.2 pp. 274-275 [5]. Therefore, the scaling factors among different CSI-RSs might differ.

5.3.2 Contention-Free Random Access for BFR

5.3.2.1 Resource Selection

In case of CFRA for BFR, the gNB explicitly provides the UE with resources for sending a RA request. The resources are associated to SSBs or CSI-RSs contained within *candidateBeamRSList*. If at least one of them is available and has an L1-RSRP above *rsrp-ThresholdSSB* or *rsrp-ThresholdSSB* depending on the case, that RS will be selected. Then, the resources associated to that RS will be used for preamble transmission.

Sometimes, RA preamble indexes are not associated to certain CSI-RSs. In case one of such CSI-RS is selected, the preamble index of an SSB included in *candidateBeamRSList* that is QCL-ed with the selected CSI-RS will be used as the preamble index reported by the UE to the gNB. After selecting resources, RA preamble transmission takes place.

If no RS contained within *candidateBeamRSList* has an L1-RSRP above the configured threshold, the RA for BFR is switched to the CBRA variant starting from the resource selection stage.

The behavior of the resource selection in CFRA for BFR shows that the suitability of beams associated to the set of resources $\bar{q}_1$ configured by the gNB is evaluated first. In other words, resources in this set are prioritized by the RA resource selection stage when performing CFRA for BFR, as mentioned in 38.300 Section 9.2.8 [4].

5.3.2.2 RA Preamble Transmission

The preamble transmission stage controls the target transmission power and instructs the physical layer to transmit the preamble using that adjusted transmission power, the selected preamble index and the PRACH occasion within the reserved PRACH occasions for CFRA. A Random-Access RNTI (RA-RNTI) is not required in this case, since the resources selected by the UE were previously allocated by the gNB. After preamble transmission takes place, the UE waits for Random-Access Response (RAR) reception.

5.3.2.3 RAR Reception

The UE was able to send a CFRA request with resources the gNB allocated for BFR. To receive a response to that request, the UE was also informed about the search spaces to monitor for a PDCCH transmission corresponding to the random-access response (RAR). This information is indicated through the parameter *recoverySearchSpaceId*. If there is a notification about an incoming PDCCH transmission from lower layers, the MAC layer checks if the transmission is addressed to the UE's C-RNTI and if the notified preamble was transmitted by the MAC entity. In case the check is positive, CFRA for BFR is declared successfully completed.

5.3.2.4 Completion of RA Procedure

Notice that the resources allocated by the gNB for CFRA in the context of BFR are not discarded. Moreover, there is no need to flush the buffer used for transmission of the MAC PDU containing a UE contention resolution identity in Msg3, since there is no Msg3 transmission for CFRA.

5.3.3 Contention-Based Random Access for BFR

Notice that the CBRA for BFR is very similar in workflow to the CBRA described for IBE in Section 3.5.1. Therefore, this subsection will mainly focus on highlighting important differences in the different stages of the CBRA procedure for BFR with respect to CBRA for IBE, while the workflow of the CBRA for IBE will remain being valid unless otherwise stated.

5.3.3.1 Msg3 Transmission

The UE requesting random access for BFR purposes had to establish connection with the network before communicating, and clearly before problems with the communication had arisen. At that instance, a C-RNTI was assigned to it. This same C-RNTI shall be used as the unique identifier that resolves contention for this particular UE. Therefore, in contrast to CBRA for IBE, Msg3 can only include a C-RNTI MAC CE in its transmission. The MAC PDU containing Msg3 is stored in buffer, as it was for CBRA for IBE.

5.3.3.2 Contention Resolution

Contention resolution for BFR monitors for a PDCCH transmission after having sent Msg3 with the UE's C-RNTI. The monitoring is carried for out an amount of time equal to *ra-ContentionResolutionTimer*. If a notification about reception of a PDCCH transmission is received from lower layers and this transmission is addressed to the C-RNTI, contention resolution is considered successful. Then, *ra-ContentionResolutionTimer* stops and the temporary C-RNTI (TC-RNTI) that the gNB generated in the RAR is discarded. The TC-RNTI is not needed because the UE is already assigned a C-RNTI.

5.4 Overview Radio Link Failure

Radio Link Failure occurs when radio problems within a cell cannot be solved by the recovery procedures present in 5G NR. One of the reasons for RLF is a notification of unsuccessful completion of a RA procedure. In the context of LR, it means that no suitable beams were found to recover the connection failure between gNB and UE. Two statements can be extracted from it. First, LR may deal with connection failure related to a beam pair, and BFR may be able to reestablish connection by switching the beam pairs used for communication. Instead, RLF may be identified, among other factors, because BFR was not able to reestablish connection. This implies that the cell currently connected to the UE cannot provide connectivity and there shall be cell reselection. For cell reselection, RRC connection reestablishment is clearly necessary. Second, BFR generally occurs more often than RLF, since the probability that connection through one beam pair within a cell is unsuitable is lower than the probability that connection through all beam pairs within the same cell is unsuitable. Fig. 5.1 shows an example of cases where beam failure and radio link failure can be detected. For beam failure, there are still beam pairs that may be able to reestablish connection between the gNB and the UE.

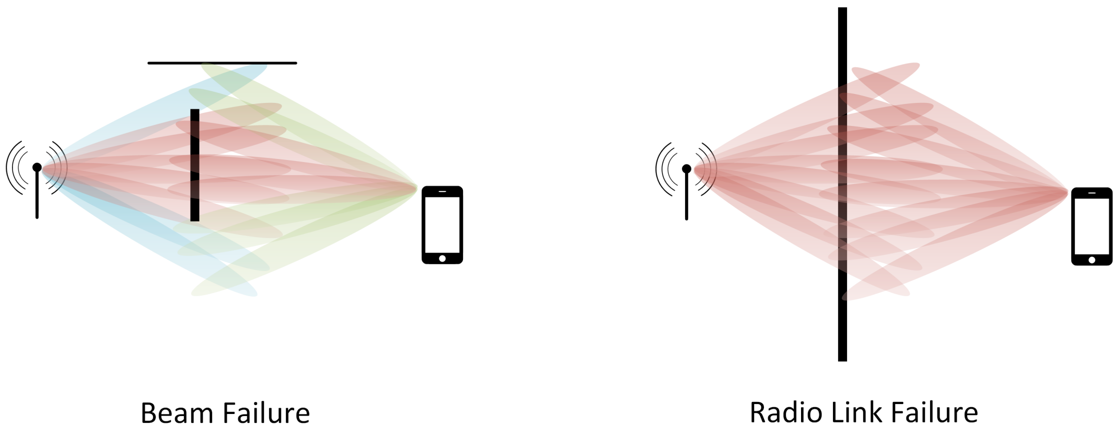


Fig. 5.1. Example scenarios Beam Failure and Radio Link Failure.

A description of RLF and RRC actions upon RLF can be found in 38.300 Section 9.2.7 [4] and 38.331 Section 5.3.10 [5], respectively.

Chapter 6

Initial Access Proposal (Confidential)

6.1 Introduction

This chapter intentionally left blank.

6.2 SSB and PRACH Occasion Mapping to Physical Resources

6.3 Overview Beam Pair Selection and Sweeping Order

6.4 Beam Sweeping Order

6.4.1 RX Beam Sweeping

6.4.2 TX Beam Sweeping

6.4.3 Summary Beam Sweeping

6.5 Beam Pair Selection

6.5.1 SS burst selection

6.5.2 Optimal Beam Pair Selection

6.5.2.1 Calculation of Valid PRACH Occasions

6.5.2.2 Beam Pair Discarding

6.5.2.3 Beam Pair Scoring

***normalizeLatency()* routine**

Chapter 7

Simulation Environment (Confidential)

7.1 Introduction

This chapter intentionally left blank.

7.2 Simulation Parameters

7.3 System Parameters

7.4 Antenna and Codebook Considerations

7.5 Link Budget

7.6 Office Layout and Simulation Scenarios

7.7 Beam Switching Capabilities

7.8 Algorithm Parameters

7.9 Simulation tools

7.10 Key Performance Indicators

7.10.1 KPIs within a simulation set

7.10.2 Comparison different simulation sets

Chapter 8

Simulation Results

8.1 Introduction

The simulation framework for analyzing the performance of the Initial Acess (IA) scheme under different configurations was defined in Chapter 7. The present chapter will first focus on presenting results for each of the simulation sets defined. Then, subsequent analysis and comparison of the algorithm's performance depending on different simulation environments will be also described. Remember the simulation environment may vary depending on:

1. Beam switching capabilities.
   (a) Low switching capabilities: 64 SSBs per RX beam switch, 8 SSBs per TX beam switch. Abbreviated to 64RX/8TX.
   (b) High switching capabilities: 1 SSBs per RX beam switch, 1 SSBs per TX beam switch. Abbreviated to 1RX/1TX.
2. Sweeping orders.
   (a) Sequential sweeping order.
   (b) Random sweeping order.
3. Coverage areas.
   (a) Good coverage: 10m range between gNB and UE.
   (b) Cell Edge: 40m range between gNB and UE.

