



جامعة الإسكندرية
ALEXANDRIA
UNIVERSITY

ALEXANDRIA UNIVERSITY
FACULTY OF ENGINEERING
Department of Communication & Electronics Engineering

5G PDSCH Simulator and DRL Approach For Designing The Optimal Precoder Vector and Power Allocation in MU-MIMO

By

**Ahmed Hany
Ahmed Al-Alwani
Abulrahman Muhammad Itman
Muhammad Emad
Momen Ashraf
Khalid Diab
Muhammad Abu-Elmagd
Muhammad Nagy**

Supervised By

Dr. Muhammad Karmoose

A Graduation Project submitted to the Department of Communication & Electronics in partial fulfillment of the requirements for the degree of B.Sc. in Communication Engineering.

Alexandria
July 2023

Contents

1	Overview	2
1.1	The mobile industry in numbers	2
1.1.1	5G in the mobile market	2
1.2	The next generation – 5G NR	3
1.2.1	5G Use Cases	3
1.2.2	Waveform, Numerology, and Frame Structure	3
1.3	5G Data Channels: Logical, Transport & Physical	4
1.3.1	5G NR logical channels	6
1.3.2	5G NR transport channels	6
1.3.3	5G NR physical channels	7
I	5G PDSCH Simulator	10
2	Channel Coding	12
2.1	Linear Coding	12
2.2	LDPC Coding	12
3	MIMO Setup	13
3.1	SISO	13
3.2	SIMO	13
3.3	MISO	13
3.4	MIMO	13
3.4.1	Diversity	13
3.4.2	Multiplexing	13
4	Reference Signals	14

<i>CONTENTS</i>	II
4.1 Overview	14
4.2 DMRS	15
4.2.1 Pilot based DMRS channel estimation	16
4.3 CSI Reference Signal	17
4.4 Channel Estimation	17
5 Simulations	19
II Deep Reinforcement Learning Model	20

List of Figures

1.1	4G vs 5G connections	2
1.2	5G Use cases classification	4
1.3	5G Frame structure	5
1.4	5G Downlink logical, transport and physical channel mapping	9
1.5	5G Uplink logical, transport and physical channel mapping	9
4.1	DMRS Mapping type A & type B	15
4.2	Single Tx Single Rx	16
4.3	Pilot signals in some REs	16
4.4	Correlation in time & frequency	17
4.5	Delay spread effect	17
4.6	Doppler spread effect	18

Chapter 1

Overview

1.1 The mobile industry in numbers

Mobile penetration is approaching saturation in most markets around the world, especially among adult and urban populations. In every region, the majority of new subscribers will be young consumers and rural dwellers. Despite increasing saturation in developed regions, there is still room for growth in many large, underpenetrated markets in developing regions. For example, India and Sub-Saharan Africa will account for around half of new mobile subscribers globally over the 2022–2030 period “Globally, there were 4.4 billion mobile internet users in 2022, equivalent to 55% of the world population. The mobile internet usage gap has narrowed markedly in the last five years – from 50% in 2017 to 41% in 2022 on average – as more people around the world rely on the internet for many daily activities, especially in the wake of the Covid-19 pandemic.

1.1.1 5G in the mobile market

“5G will overtake 4G in 2029 to become the dominant mobile technology by the end of this decade” 5G adoption continues to rise due to new network deployments and cheaper devices. As of January 2023, there were 229 commercial 5G networks around the world and over 700 5G smartphone models had been launched, including more than 200 in 2022. The number of connections on legacy networks (2G and 3G) will continue to decline in the coming years as users migrate to 4G and 5G, resulting in more network shutdowns. To date, operators have announced plans to shut down 96 2G networks and 107 3G networks around the world.

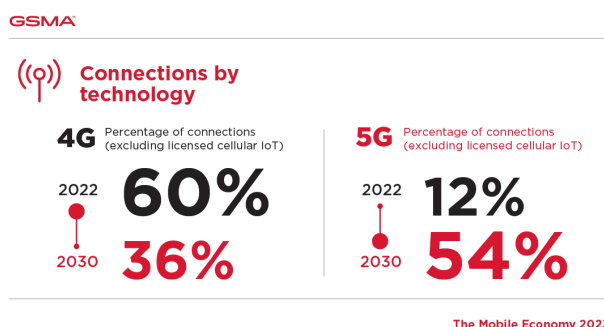


Figure 1.1: 4G vs 5G connections

1.2 The next generation – 5G NR

Despite LTE being a very capable technology, there are requirements not possible to meet with LTE or its evolution. Furthermore, technology development over the more than 10 years that have passed since the work on LTE was initiated allows for more advanced technical solutions. To meet these requirements and to exploit the potential of new technologies, 3GPP initiated the development of a new radio access technology known as NR (New Radio). A workshop setting the scope was held in the fall of 2015 and technical work began in the spring of 2016. The first version of the NR specifications was available by the end of 2017 to meet commercial requirements on early 5G deployments already in 2018. NR reuses many of the structures and features of LTE. However, being a new radio-access technology means that NR, unlike the LTE evolution, is not restricted by a need to retain backwards compatibility. The requirements on NR are also broader than what was the case for LTE, motivating a partly different set of technical solutions.

1.2.1 5G Use Cases

In the context of 5G, one is often talking about three distinctive classes of use cases: enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low-latency communication (URLLC)

- eMBB corresponds to a more or less straight forward evolution of the mobile broadband services of today, enabling even larger data volumes and further enhanced user experience, for example, by supporting even higher end-user data rates.
- mMTC corresponds to services that are characterized by a massive number of devices, for example, remote sensors, actuators, and monitoring of various equipment. Key requirements for such services include very low device cost and very low device energy consumption, allowing for very long device battery life of up to at least several years. Typically, each device consumes and generates only a relatively small amount of data, that is, support for high data rates is of less importance.
- URLLC type-of-services are envisioned to require very low latency and extremely high reliability. Examples hereof are traffic safety, automatic control, and factory automation.

It is important to understand that the classification of 5G use cases into these three distinctive classes is somewhat artificial, primarily aiming to simplify the definition of requirements for the technology specification. There will be many use cases that do not fit exactly into one of these classes. Just as an example, there may be services that require very high reliability but for which the latency requirements are not that critical. Similarly, there may be use cases requiring devices of very low cost but where the possibility for very long device battery life may be less important.

1.2.2 Waveform, Numerology, and Frame Structure

The choice of radio waveform is the core physical layer decision for any wireless access technology. After assessments of all the waveform proposals, 3GPP agreed to adopt orthogonal frequency division multiplexing (OFDM) with a cyclic-prefix (CP) for both DL and UL

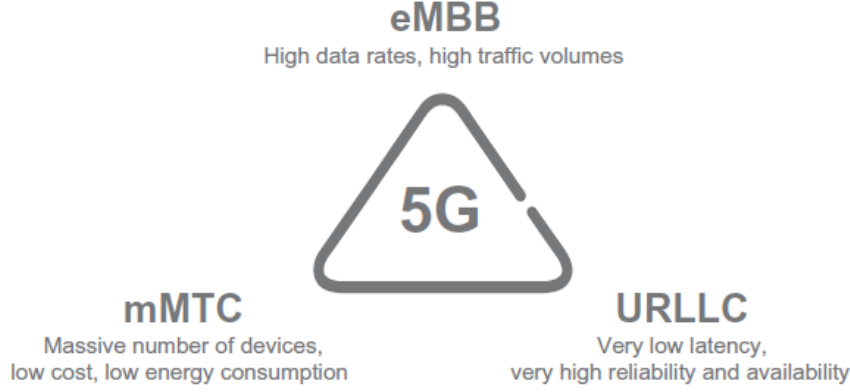


Figure 1.2: 5G Use cases classification

transmissions. CP-OFDM can enable low implementation complexity and low cost for wide bandwidth operations and multiple-input multiple-output (MIMO) technologies. NR supports operation in the spectrum ranging from sub-1 GHz to millimeter wave bands. Two frequency ranges (FR) are defined in Release 15:

- FR1: 450 MHz – 6 GHz, commonly referred to as sub-6 GHz.
- FR2: 24.25 GHz – 52.6 GHz, commonly referred to as millimeter wave.

Scalable numerologies are key to support NR deployment in such a wide range of spectrum. NR adopts flexible sub-carrier spacing of $2^\alpha \times 15$ kHz ($\alpha = 0, 1, \dots, 4$) scaled from the basic 15 kHz sub-carrier spacing in LTE. Accordingly, the CP is scaled down by a factor of 2^α from the LTE CP length of $4.7 \mu\text{s}$. This scalable design allows support for a wide range of deployment scenarios and carrier frequencies. At lower frequencies, below 6 GHz, cells can be larger and sub-carrier spacings of 15 kHz and 30 kHz are suitable. At higher frequencies, cells and delay spread are typically smaller and the CP lengths provided by the 60 and 120 kHz numerologies are sufficient.

A frame has a duration of 10ms and consists of 10 subframes. This is the same as in LTE, facilitating NR and LTE coexistence. Each subframe consists of 2^α slots of 14 OFDM symbols each. Although a slot is a typical unit for transmission upon which scheduling operates, NR enables transmission to start at any OFDM symbol and last only as many symbols as needed for the communication. This type of “mini-slot” transmission can thus facilitate very low latency for critical data as well as minimize interference to other links per the lean carrier design principle that aims at minimizing transmissions. Latency optimization has been an important consideration in NR. Many other tools besides “mini-slot” transmission have been introduced in NR to reduce latency.