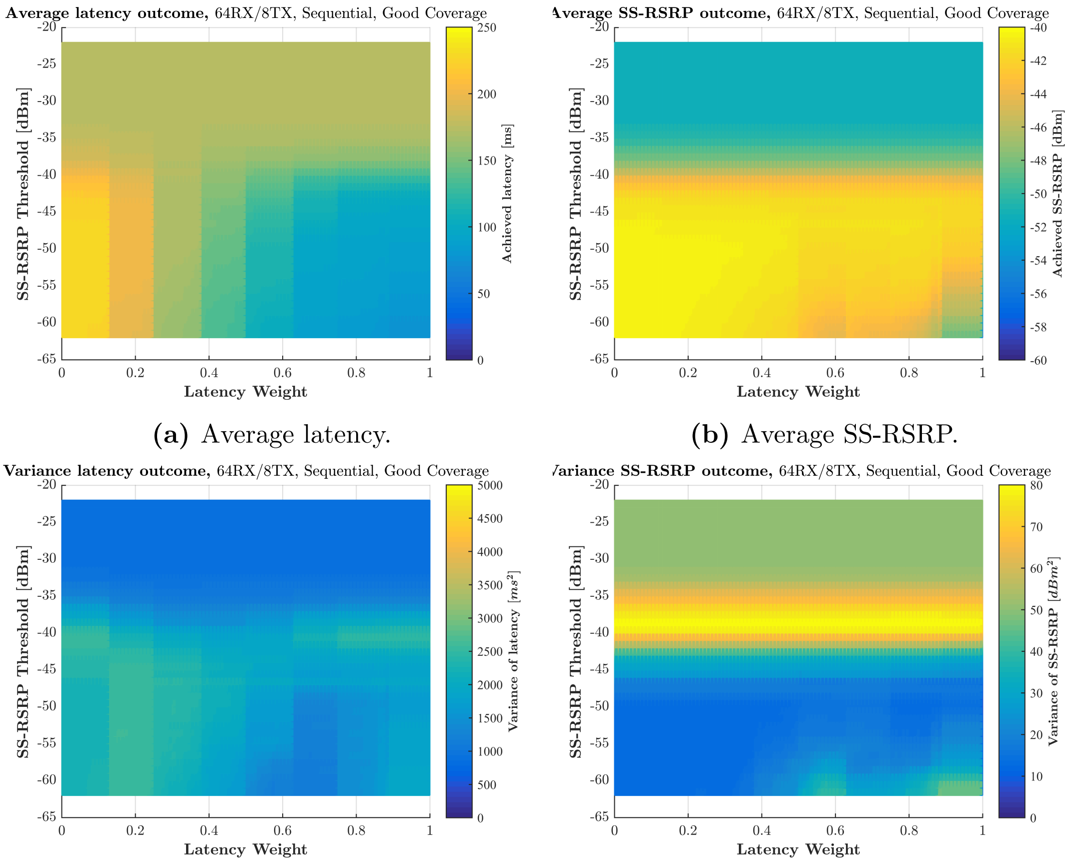
Also notice that upon each simulation environment, the algorithm will establish connection with different configurations of

1. latency weight, and
2. SS-RSRP threshold.

8.2 Result Analysis

8.2.1 Low-switching-capabilities Use Case: 64RX/8TX

Figs. 8.1 - 8.4 show the statistics of achieved latency and SS-RSRP when the switching capabilities at gNB and UE are 64 SSBs per RX beam and 8 SSBs per TX beam, respectively.



(a) Average latency. **(b)** Average SS-RSRP.

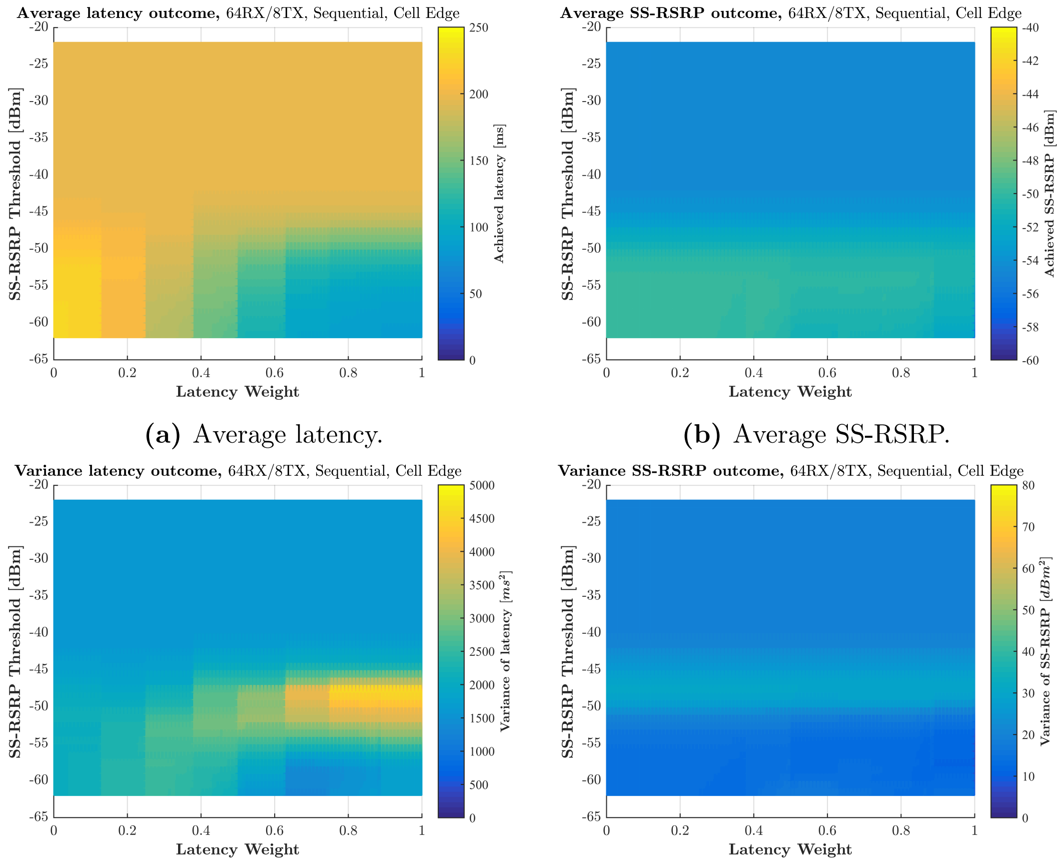
(c) Variance of latency. **(d)** Variance of SS-RSRP.

Fig. 8.1. Results for simulation set 64 SSB per RX beam, 8 SSB per TX beam, sequential sweeping order, Good Coverage scenario.

The x-axis of every plot depicts different configurations of latency weight for the IA algorithm. Therefore, the x-axis ranges from 0 to 1, where 0 corresponds to the corner case exhaustive search and 1 to the corner case fast search. The y-axis of every plot depicts different configurations of SS-RSRP threshold (in dBm) for the IA algorithm. The threshold ranges from -62 dBm to -22 dBm, which allows to appreciate the behavior of the algorithm when suitable beam pairs are found and when no suitable beam pairs are found because the threshold is too high. The extension of the axes agrees with the parameter configuration considered in Section 7.8.

The z-axis, illustrated through a color scale, describes 4 different quantities depending on the plot. They are average latency (in ms), average SS-RSRP (in dBm), variance of the latency (in ms^2) and variance of the SS-RSRP (in dBm^2) that were achieved with a certain configuration of the algorithm.

When looking at the average achieved latency of the algorithm for different configurations, abrupt latency changes evenly distributed across the x-axis on the lower part of the surface plot are noticeable. Notice that this axis corresponds to different configurations of latency weights, i.e. how much priority is given to the latency when establishing connection. Referring to Section 6.5.1, it can be inferred that the "subsections" of average achieved latency are related to the SS burst selection procedure. There are 8 major "subsections" in the surface plot, and notice there are 8 DL RX beams used for IA by the UE. For the corner cases, exhaustive search is reached when $ssBurstIndex = rxBeams = 8$, and fast search is performed when $ssBurstIndex = 1$.



(a) Average latency.

(b) Average SS-RSRP.

(c) Variance of latency.

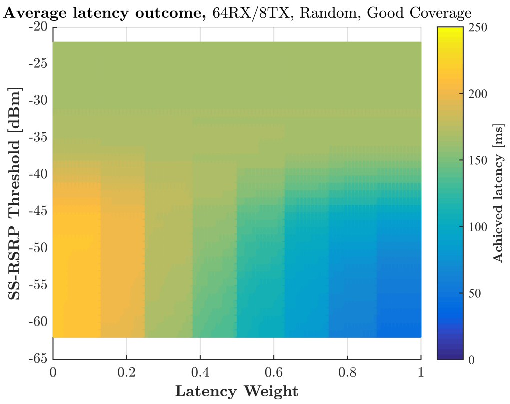
(d) Variance of SS-RSRP.

Fig. 8.2. Results for simulation set 64 SSB per RX beam, 8 SSB per TX beam, sequential sweeping order, Cell Edge scenario.

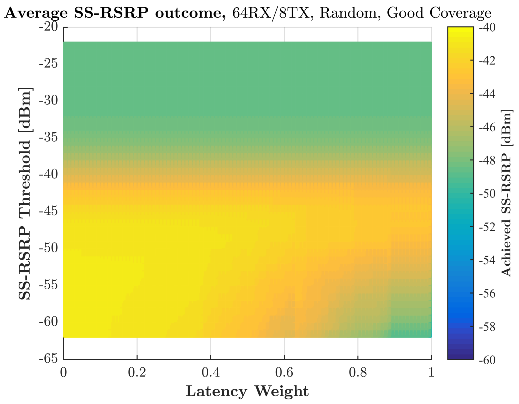
Every time the latency weight increases, the SS burst index increases in discrete steps. When the SS burst increases, the algorithm needs to wait an amount of time equal to an SS burst periodicity of 20 ms before it can select a PRACH occasion. The gaps can be partly explained according to this mechanism. However, for some plots such as the ones depicted in Figs. 8.1a and 8.2a, the latency gaps among high latency weights are not as noticeable as for Figs. 8.3a and 8.4a. This illustrates the expected behavior when no suitable beam pairs were found after a certain number of *ssBurstIndex* SS bursts have passed. In such case, the algorithm moves toward the next SS burst to find suitable SS-RSRP measurements and does so until either suitable beam pairs are found or exhaustive search is reached. In general, the average achieved latencies range from around 50 ms to around 230 ms. Consider that the fastest connections would be achieved in the first PRACH occasions, right after measurements from the first SS burst have been collected. This event occurs at the end of the first radio frame for the current environment, which takes place at almost 10 ms. This implies, the lowest latencies the algorithm can achieve are in average approximately 40 ms higher than the lowest achievable latencies that any procedure could achieve for such environment.

On the upper part of the average achieved latency plots, a constant region is depicted irrespective of the latency weight parameter. The region illustrates the behavior of the algorithm when no suitable beam pairs are found. Suitable beam pairs cannot be found when

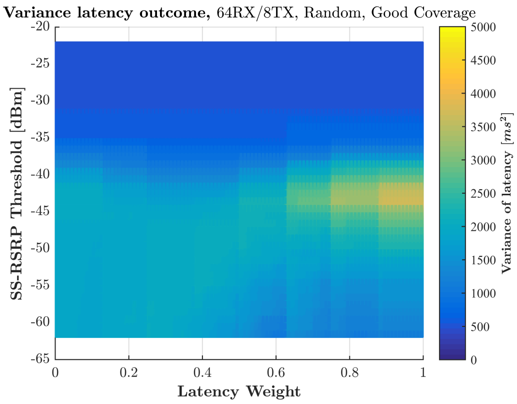
1. no SSBs could be successfully decoded, or



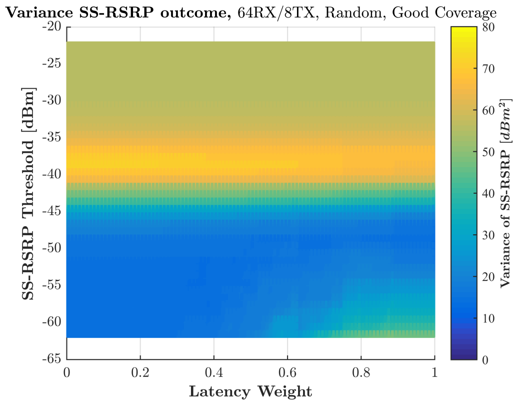
(a) Average latency.



(b) Average SS-RSRP.



(c) Variance of latency.



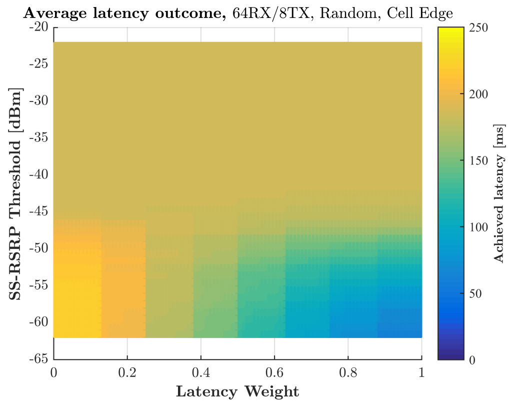
(d) Variance of SS-RSRP.

Fig. 8.3. Results for simulation set 64 SSB per RX beam, 8 SSB per TX beam, random sweeping order, Good Coverage scenario.

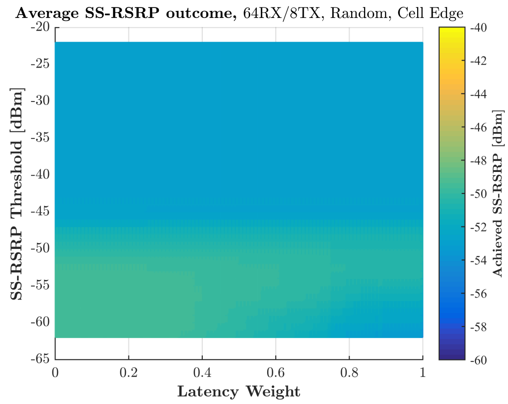
2. the configured SS-RSRP threshold is higher than every SS-RSRP measured from successfully decoded SSBs.

Since the plotted results already discarded the first option, the region appears after the configured SS-RSRP threshold is higher than every available SS-RSRP measurement. In such case, a beam pair is selected according to the statement from Table **??**. This implies that the selected beam pair is associated to a PRACH occasion that may take place as fast as right after exhaustive search has been carried out. Exhaustive search takes a total time of just below $(rxBeams - 1) \cdot T_{SSBurst} + T_f = 7 \cdot 20ms + 10ms = 150ms$. Consequently, all configurations establish connection after this time. Table 8.1 collects the average latency results when no suitable beam pairs were found due to an algorithm configuration with high SS-RSRP threshold. As the results show, the algorithm establishes connection in average faster for good coverage positional range – i.e. 10m range – than for cell edge positional range – 40m range –. The reason for this phenomenon is that the probability of correctly decoding SSBs at closer range is higher, since the power received by the UE is in general higher in comparison to a further range. This implies that the relatively fewer successfully decoded SSBs in a cell edge scenario may be associated to PRACH occasions taking place few more radio frames after exhaustive search has been carried out.

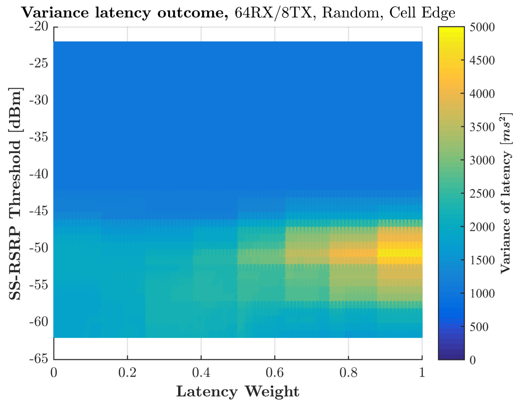
Notice that the region where no suitable beam pairs are found may start at different configurations of SS-RSRP threshold. It depends on the positional range between UE and gNB. The explanation is also in the power received by the UE, which depends on



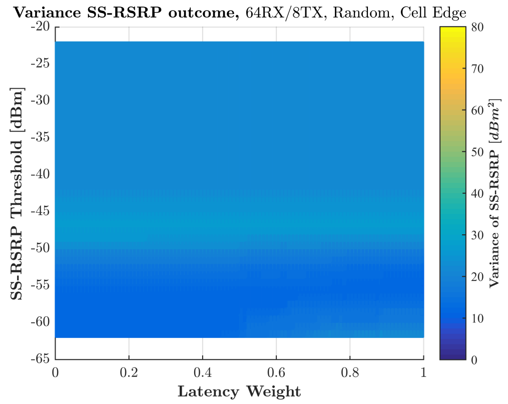
(a) Average latency.



(b) Average SS-RSRP.



(c) Variance of latency.



(d) Variance of SS-RSRP.

Fig. 8.4. Results for simulation set 64 SSB per RX beam, 8 SSB per TX beam, random sweeping order, Cell Edge scenario.

the distance between gNB and UE. Depending on this range, the best beam pairs will show higher or lower SS-RSRP values. The transition from having suitable beam pairs to not having any is smooth due to the multiple simulation runs that were carried out for each simulation set. Since the QuaDRiGa model is a stochastic radio channel model, its large-scale and short-scale parameters change with every simulation. Additionally, the antenna array used for the simulation does not show a constant gain over every beam, but it instead changes depending on its direction. Therefore, when position changes in every simulation run, its corresponding best beam pair and beam pair's gain also change. This generates a zone where some simulation runs show no suitable beam pairs, while others do. Such zone is not reliable, and its variance measurements confirm that. The variance in latency of Figs. 8.1 - 8.4 is always highest when the transition from 'suitable beam pairs found' to 'no suitable beam pairs found' happens.

When looking at the average SS-RSRP outcomes in Figs. 8.1b - 8.4b, the transitions for varying latency weight configurations are much smoother than the average latency transitions. Remember the time gaps in the latency outcomes were caused by the reception of SS-RSRP measurements through SS bursts, which come in separately in time. In the first SS bursts, it may not possible to collect as many measurements as wished to achieve a high SS-RSRP connection. Hence, some abrupt SS-RSRP changes can be seen in Figs. 8.1b and 8.3b for high latency weights. This is not that noticeable in Figs. 8.2b and 8.4b. As pointed out in the latency analysis, more SS bursts may be necessary to successfully receive SSBs, which implies that high latency weights may collect similar

Table 8.1: Average results for no suitable beam pairs found, 64RX/8TX.

Use case	Order	Area	Latency [ms]	SS-RSRP [dBm]
64RX/8RX	Sequential	Good Coverage	174.4	-51.39
64RX/8RX	Sequential	Cell Edge	197.5	-54.45
64RX/8RX	Random	Good Coverage	167.5	-48.75
64RX/8RX	Random	Cell Edge	184.2	-53.1

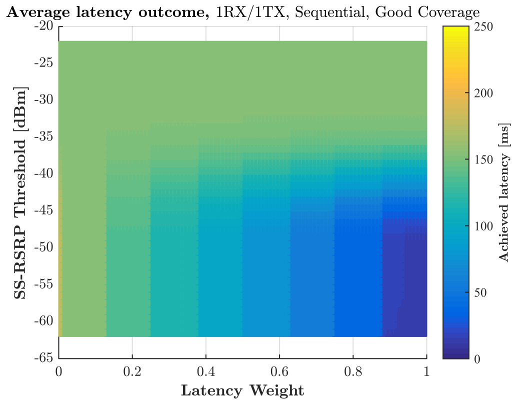
amounts of measurements than lower latency weights. Then, the achieved SS-RSRP surface is smooth when decreasing the latency weight for selecting a suitable beam pair. The average SS-RSRP seems not to increase significantly for latency weights below 0.5 approximately – i.e. half priority to latency and half priority to power –. Such decrease in the increase rate for SS-RSRP is expected, since the search carried out by the IA scheme gets closer to exhaustive search. Then, the probability of having found beam pairs with SS-RSRPs among the highest increases. At low values of latency weight, increasing the search time does not have such a positive impact on the average achieved SS-RSRP as when doing so for high values of latency weight. In general, the average achieved SS-RSRP approximately ranges between -53 dBm and -49 dBm for Cell Edge and between -49 dBm and -40 dBm for Good Coverage. Most of the average achieved SS-RSRP values in the zone where suitable beam pairs were found correspond to high SS-RSRP values, since either low latency weights or high SS-RSRP thresholds force the algorithm to select beam pairs with high SS-RSRPs.

Besides, it is worth noticing that the SS-RSRP threshold configured for the algorithm influences more the outcome as the latency weight is higher, when suitable beam pairs are found. At the corner case exhaustive search, the algorithm is looking for the beam pair that guarantees connection with highest SS-RSRP. If the SS-RSRP threshold configuration makes the algorithm label some beam pairs that do not have the highest SS-RSRP as unsuitable, it does not change the fact that the beam pair with the highest SS-RSRP will be selected by the UE. Then, the SS-RSRP threshold is not a decisive factor into exhaustive search unless it renders all beam pairs unsuitable. Therefore, the achieved average SS-RSRP for a configured latency weight 0 remains constant when suitable beam pairs can be found according to the configured SS-RSRP threshold.