1.3 5G Data Channels: Logical, Transport & Physical

In order to be able to carry the data across the 5G radio access network, the data and information is organized into a number of data channels. By organizing the data into various channels the 5G communications system is able to manage the data transfers in an orderly fashion and the system is able to understand what data is arriving and hence it is able to process it in the

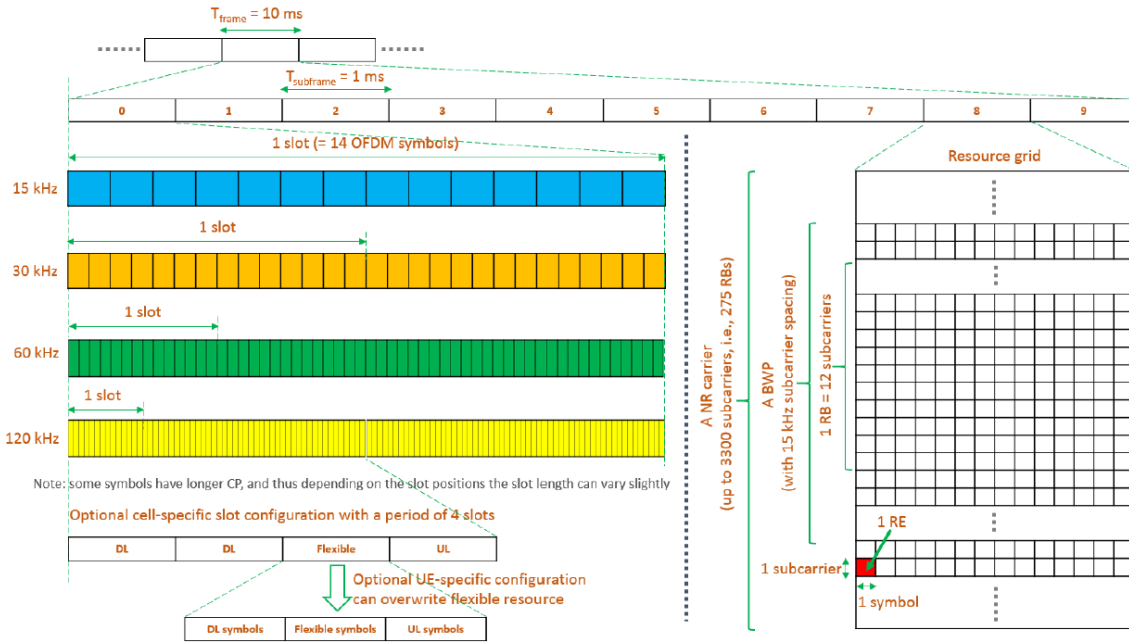


Figure 1.3: 5G Frame structure

required fashion. As there are many different types of data that need to be transferred - user data obviously needs to be transferred, but so does control information to manage the radio communications link, as well as data to provide synchronization, access and the like. All of these functions are essential and require the transfer of data over the radio access network. The 5G mobile or wireless communications system uses a similar access stratum to that used by 4G LTE. Although there are two protocol stacks: user plane and control plane, they still adopt the familiar OSI reference model. As a result there are various protocol layers and accordingly there are several data channel layers that are defined for the radio communications. In order to group the data to be sent over the 5G NR radio access network, the data is organised in a very logical way. As there are many different functions for the data being sent over the radio communications link, they need to be clearly marked and have defined positions and formats. To ensure this happens, there are several different forms of data "channel" that are used. The higher level ones are "mapped" or contained within others until finally at the physical level, the channel contains data from higher level channels. In this way there is a logical and manageable flow of data from the higher levels of the protocol stack down to the physical layer. There are three main types of data channels that are used within mobile communications systems. This is true for 5G systems, and accordingly the hierarchy is given below.

- Logical channel: Logical channels can be one of two groups: control channels and traffic channels:
 - Control channels: The control channels are used for the transfer of data from the control plane
 - Traffic channels: The traffic logical channels are used for the transfer of user plane data.
- Transport channel: Is the multiplexing of the logical data to be transported by the physical layer and its channels over the radio interface.
- Physical channel : The physical channels are those which are closest to the actual transmission of the data over the radio access network / 5G RF signal. They are used to

carry the data over the radio interface.

The physical channels often have higher level channels mapped onto them to provide a specific service. Additionally, the physical channels carry payload data or details of specific data transmission characteristics like modulation, reference signal multiplexing, transmit power, RF resources, etc.

1.3.1 5G NR logical channels

There are several different logical channels that are used within the 5G NR radio access network. Some of them will be familiar names from the 4G LTE system as the names have been carried over.