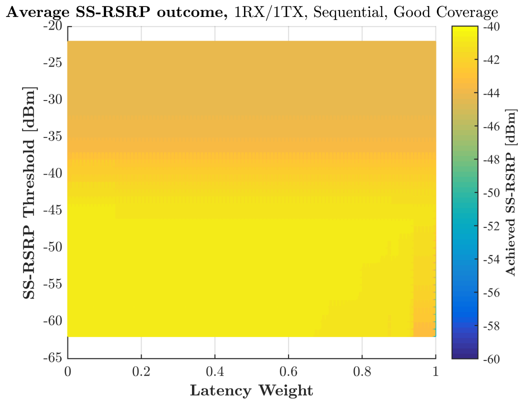
The transition zone from 'suitable beam pairs found' to 'no suitable beam pairs found' for the SS-RSRP statistics coincides – and even shows the abrupt changes in variance in a clearer way – with the transition zone according to latency statistics. Therefore, SS-RSRP statistics inside the transition zone are not considered for later comparison analysis either. When no suitable beam pairs are found, the algorithm selects a beam pair mostly considering the timing of the next available PRACH occasion without considering discarding based on the SS-RSRP threshold configuration – since it was too high –. Therefore, the average achieved SS-RSRP when no suitable beam pairs are found ends up resembling the average achieved SS-RSRPs for lowest SS-RSRP threshold and highest latency. Table 8.1 additionally collects the average SS-RSRP results when no suitable beam pairs were found due to an algorithm configuration with high SS-RSRP threshold. As expected, the average achieved SS-RSRP when no suitable beam pairs are found is higher for Good Coverage range. This occurs due to the device being closer to the gNB, hence receiving SSBs generally with higher SS-RSRP. Then, the average achieved SS-RSRP consequentially increases in comparison with a Cell Edge scenario.

8.2.2 High-switching-capabilities Use Case: 1RX/1TX

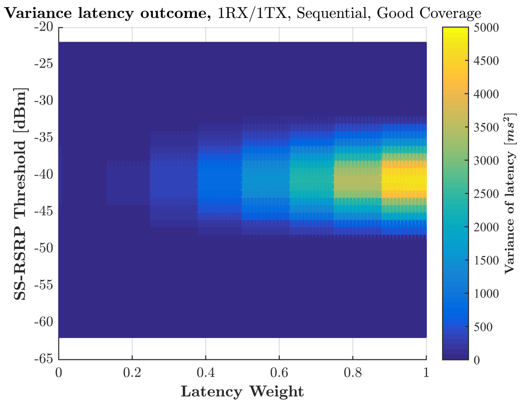
Figs. 8.5 - 8.8 show the statistics of achieved latency and SS-RSRP when the switching capabilities at gNB and UE are 1 SSBs per TX beam and 1 SSBs per RX beam, respectively.



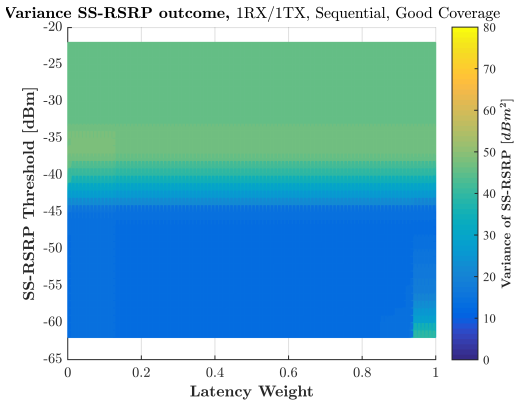
(a) Average latency.



(b) Average SS-RSRP.



(c) Variance of latency.



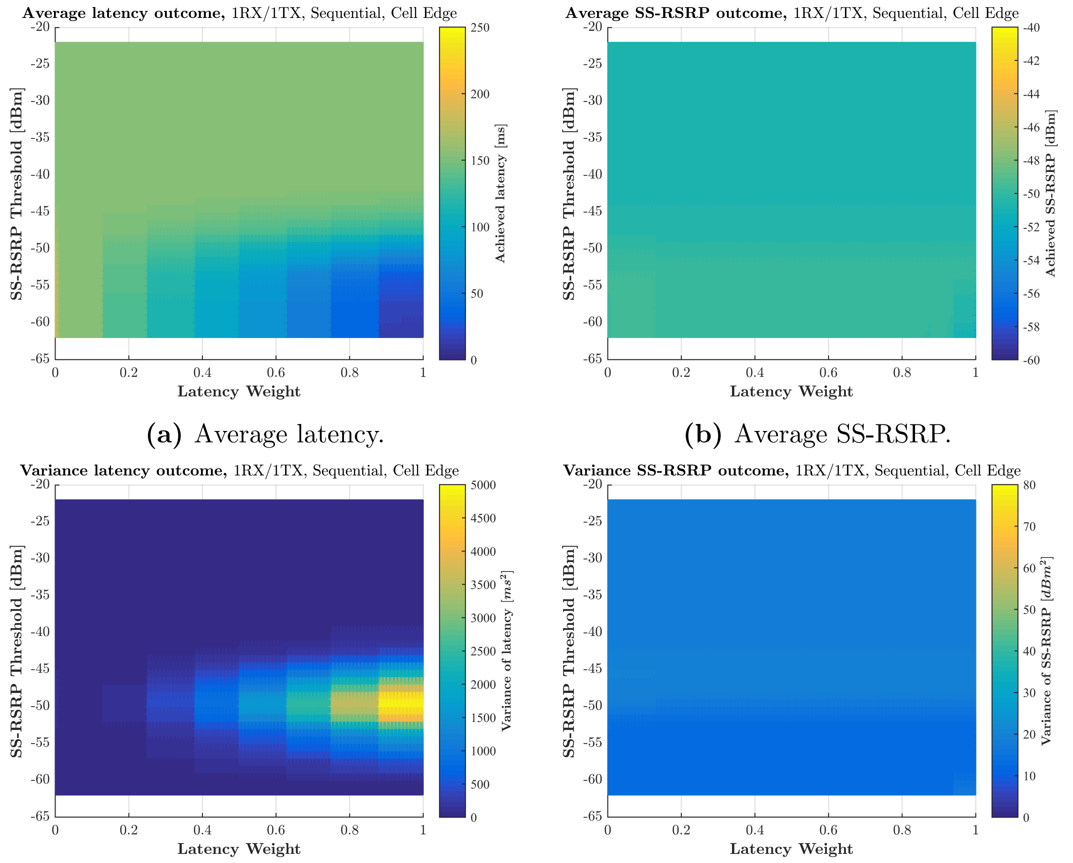
(d) Variance of SS-RSRP.

Fig. 8.5. Results for simulation set 1 SSB per RX beam, 1 SSB per TX beam, sequential sweeping order, Good Coverage scenario.

The plots illustrate the same quantities and axis configurations as for the analysis on low beam switching capabilities carried out in Section 8.2.1.

As expected, the behavior in terms of latency and power stays unchanged with respect to the behavior described in Section 8.2.1. However, the interval for average achieved latency approximately ranges now from 20 ms to 180 ms, as it can be seen in Figs. 8.5a - 8.8a. This interval contrasts with the range of average achieved latencies for switching capabilities 64RX/8TX, which ranged approximately from 50 ms to 230 ms. It basically indicates lower latencies for configurations closer to the corner cases of fast search and exhaustive search. It also implies, the lowest latencies the algorithm can achieve are in average approximately 10 ms higher than the lowest achievable latencies that any procedure could achieve for such environment.

From the average achieved SS-RSRP outcomes in Figs. 8.5b - 8.8b, the maximum achievable SS-RSRP is expected to remain the same, since the positional changes keep being the same with respect to the ones used for low beam switching capabilities. Nevertheless, the lower bound may change when configuring the algorithm with parameters close or corresponding to fast search. Sequential beam sweeping clearly benefited from



(a) Average latency. **(b)** Average SS-RSRP.

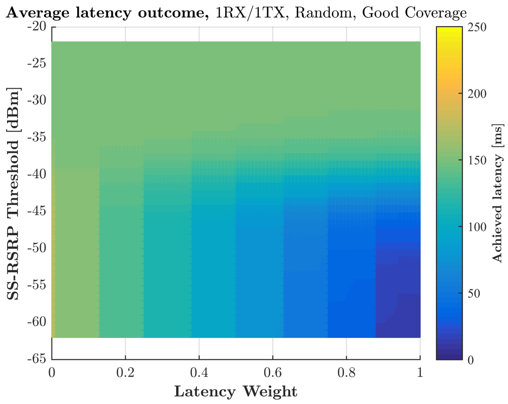
(c) Variance of latency. **(d)** Variance of SS-RSRP.

Fig. 8.6. Results for simulation set 1 SSB per RX beam, 1 SSB per TX beam, sequential sweeping order, Cell Edge scenario.

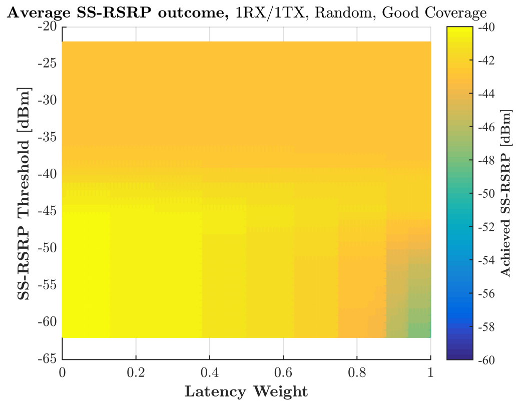
the improvement in beam switching capabilities, establishing a general lower bound of around -43 dBm and -50 dBm at Good Coverage and Cell Edge, respectively. For the corner case fast search, the absolute lower bound stays similar as for low beam switching capabilities. Random sweeping on the other hand, did not raise much its lower average achieved SS-RSRP bound when increasing beam switching capabilities. The lower bounds for average achieved SS-RSRP when applying random beam sweeping at high beam switching capabilities are around -48 dBm and -52 dBm at Good Coverage and Cell Edge, respectively. For SS-RSRP outcomes with sequential order (Figs. 8.5b and 8.6b), notice that the achieved SS-RSRP is relatively constant for almost all algorithm configurations when suitable beam pairs can be found. This is going to be discussed in Section 8.3.2.1, when beam switching capabilities are compared.