- **Broadcast Control Channel (BCCH):** The BCCH is used within the downlink, and it is used for sending broadcast style information to the UE within that cell. The system information transmitted by the 5G NR BCCH is divided into different blocks:
 - **Master Information Block (MIB):** There is one MIB and this is mapped onto the BCH transport channel and then to the PBCH physical channel.
 - **System Information Block (SIB):** There are several system information blocks, SIBs. These are mapped onto the DL-SCH transport channel and then onto the PDSCH physical channel.
- **Paging Control Channel (PCCH):** This is a Downlink channel. It is used to page the UEs whose location at cell level is not known to the network. As a result the paging message needs to be transmitted in multiple cells. The PCCH is mapped to the PCH transport channel and then to the PDSCH physical channel.
- **Common Control Channel (CCCH):** This 5G channel is used on both the downlink and uplink for transmitting control information to and from the user equipments or mobiles. The channel is used for initial access, i.e. those mobiles that do not have a radio resource control, RRC connection.
- **Dedicated Control Channel (DCCH):** The DCCH is used within the uplink and downlink to carry dedicated control information between the UE or mobile and the network. It is used by the UE and the network after a radio resource control, RRC connection has been established.
- **Dedicated Traffic Channel (DTCH):** This 5G channel is present in both the uplink and downlink. It is dedicated to one UE and is used for carrying user information to and from a specific UE and the network.

1.3.2 5G NR transport channels

There are five different transport channels. Some are used on the uplink, others on the downlink, and some can be used on both.

- **Broadcast Channel (BCH):** The BCH 5G channel is used in the downlink only for transmitting the BCCH system information and specifically the Master Information Block, MIB, information. In order that the data can be utilised, it has a specific format.

- **Paging Channel (PCH):** The PCH is used for carrying paging information from the PCCH logical channel. The PCH supports discontinuous reception, DRX, to enable the UE to save battery power by waking up at a specific time to receive the PCH.
In order that the PCH is received by all mobiles / UEs in the cell, the PCH must be broadcast over the entire cell as a single message, or where beam forming is used, this can be done using several different PCH instances.
- **Downlink Shared Channel (DL-SCH):** As the name indicates, this is a downlink only channel. It is the main transport channel used for transmitting downlink data and it supports all the key 5G NR features. These include: dynamic rate adaptation; HARQ, channel aware scheduling, and spatial multiplexing.
The DL-SCH is also used for transmitting some parts of the BCCH system information, specifically the SIB. Each UE has a DL-SCH for each cell it is connected to.
- **Uplink Shared Channel (UL-SCH):** This is the uplink counterpart to the DL-SCH that is, the uplink transport channel used for transmission of uplink data.
- **Random-Access Channel (RACH):** The RACH is a transport channel, which carries the random access preamble which is used to overcome the message collisions that can occur when UEs access the system simultaneously.

1.3.3 5G NR physical channels

The 5G physical channels are used to transport information over the actual radio interface. They have the transport channels mapped into them, but they also include various physical layer data required for the maintenance and optimization of the radio communications link between the UE and the base station. The 5G mobile communications physical layer channels resemble those of 4G LTE, but PHICH and PCICH have been removed. The HARQ operation has also been updated to be more flexible. Also the downlink control channel PDCCH is now administered by layer 3 procedures. There are three physical channels for each of the uplink and downlink:

5G NR Downlink Physical Channels

- **Physical downlink shared channel (PDSCH):** The 5G NR physical downlink shared channel, PDSCH carries data sharing the capacity on a time and frequency basis. The PDSCH physical channel carries a variety of items of data: user data; UE-specific higher layer control messages mapped down from higher channels; system information blocks (SIBs) & paging.
The PDSCH uses an adaptive modulation format dependent upon the link conditions, i.e. signal to noise ratio. It also uses a flexible coding scheme. The combination of these means that there is a flexible coding and data rate.
- **Physical downlink control channel (PDCCH):** As the name implies, the 5G physical downlink control channel carries downlink control data. Its primary function is scheduling the downlink transmissions on the PDSCH and also the uplink data transmissions on the PUSCH.
The PDCCH uses QPSK as its modulation format and polar coding as the coding scheme, except for small packets of data.
- **Physical broadcast channel (PBCH):** This 5G channel forms part of the synchronization signal block. Its function is to provide UEs with the Master Information Block, MIB.

A further function of the PBCH in conjunction with the control channel is to support the synchronization of time and frequency. This aids with cell acquisition, selection and re-selection.

The PBCH uses a fixed data format and there is one block that extends over a TTI of 80ms, uses QPSK modulation and it transmits a cell specific demodulation reference signal, DMRS pattern that can be used aid with beam-forming.

5G NR Uplink Physical Channels

- Physical random access channel (PRACH): This 5G channel - the physical random access channel, PRACH, is used for channel access. It transmits an initial random access preamble consisting of sequences which may be of two different lengths:
 - A long sequence is 839 which is applied to the subcarrier spacings of 1.25kHz and 5 kHz
 - Short sequence lengths of 139 are applied to subcarrier spacings of 15 kHz and 30 kHz (FR1 bands) and 60 kHz and 120 kHz (FR2 bands).
- Physical uplink shared channel (PUSCH): The 5G physical uplink shared channel, PUSCH, is the counterpart of the PDSCH. It is used to carry data from the UL-SCH and its higher mapped channels on a frequency and time-shared basis.

Like the PDSCH, The PUSCH also has a very flexible format. The allocation of frequency resources is undertaken using resource blocks along with a flexible modulation and coding scheme dependent upon the link signal to noise ratio.

To support the channel link estimation and demodulation, the PUSCH contains DMRS signals.
- Physical uplink control channel (PUCCH): The 5G physical uplink control channel, PUCCH, carries the uplink control data. It is also possible that dependent upon the resource allocation the uplink control information or data may also be sent on the PUSCH, even though in the downlink direction, control information is always sent on the PDCCH.

The use of these 5G channels provide a method for organizing the data flow over the radio interface of the 5G communications network. Using channels enables the communications system to recognize the type of data that is being sent, and to deal with it accordingly. The format used is very similar to that employed on 4G LTE and it built on the technology of previous mobile communications or mobile phone generations.

Figures 4 & 5 shows the mapping between logical, transport and physical channels in both DL and UL

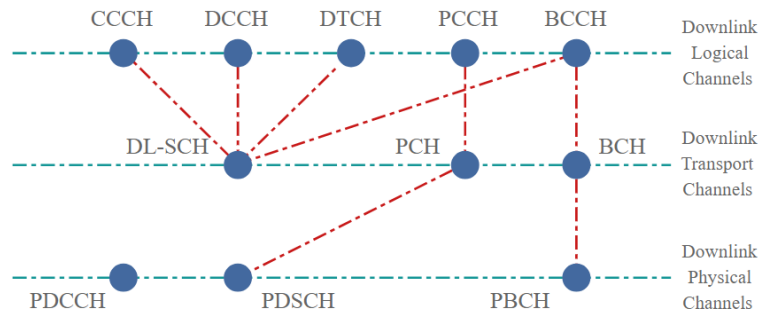


Figure 1.4: 5G Downlink logical, transport and physical channel mapping

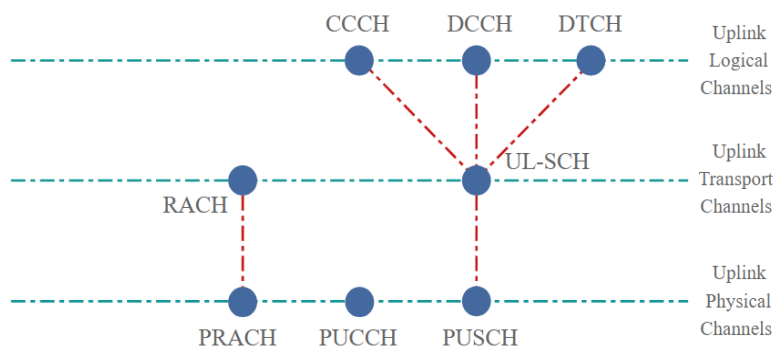


Figure 1.5: 5G Uplink logical, transport and physical channel mapping

Part I

5G PDSCH Simulator

PDSCH overview & Motivation

The Physical Downlink Shared Channel (PDSCH) is a crucial component of 5G wireless communication systems that enables high-speed data transmission with low latency. As a team, we were intrigued by the potential of 5G technology to revolutionize the way we communicate and connect with each other. We were particularly interested in the PDSCH channel, as it plays a critical role in achieving the high data rates and low latency that are essential for applications such as virtual reality, autonomous driving, and the Internet of Things (IoT).

We were also motivated by the technical challenges involved in simulating the PDSCH channel accurately. 5G is a complex and evolving technology that requires a deep understanding of wireless communication systems, signal processing, and coding theory. Our project aimed to develop a MATLAB based simulation model that could capture the unique characteristics of PDSCH and provide insights into its performance under different conditions.

In this Part, we will delve into the technical details of PDSCH and explain how our simulation model was designed and implemented. We will also discuss the results of our simulation experiments and highlight the insights we gained from them. Our hope is that this work will contribute to the ongoing efforts to improve the performance and reliability of 5G networks.

Designing and implementing a simulation model for PDSCH requires a detailed understanding of the 5G standard specifications, as well as knowledge of wireless communication systems, signal processing, and coding theory. Here is an overview of the steps we took to design and implement our simulation model:

Our simulation model for PDSCH in 5G wireless communication systems consists of several key blocks that are critical to achieving high-speed data transmission with low latency. These blocks include channel coding, MIMO setups, reference signals, and channel estimation.

The channel coding block is responsible for protecting the data from errors that may be introduced during wireless transmission. We simulated both linear block codes and LDPC coding to evaluate their performance under different conditions.

The MIMO setups block allows for multiple antennas to be used at both the transmitter and receiver, which can improve the quality and reliability of wireless communication. We simulated several MIMO setups, including SISO, SIMO, and MIMO, to gain insights into the performance of PDSCH under different conditions.