For sequential and random beam sweeping, the average SS-RSRP seems not to increase significantly for latency weights below 0.9 and 0.6 respectively – more priority on latency than on power –. As with low beam switching capabilities, at lower values of latency weight, increasing the search time does not have such a positive impact on the average achieved SS-RSRP as when doing so for higher values of latency weight.

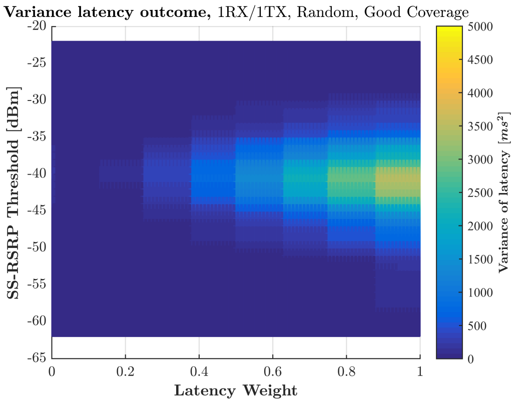
The transition zone between 'suitable beam pairs found' and 'no suitable beam pairs found', as with low beam switching capabilities, is smooth and has high variance. Therefore, their results are not going to be considered for further analysis. When no suitable beam pairs are found, the algorithm follows the statement **??** to establish connection through a beam pair. The achieved average latency and SS-RSRP values for high beam



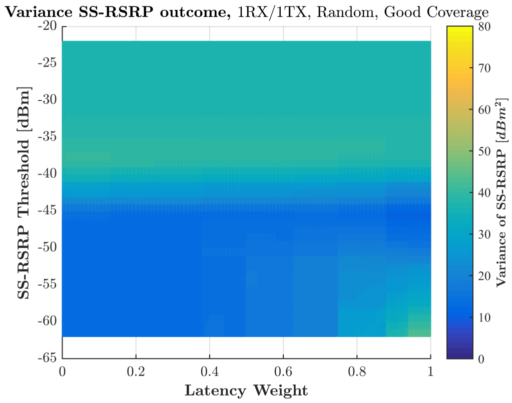
(a) Average latency.



(b) Average SS-RSRP.

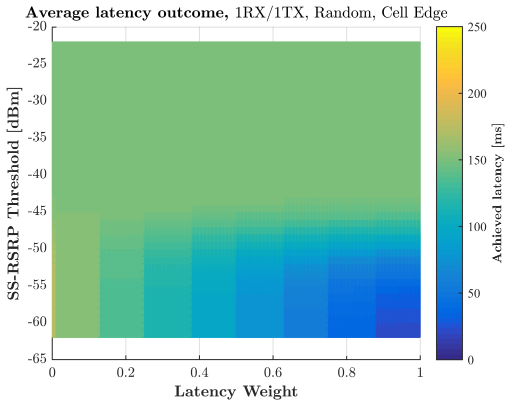


(c) Variance of latency.

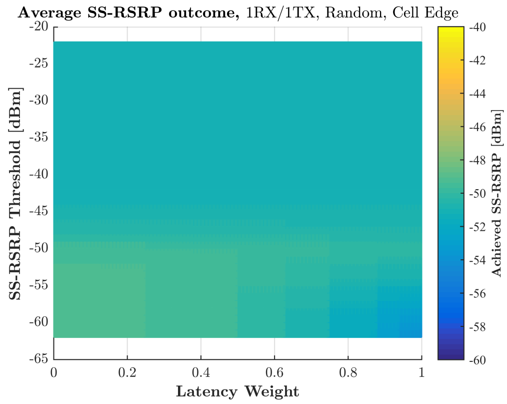


(d) Variance of SS-RSRP.

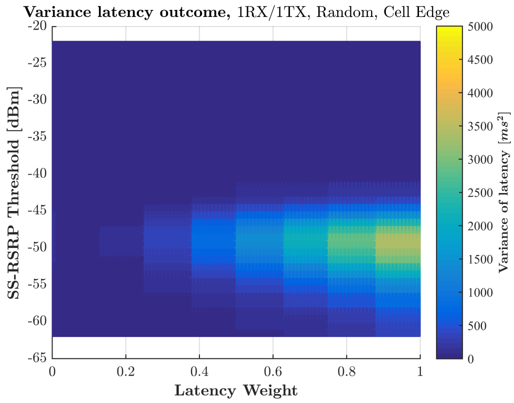
Fig. 8.7. Results for simulation set 1 SSB per RX beam, 1 SSB per TX beam, random sweeping order, Good Coverage scenario.



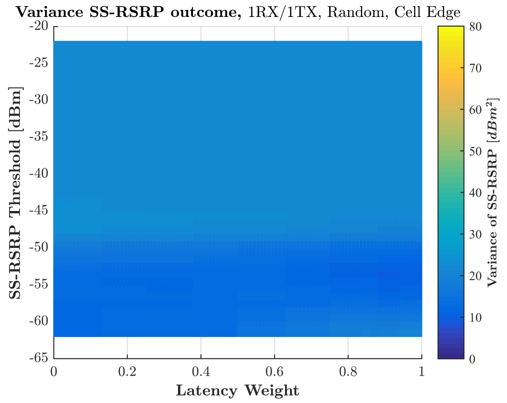
(a) Average latency.



(b) Average SS-RSRP.



(c) Variance of latency.



(d) Variance of SS-RSRP.

Fig. 8.8. Results for simulation set 1 SSB per RX beam, 1 SSB per TX beam, random sweeping order, Cell Edge scenario.

switching capabilities are collected in Table 8.2.

Table 8.2: Average results for no suitable beam pairs found, 1TX/1RX.

Use case	Order	Area	Latency [ms]	SS-RSRP [dBm]
1RX/1RX	Sequential	Good Coverage	153	-44.24
1RX/1RX	Sequential	Cell Edge	154	-50.83
1RX/1RX	Random	Good Coverage	150.7	-43.09
1RX/1RX	Random	Cell Edge	151.8	-51.19

8.3 Comparison Between Configurations

To analyze the performance difference between configurations, it is necessary to distinguish between outcomes when suitable beam pairs were found and when they were not found. The transition zone between those two cases, as stated in Sections 8.2.1 and 8.2.2, is going to be discarded for comparisons.

8.3.1 No suitable beam pairs found

For the case where no suitable beam pairs were found, the plotted regions showed constant results. The latency weight configuration does not affect the outcome and the SS-RSRP threshold configuration is too high to select suitable beam pairs. Therefore, all results can be organized in single values that represent the outcomes for all unsuitable configurations. Table 8.3 collects average outcomes when no suitable beam pairs are found due to the SS-RSRP threshold configuration.

Table 8.3: Average results for no suitable beam pairs found.

Use case	Order	Area	Latency [ms]	SS-RSRP [dBm]
64RX/8RX	Sequential	Good Coverage	174.4	-51.39
64RX/8RX	Sequential	Cell Edge	197.5	-54.45
64RX/8RX	Random	Good Coverage	167.5	-48.75
64RX/8RX	Random	Cell Edge	184.2	-53.1
1RX/1RX	Sequential	Good Coverage	153	-44.24
1RX/1RX	Sequential	Cell Edge	154	-50.83
1RX/1RX	Random	Good Coverage	150.7	-43.09
1RX/1RX	Random	Cell Edge	151.8	-51.19

From Table 8.3, it is clear that the algorithm's performance when no suitable beam pairs have been found completely improves in terms of average achieved latency and SS-RSRP when high beam switching capabilities – i.e. 1RX/1TX – are used, with respect to the performance for low beam switching capabilities – i.e. 64RX/8TX –. That holds for every sweeping order and every positional range. It is also worth noticing that the gains in both latency and SS-RSRP are bigger for Good Coverage range, compared to the Cell Edge range. For Good Coverage range, latency gains are around 38 ms and SS-RSRP gains around 6 dB, whereas latency and SS-RSRP gains are around 18 ms and 3 dB for Cell Edge range. This goes to show that the performance improvement when enhancing beam switching capabilities, under no suitable beam pairs found, decreases when the range between gNB and UE increases.

When establishing comparisons between sequential and random beam sweeping orders, there are no big differences in the results. Random beam sweeping performs slightly better, in terms of both latency and SS-RSRP, compared to sequential beam sweeping. This improvement decreases upon beam switching capabilities enhancement. Latency and SS-RSRP gains of around 9 ms and 3 dB are shown for low beam switching capabilities – i.e. 64RX/8TX –. For high beam switching capabilities – i.e. 1RX/1TX –, latency and SS-RSRP gains are around 3 ms and 0 dB.

8.3.2 Suitable beam pairs found

When suitable beam pairs are found, resulting outcomes depend on the configurations of latency weight and SS-RSRP threshold. As discussed in Section 8.2, there is a transition zone to 'no suitable beam pairs found' that is not reliable for analysis. It is necessary to exclude it from the comparison analysis carried out in this section.

According to Section 8.2, the achieved average SS-RSRP should remain constant for the corner case exhaustive search, i.e. when latency weight is equal to zero. This holds irrespective of the SS-RSRP threshold configuration, as long as the configuration does not render all beam pairs unsuitable. It then makes sense to restrict the reliable zone when beam pairs are found up to an SS-RSRP threshold configuration that guarantees the achieved average SS-RSRP remains relatively constant. A tolerance of 0.1 dB variation between the predicted achieved average SS-RSRP and the plotted achieved average SS-RSRP is taken as the measure rule to establish an upper boundary to the SS-RSRP threshold configuration. This boundary limits the analysis zone for comparison between results when suitable beams pairs are found. Since the positional ranges Good Coverage and Cell Edge show different extents for the zone where suitable beam pairs are found, the SS-RSRP threshold boundaries vary depending on the positional range. For Good Coverage range, the upper boundary was found to be -49 dBm. For the Cell Edge range, the upper boundary was found to be -55 dBm. The comparisons made in the following subsections will make use of these boundaries to delimit the analysis zone of the results presented in Section 8.2.