The reference signals block provides important information about the wireless channel, such as channel state information and data demodulation and decoding. We focused on two types of reference signals: CSI-RS and DMRS, which are used for channel estimation, synchronization, and data demodulation.

Finally, the channel estimation block is responsible for accurately estimating the wireless channel conditions and compensating for any distortion or interference that may be present. We spent a significant amount of time on channel estimation, which is essential for accurately simulating the performance of PDSCH under realistic conditions.

In the following sections, we will discuss each of these blocks in detail, including the technical details of how they were implemented and the results of our simulation experiments.

Chapter 2

Channel Coding

Introduction

2.1 Linear Coding

2.2 LDPC Coding

Chapter 3

MIMO Setup

Overview

3.1 SISO

3.2 SIMO

3.3 MISO

3.4 MIMO

3.4.1 Diversity

3.4.2 Multiplexing

Chapter 4

Reference Signals

4.1 Overview

Reference signals are predefined signals occupying specific resource elements within the down-link time-frequency grid. The NR specification includes several types of reference signals transmitted in different ways and intended to be used for different purposes by a receiving device. Unlike LTE, which relies heavily on always-on, cell-specific reference signals in the down-link for coherent demodulation, channel quality estimation for CSI reporting, and general time-frequency tracking, NR uses different down-link reference signals for different purposes. This allows for optimizing each of the reference signals for their specific purpose. It is also in line with the overall principle of ultra-lean transmission as the different reference signals can be transmitted only when needed. Later release of LTE took some steps in this direction, but NR can exploit this to a much larger degree as there are no legacy NR devices to cater for.

The NR reference signals include:

- Demodulation reference signals (DMRS) for PDSCH are intended for channel estimation at the device as part of coherent demodulation. They are present only in the resource blocks used for PDSCH transmission. Similarly, the DMRS for PUSCH allows the gNB to coherently demodulate the PUSCH.
- Phase-tracking reference signals (PTRS) can be seen as an extension to DMRS for PDSCH/PUSCH and are intended for phase-noise compensation. The PT-RS is denser in time but sparser in frequency than the DM-RS, and, if configured, occurs only in combination with DMRS.
- CSI reference signals (CSI-RS) are downlink reference signals intended to be used by devices to acquire down-link channel-state information (CSI). Specific instances of CSI reference signals can be configured for time/frequency tracking and mobility measurements.
- Tracking reference signals (TRS) are sparse reference signals intended to assist the device in time and frequency tracking
- Sounding reference signals (SRS) are uplink reference signals transmitted by the devices and used for uplink channel-state estimation at the base stations.

The previous section assumed full knowledge of the channel characteristics at both transmitter and receiver sides, this section discusses how such knowledge is gained by focusing on two important reference signals : CSI-RS and DMRS.

The propagation channel depends on the transmit frequency. Therefore, if up-link and down-link operate on two different frequencies as is the case in FDD, there is no choice but relying on the receiver to communicate information about the channel back to the transmitter. This is the case at the bottom right.

In the case of TDD, where the up-link and down-link share the same transmit frequency, it is possible, on the other hand, to estimate the down-link channel based on measurements on up-link transmission (or the opposite). In this section we focus on the FDD transmission case.

4.2 DMRS

The DM-RS in NR provides quite some flexibility to cater for different deployment scenarios and use cases: a front-loaded design to enable low latency, support for up to 12 orthogonal antenna ports for MIMO, transmissions duration from 2 to 14 symbols, and up to four reference-signal instances per slot to support very high-speed scenarios. To achieve low latency, it is beneficial to locate the demodulation reference signals early in the transmission, sometimes known as front-loaded reference signals. This allows the receiver to obtain a channel estimate early and, once the channel estimate is obtained, process the received symbols on the fly without having to buffer a complete slot prior to data processing. This is essentially the same motivation as for the frequency-first mapping of data to the resource elements. Two main time-domain structures are supported, differing in the location of the first DM-RS symbol:

- Mapping type A, where the first DMRS is located in symbol 2 or 3 of the slot and the DMRS is mapped relative to the start of the slot boundary, regardless of where in the slot the actual data transmission starts. This mapping type is primarily intended for the case where the data occupy (most of) a slot. The reason for symbol 2 or 3 in the down-link is to locate the first DMRS occasion after a CORESET located at the beginning of a slot.
- Mapping type B, where the first DMRS is located in the first symbol of the data allocation, that is, the DMRS location is not given relative to the slot boundary but rather relative to where the data are located. This mapping is originally motivated by transmissions over a small fraction of the slot to support very low latency and other transmissions that benefit from not waiting until a slot boundary starts but can be used regardless of the transmission duration.

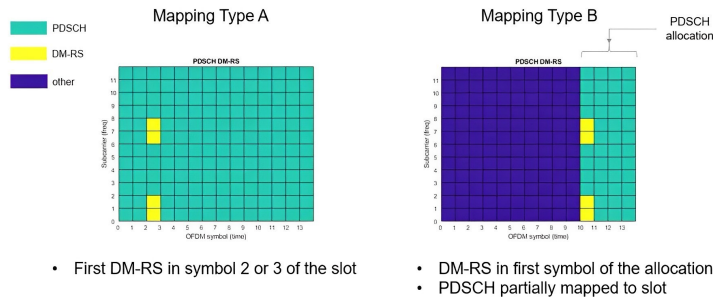


Figure 4.1: DMRS Mapping type A & type B

Although front-loaded reference signals are beneficial from a latency perspective, they may not be sufficiently dense in the time domain in the case of rapid channel variations. To support high-speed scenarios, it is possible to configure up to three additional DM-RS occasions in a slot. The channel estimator in the receiver can use these additional occasions for more accurate channel estimation, for example, to use interpolation between the occasions within a slot.

4.2.1 Pilot based DMRS channel estimation

Assume a single antenna port at both Tx and Rx.

$$y = h_{11}x$$

In order to know h_{11} , we need to send a symbol x which is known at the receiver, then h_{11} can be calculated as:

$$h_{11} = \frac{y}{x}$$

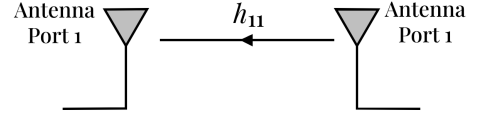


Figure 4.2: Single Tx Single Rx

This known symbol x is called a pilot symbol. The problem with this approach is that there exists a channel coefficient need to be known for each RE in the PDSCH which requires sending pilots in all REs, hence there will not be any place for data bits. The solution to this problem is to send pilot symbols in some REs as shown in the figure to determine the channel coefficients in those REs.

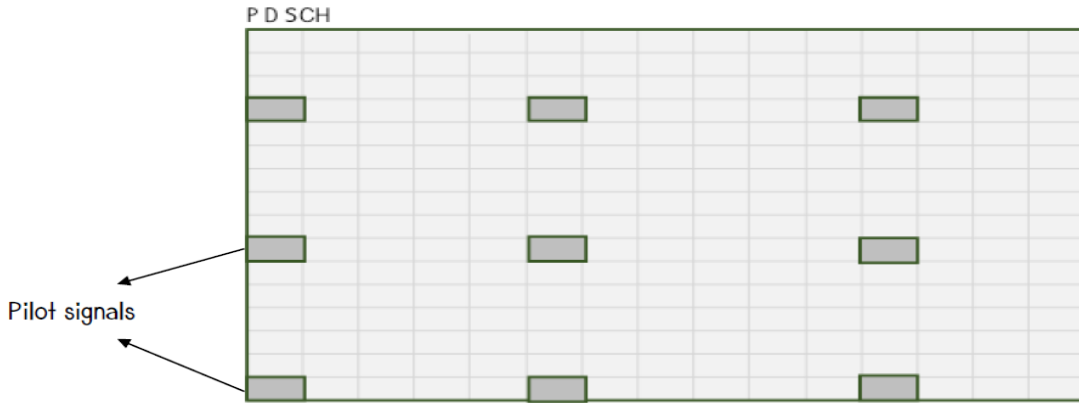


Figure 4.3: Pilot signals in some REs

Use time/frequency correlation to determine channel coefficients in other REs

For the above property to be used time and frequency correlations must be determined, these are known using coherence time and coherence bandwidth.

Coherence bandwidth is a statistical measurement of the range of frequencies over which the channel can be considered "flat", or in other words the approximate maximum bandwidth or frequency interval over which two frequencies of a signal are likely to experience comparable or correlated amplitude fading. If the multi-path time delay spread equals D seconds, then the coherence bandwidth B_c is given approximately by the equation