8.3.2.1 Comparison beam switching capabilities

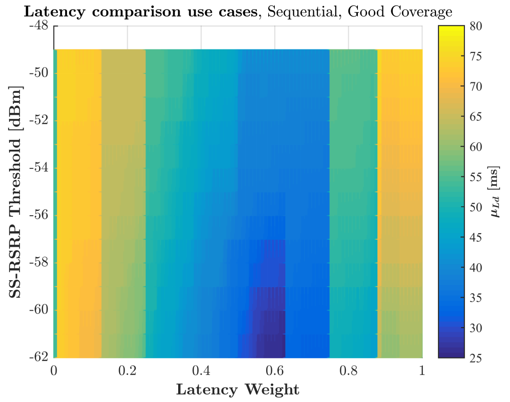
Figs. 8.9 - 8.12 show a comparison between low and high beam switching capabilities, according to Eqs. **??** and **??**. The x- and y-axis correspond to configurations of latency weight and SS-RSRP threshold, as they did when analyzing individual simulation results. The plotting range of the SS-RSRP threshold axis is limited to the upper boundaries considered for analysis when suitable beam pairs are found.

The baseline/reference results are those achieved by configurations with low beam switching capabilities, i.e. 64RX/8TX. The results under test are those achieved by high beam switching capabilities, i.e. 1RX/1TX. Therefore, the comparison metrics μ_{Ld} and μ_{SSd} should be interpreted as

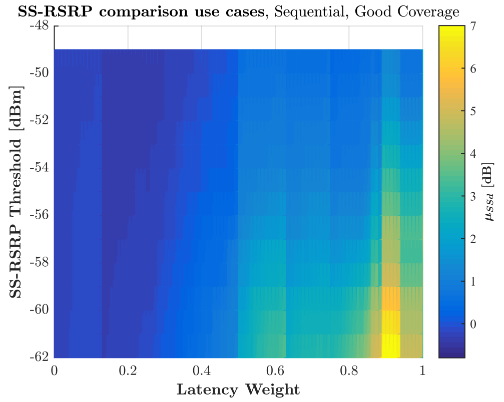
$$\mu_{Ld,switching} = \mu_{L,ideal,64RX/8TX} - \mu_{L,ideal,1RX/1TX},$$

$$\mu_{SSd,switching} = \mu_{SS,ideal,1RX/1TX} - \mu_{SS,ideal,64RX/8TX}.$$

Positive values in the metrics indicate that a configuration with high beam switching capabilities achieves better results than a configuration with low beam switching capabilities in terms of either latency (in ms) or SS-RSRP (in dBm). Negative values indicate that the configuration with low beam switching capabilities achieves better results than a configuration with high beam switching capabilities in terms of either latency (in ms) or SS-RSRP (in dBm).

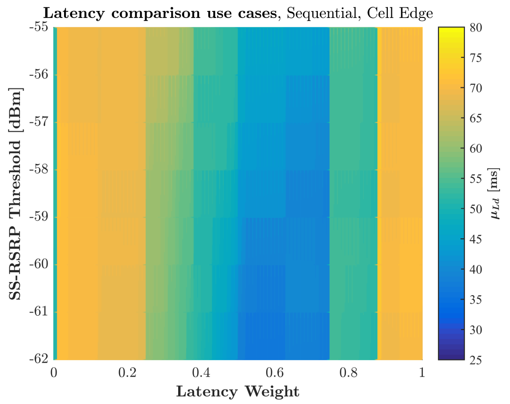


(a) Latency comparison.

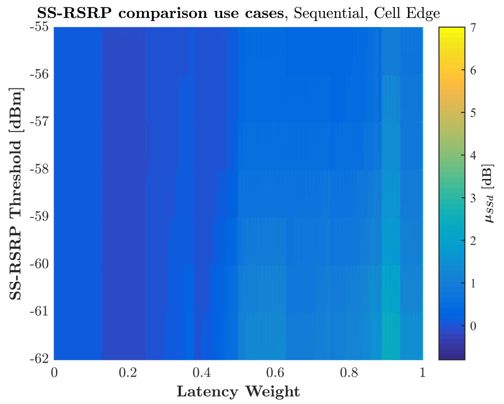


(b) SS-RSRP comparison.

Fig. 8.9. Comparison of use cases, sequential order, Good Coverage scenario.



(a) Latency comparison.

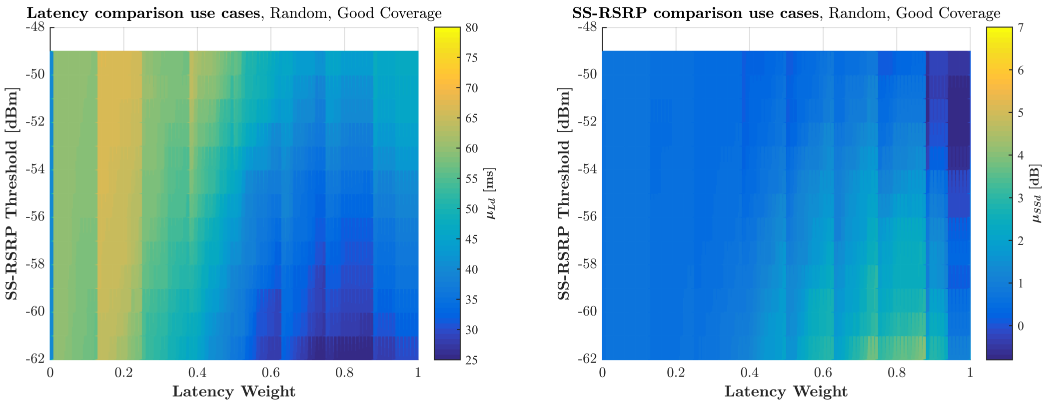


(b) SS-RSRP comparison.

Fig. 8.10. Comparison of use cases, sequential order, Cell Edge scenario.

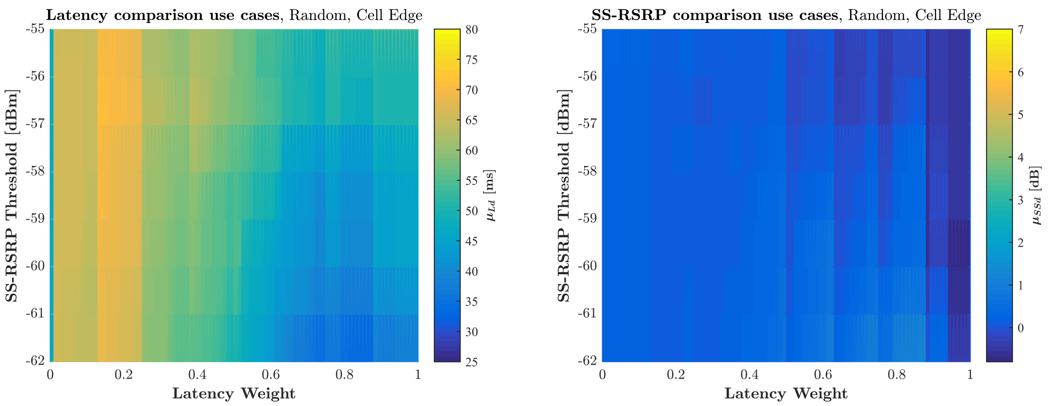
Focusing first on latency comparisons (Figs. 8.9a - 8.12a), the improvement is evident when moving from low to high beam switching capabilities. The minimum improvement in terms of latency, irrespective of sweeping order or positional range, is 25 ms. In other words, increasing beam switching capabilities to 1RX/1TX guarantees the achieved latency of the IA algorithm to be at least 25 ms lower than the achieved latency when using 64RX/8TX as beam switching capabilities. Moreover, the gains in terms of latency can increase up to 80 ms for latency weight configurations close to corner case configurations, i.e. close to 0 or 1.

Let us take a look at the parameters configuration described in Chapter 7, and additionally into the PRACH occasion configuration given by the index 194, as seen in Fig. **??**. The number of SSB per RACH occasion is 2, and there are 2 PRACH occasions in every PRACH slot that comes every 10 ms. Then, 4 SSBs can be associated per PRACH slot and 8 SSBs can be associated in a time interval of 20 ms. The SSBs may be transmitted over different DL TX beams and received over different DL RX beams depending on the switching capabilities of gNB and UE. The number of DL TX and DL RX beams is equal to 8. The PRACH request to be sent to the gNB informs about the chosen DL TX beam only. When the beam switching capabilities are 1RX/1TX, the gNB sends every next SSB within an SS burst over a different DL TX beam. For



(a) Latency comparison. **(b)** SS-RSRP comparison.

Fig. 8.11. Comparison of use cases, random order, Good Coverage scenario.



(a) Latency comparison. **(b)** SS-RSRP comparison.

Fig. 8.12. Comparison of use cases, random order, Cell Edge scenario.

the PRACH occasion mapping, this means the UE has the possibility to inform about 4 different DL TX beams every 10 ms, and the possibility to inform about all 8 different DL TX beams after 20 ms. When the beam switching capabilities are 64RX/8TX, the gNB sends every group of 8 SSBs within an SS burst over a different DL TX beam. For the PRACH occasion mapping, this means the UE has the possibility to inform about 1 DL TX beams every 20 ms, and the possibility to inform about all 8 different DL TX beams after 160 ms. The UE has the possibility to inform the gNB about a wider variety of DL TX beams in a significantly shorter amount of time for high beam switching capabilities. Irrespective of the algorithm's configuration for latency weight and SS-RSRP threshold, the selected beam pair is likely to be associated to a PRACH occasion taking place faster for high beam switching capabilities. It is then expected that the results in terms of latency are better for high beam switching capabilities.

Regarding SS-RSRP performance, the comparison can be grouped into positional ranges. For the good coverage range (Figs. 8.9a and 8.11a), there is a generalized slight SS-RSRP increase of 1 dB for high beam switching capabilities compared to low beam switching capabilities. Also, there is a bigger increase in the achieved SS-RSRP, ranging from 2 dB to 7 dB, for latency weight configurations higher than 0.5, i.e. latency prioritized over power. This can be explained once again from the parameter configurations and the PRACH occasion mapping scheme. As previously mentioned, the UE can inform the gNB faster about a wider variety of DL TX beams for high beam switching capabilities. A wider variety of DL TX beams also implies that, for high latency weights, there is more likelihood of selecting a PRACH occasion associated to a beam pair with higher SS-RSRP.

For the cell edge range (Figs. 8.10a and 8.12a), there is a generalized SS-RSRP increase of 1 dB for high beam switching capabilities compared to low beam switching capabilities. For this positional range however, the achieved SS-RSRP for high beam switching capabilities tends to be similar to that of low beam switching capabilities.

Wrapping up on the comparison between beam switching capabilities, the average latency results given out by the algorithm were found to be faster for high beam switching capabilities, whereas the average SS-RSRP results were found to be similar or slightly higher with respect to low beam switching capabilities. This ultimately indicates that higher beam switching capabilities enhance the performance of the Initial Access stage, and should be clearly considered when designing a real-time implementation. The performance enhancement also decreases when the range between gNB and UE increases, as it happened when no suitable beam pairs were found (Section 8.3.1).

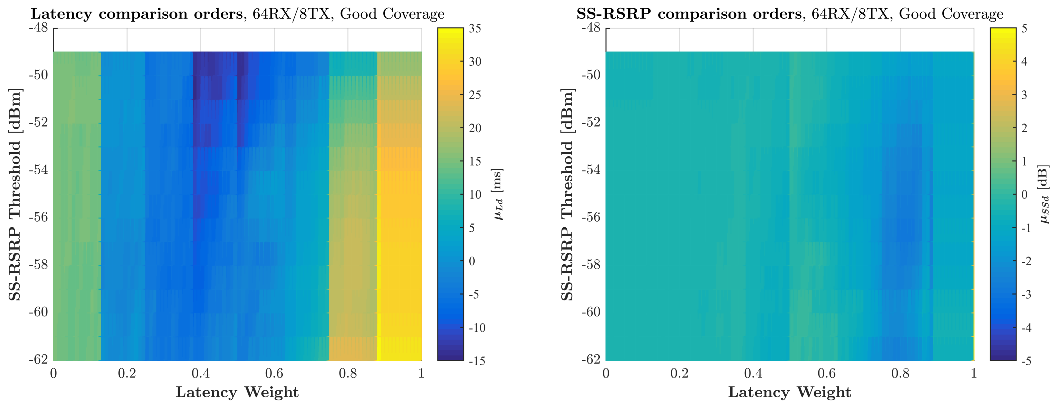
8.3.2.2 Comparison beam sweeping orders

Figs. 8.13 - 8.15 show a comparison between sequential and random beam sweeping orders, according to Eqs. **??** and **??**. The baseline/reference results are those achieved by configurations with sequential beam sweeping. The results under test are those achieved by random beam sweeping. Therefore, the comparison metrics μ_{Ld} and μ_{SSd} should be interpreted as

$$\mu_{Ld,orders} = \mu_{L,ideal,sequential} - \mu_{L,ideal,random},$$

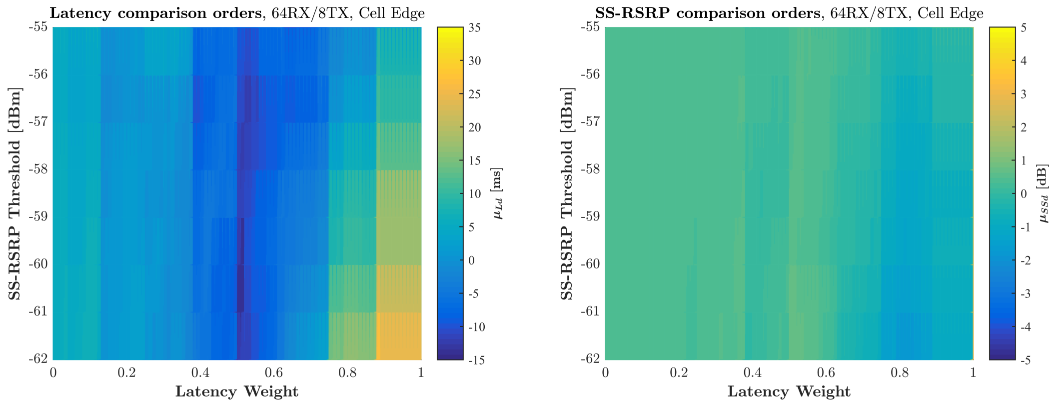
$$\mu_{SSd,orders} = \mu_{SS,ideal,random} - \mu_{SS,ideal,sequential}.$$

Positive values in the metrics indicate that a configuration with random beam sweeping achieves better results than a configuration with sequential beam sweeping in terms of either latency (in ms) or SS-RSRP (in dBm). Negative values indicate that the configuration with sequential beam sweeping achieves better results than a configuration with random beam sweeping in terms of either latency (in ms) or SS-RSRP (in dBm).



(a) Latency comparison. **(b)** SS-RSRP comparison.

Fig. 8.13. Comparison of sweeping orders, 64 SSB per RX beam, 8 SSB per TX beam, Good Coverage scenario.



(a) Latency comparison. **(b)** SS-RSRP comparison.

Fig. 8.14. Comparison of sweeping orders, 64 SSB per RX beam, 8 SSB per TX beam, Cell Edge scenario.

When comparing sequential and random sweeping orders for high beam switching capabilities, the behaviors for Good Coverage (Fig. 8.13) and Cell Edge (Fig. 8.14) follow the same patterns. However differences are less accentuated for the Cell Edge range, since the variation in the received power for each successfully received SSB is not as high as for the Good Coverage range.

For latency weight values close to 1, random beam sweeping clearly achieves a PRACH request in less time while maintaining the SS-RSRP comparable to that of sequential beam sweeping. For Good Coverage range, the latency gains for random sweeping are as high as 35 ms, whereas the SS-RSRP losses get as high as 2 dB. For Cell Edge range, the latency gains get as high as 25 ms, whereas the SS-RSRP losses get as high as 1 dB.

For latency weight values close to 0, random beam sweeping also achieves a PRACH request in less time while maintaining the SS-RSRP comparable to that of sequential beam sweeping or even slightly increasing it. For Good Coverage range, the latency gains for random sweeping are as high as 15 ms, whereas the SS-RSRP gains get as high as 0.5 dB. For Cell Edge range, the latency gains get as high as 8 ms, whereas the SS-RSRP gains get as high as 0.5 dB.

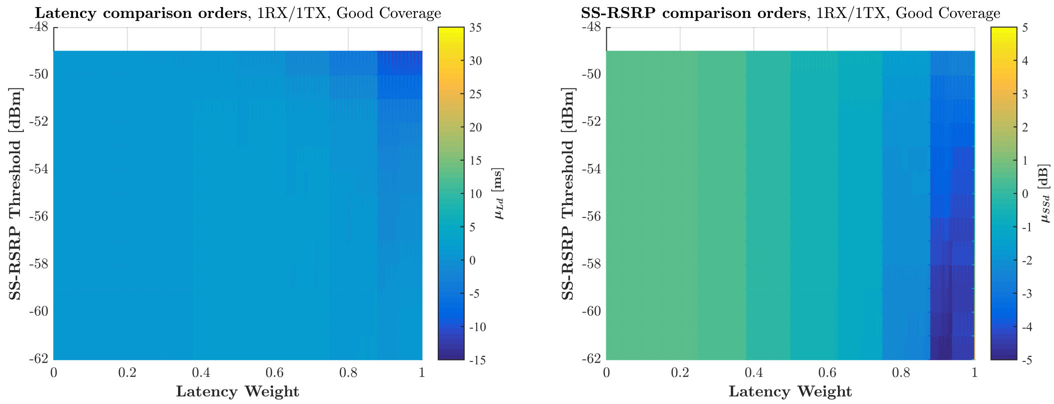
For latency weight values close to 0.5, random sweeping shows comparable latencies or losses with respect to sequential sweeping, whereas SS-RSRP gains slightly increase. For Good Coverage range, latency losses for random sweeping vary around 5 ms, whereas SS-RSRP gains are just above 0.5 dB. For Cell Edge range, latency losses for random sweeping vary around 10 ms, whereas SS-RSRP gains are around 1 dB.

There is no clear impact of the SS-RSRP threshold configuration on the comparison between sweeping orders when suitable beam pairs are found. Its effect varies depending on the configuration of latency weight for every comparison.

For low beam switching capabilities, performances of sequential and random sweeping are comparable except for latency weight configurations very close to 1 and SS-RSRP threshold configurations closer to the highest measured SS-RSRPs. Comparison plots in Good Coverage and Cell Edge range are shown in Figs. 8.15 and 8.16, respectively.

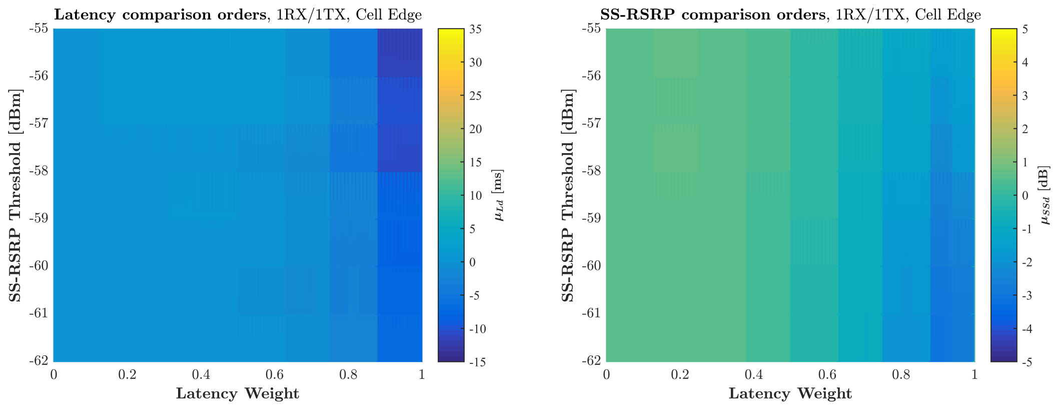
In terms of latency, both sequential and random sweeping achieve the same latencies in their PRACH requests for latency weight configurations up to 0.8. For higher latency weight values, random sweeping presents losses of around 2.5 ms and 5 ms compared to sequential order, for Good Coverage and Cell Edge ranges respectively.

In terms of SS-RSRP, random sweeping show gains of almost 1 dB for latency weight



(a) Latency comparison. **(b)** SS-RSRP comparison.

Fig. 8.15. Comparison of sweeping orders, 1 SSB per RX beam, 1 SSB per TX beam, Good Coverage scenario.



(a) Latency comparison. **(b)** SS-RSRP comparison.