$$B_c \approx \frac{1}{D}$$

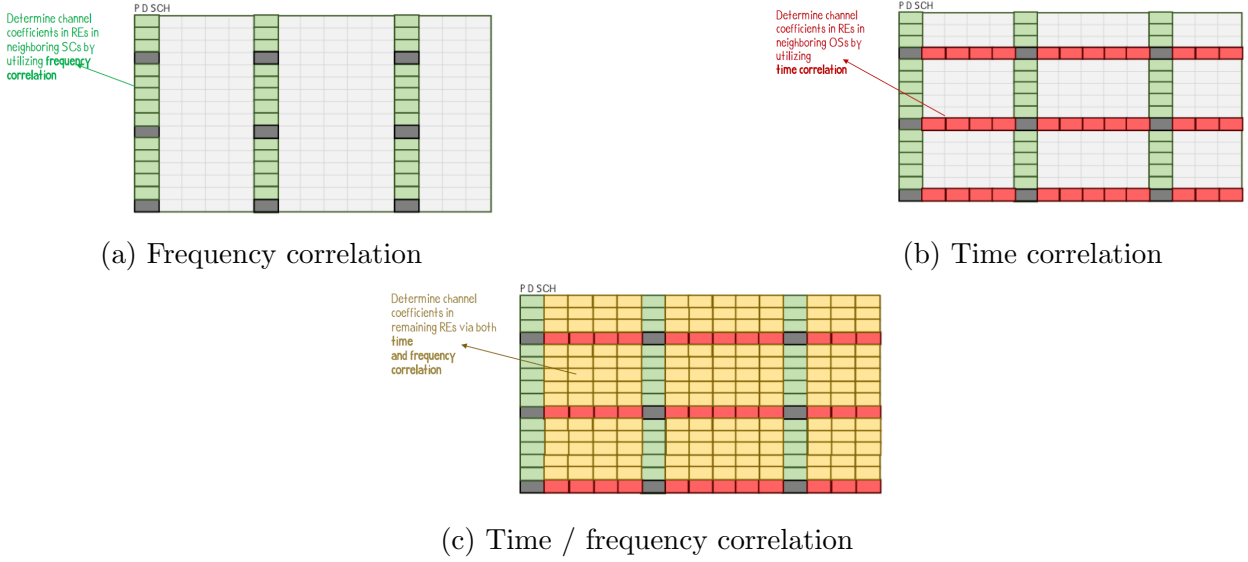


Figure 4.4: Correlation in time & frequency

Hence if the delay spread is small, frequency correlation is high which means we need less pilots density in the frequency domain.

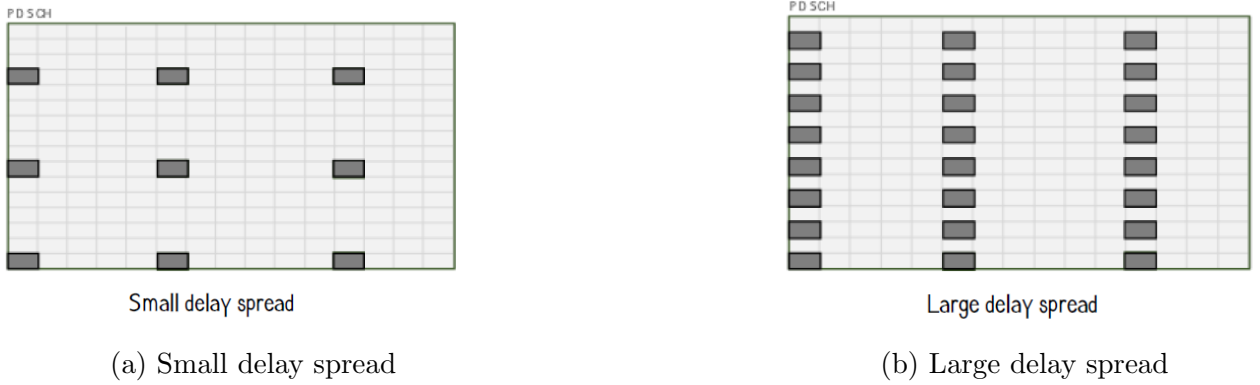


Figure 4.5: Delay spread effect

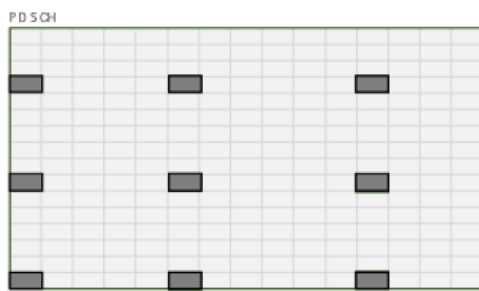
Coherence time is the time duration over which the channel impulse response is considered to be not varying. Such channel variation is much more significant in wireless communications systems, due to Doppler effects. If the maximum doppler spread equals f_m Hz, then the coherence time T_c is given approximately by the equation

$$T_c \approx \frac{1}{f_m}$$

Hence if the doppler spread is small, time correlation is high which means we need less pilots density in the time domain.

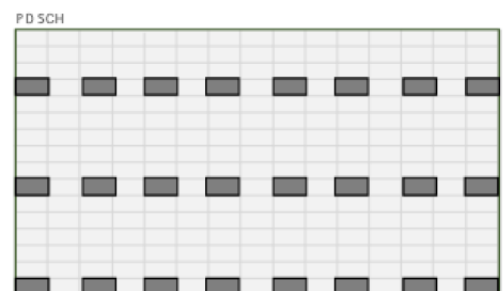
4.3 CSI Reference Signal

4.4 Channel Estimation



Small Doppler spread

(a) Small Doppler spread



Large Doppler spread

(b) Large Doppler spread

Figure 4.6: Doppler spread effect

Chapter 5

Simulations

Part II

Deep Reinforcement Learning Model