Fig. 8.16. Comparison of sweeping orders, 1 SSB per RX beam, 1 SSB per TX beam, Cell Edge scenario.

configurations up to 0.5. Higher latency weight configurations decrease the gains and generate losses as their value comes closer to 1. The maximum losses of random sweeping compared to sequential sweeping are around 5 dB for Good Coverage range and 2.5 dB for Cell Edge range.

The SS-RSRP threshold configuration has a clear impact on the comparison for latency weight configurations close to 1. When the SS-RSRP threshold increases, the latency losses increase, whereas the SS-RSRP losses considerably decrease.

Chapter 9

Conclusions

The 3rd Generation Partnership Project (3GPP), as it has done since the development of 2G networks, keeps unifying research efforts towards higher-quality communications. 5G is the cellular worldwide technology being currently developed by organizations taking part at 3GPP. 5G New Radio (NR) is the first cellular standard covering millimeter-wave (mmWave) frequencies. mmWave transmissions suffer from stronger propagation losses that render communication challenging at higher frequencies. Highly directional transmissions over multiple transmit (TX) and receive (RX) antennas – i.e. beamforming – are essential to compensate for those losses. The present thesis addressed the guidelines on beamforming for 5G NR, investigated, delivered, assessed and evaluated an implementation proposal for one of the procedures leveraging beamforming.

In a first part, 3GPP specifications regarding multi-antenna communications at Physical, Medium Access Control (MAC) and Radio Resource Control (RRC) layers were analyzed. An interpretation of the procedures by which beamformed connectivity is established and retained, known as Beam Management (BM) procedures, was compiled according to the 3GPP specifications in their Release 15 (Rel-15). Release 15 corresponds to the standards enabling the first phase of 5G deployment. The present interpretation offers the reader a clear understanding collected from multiple specification documents. This work assembles all necessary pieces to get a compact explanation of Beam Management that gives thorough references to find further implementation-oriented details and state-of-the-art research initiatives.

Initial Beam Establishment (IBE) is embedded into the procedures necessary to carry out Public Land Mobile Network (PLMN) selection, cell selection, Initial Access (IA) and Radio Resource Control (RRC) connection establishment. Beam sweeping is jointly carried out at gNB and UE to discover suitable beam pairs that allow to establish connection. Synchronization Signal/PBCH (SS/PBCH) blocks, also known as Synchronization Signal Blocks (SSBs) are the signals used to synchronize and source of measurements and beam identification. After selecting certain PLMN, cell and beam pair, the UE sends to the gNB a request known as Physical Random Access Channel (PRACH) request as part of the Random Access (RA) procedure used in the context of IA. There, it informs about the Downlink (DL) transmit (TX) beam the gNB has to use to establish connection with the UE. When the request is successful, additional information exchange fundamental to ensure connectivity comes at RRC connection establishment. This information exchange may contain parameters that configure the other two BM procedures used later.

Beam Adjustment (BA) is the BM procedure used after IBE to adjust the beam pair over which gNB and UE are communicating. BA updates the communication beam pair together with Beam Indication, a procedure through which the gNB is able to tell the UE which DL TX beam or UL receive (RX) beam it is going to use. Then, the UE can use a respective DL RX beam or UL TX beam that guarantees connectivity. BA carries out beam sweeping at gNB and UE separately, so that one beam of the beam pair is adjusted upon movements or blockage. Beam sweeping does not necessarily cover all directions, but the relevant ones the gNB selects by associating beams to reference signal resources. SSBs and Channel State Information Reference Signals (CSI-RSs) are used for adjusting Downlink (DL) communication. Sounding Reference Signals are used for adjusting Uplink (UL) communication.

Link Recovery (LR) is a group of two procedures, namely Beam Failure Detection (BFD) and Beam Failure Recovery (BFR). They shall be able to tell when the beamformed connection has been deteriorated and could not be improved by BA. Similar to IBE in its IA stage, beam sweeping at gNB and UE, and RA, shall be carried out to recover from beam failure. Signals used for LR are SSBs and CSI-RSs. There may be pre-configured dedicated resources that enhance recovery. When LR cannot reestablish connection, Radio Link Failure (RLF) is declared.

A second part analyzed the guidelines given by 3GPP Rel-15 regarding IA even further, and presented a standards-compliant implementation proposal that follows them. An algorithm to perform beam pair selection in the IA stage of IBE was conceived. The algorithm unifies and extends the flexibility of the current approaches used for performing IA in public research, namely exhaustive and fast search. It does so by realizing a framework of priorities given to power and time, where full priority to power and time corresponds to exhaustive and fast search, respectively. The priorities for power and time can and should be configured according to the needs in terms of connectivity requirements of each application. The beam pair selection algorithm considers the time-domain arrangement of opportunities the UE has to transmit the PRACH request to the gNB about the DL TX beam selected. These opportunities are named PRACH occasions, are configurable by the gNB and not all of them are allowed to inform about a certain DL TX beam. Additionally, behavior definition upon no suitable beam pairs being found is included into the algorithm. Description or mention of this case was not found by the author in public research results. A proposal containing all previously mentioned features into a single algorithm is novel and 3GPP-compliant. The algorithm is to be implemented at the UE side, whereas the entire IA scheme proposal includes features for gNB beam sweeping as well.

A third part evaluated the implementation proposal upon different configurations and conditions. A testing environment for the IA scheme proposal was established and developed in MATLAB during the work towards this thesis. It consists in stochastic simulation of the radio channel and the behavior of the proposed algorithm upon reception of SSB-based measurements, referred to as SS-RSRP measurements. The model of the algorithm was configured with latency priorities going from lowest (zero) to highest (one) and power level thresholds going from accepting every successfully received beam pair to rejecting all of them. The latency from the start of the first radio frame sent by the gNB up to the time instance when the UE sends a PRACH request to the gNB, and the power that will be achieved by that connection, were selected as Key Performance Indicators (KPIs).

Different beam switching capabilities, beam sweeping orders and positional ranges were tested for a gNB transmitting over 8 DL TX beams and a UE receiving over 8 DL RX beams.

From the individual results obtained for each simulation set tested, it can be concluded that carrying exhaustive search is not time-optimal when the gNB transmits over 8 TX beams and the UE receives over 8 RX beams. Comparable connection power levels can be achieved by setting lower priority to power. This reduces the amount of beam pair combinations tried out. However, not all beam pair combinations need to be evaluated before finding one with power levels comparable to the highest. This reduces the PRACH request delay without sacrificing link quality.

While analyzing the previous statement and comparing against publicly available research, no in-context analysis was found to be carried out for link quality in the literature. Misdetection probability measurements are determining if a connection is good according to literature, meaning that a connection is bad if it is not a connection with the highest power. However, they cannot tell if the achieved connection provides with power levels close or far to the highest. Therefore, putting into context the achieved connection power levels is recommended for future research.

When working at limited coverage or cell edge, the algorithm tends to perform closer to exhaustive search, since a significant amount of SSBs are not correctly received, and thus ignored.

Enhancement of the beam switching capabilities significantly increases the performance for all possible configurations of power level threshold and latency priority, when suitable beam pairs were either found or not found. When suitable beam pairs were found, it follows that this enhancement allows to achieve power levels comparable to the highest with higher latency priorities. It then reduces the time necessary for the UE to send a PRACH request to the gNB. The performance improvement however, decreases slowly when the range between gNB and UE increases, i.e. gNB and UE get further apart from each other. Summing up, fast-search-like algorithm configurations may be recommended over exhaustive-search-like algorithm configurations depending on available antenna codebooks and system capabilities.

Future efforts include simulation upon different configurations of Time Division Duplexing (TDD) schemes, RA configurations, antenna codebooks, beam switching capabilities, radio channel scenarios and sweeping schemes that optimize search for SSBs with high power levels. Apart from simulations, a bigger effort comes with real-time implementation of the work delivered in this thesis. From the memory and complexity point of view, the solution is expected not to cause impeding issues.

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Acknowledgements

Primero que todo, quisiera agradecer especialmente a mis padres y a mi tía Ana por todo el apoyo que me han brindado desde siempre. Me siento increíblemente afortunado de tenerlos a mi lado, cada momento compartido es un regalo de Dios que no cambiaría por nada en este mundo. Gracias por orientarme y aguantarme jajaja. Extiendo las gracias a toda mi familia siempre tan afectuosa y única, que define absolutamente todo lo que puedo llamar hogar. Aunque generalmente no escuchan esto de mí, quiero hacerles saber que los quiero con todo mi corazón, que ustedes son mi motor, lo más grande que tengo en la vida y que por ustedes soy capaz de hacer lo inimaginable. Ustedes me han traído hasta donde estoy ahora y por ustedes seguiré luchando en esta vida. Se me alargaría mucho esta sección agradeciéndoles, imagínense mejor todos estos capítulos diciendo "los quiero mucho".

También quisiera agradecer a mis amigos que me han acompañado a lo largo del camino. Ratón, Osendo, Evo, jajaja sé que siempre podré contar con ustedes aunque la distancia nos separe. Me alegra saber que aún después de todo este tiempo, todo siga siendo como antes. Marcio, Melo, Carlos, Cami, Chucho, David, gracias por haberse convertido en mi segunda familia, siempre pienso en ustedes. Ustedes me han demostrado que la amistad significa lealtad, confianza, comprensión, autenticidad, perdón y mucho más. Todo lo que hemos pasado juntos son momentos que no voy a olvidar. Hernán, sé que más rápido encuentro trabajo antes que llegues a leer esto, también te quería dar las gracias por recibirnos y ayudarnos cuando recién llegamos a Turín. Kedar, I am glad to have met such a pure and peaceful person, thanks for being there this whole time bro.

Herzlichen Dank zu Achim. Deine Beratung hat nicht nur meine Masterarbeit, sondern auch mein Leben beeinflusst. Diese 9 Monaten unter deiner Betreuung waren unter der produktivsten in meiner Karriere. Ich bin echt dankbar, viel mehr als einen Betreuer gefunden zu haben. Grazie mille al mio tutore Roberto per essere sempre disposto ad aiutare da Torino con lo sviluppo della tesi di laurea e per la sua preoccupazione per il mio benessere all'estero. Il suo eroico sforzo supportando i miei obiettivi è stato notabile.

To everybody else that has been so special in my life, sorry for my bad memory. Thanks to you all too.