Link Level Simulation of PUSCH DM-RS(Transceiver), PUSCH PT-RS, PUCCH DM-RS on MATLAB

A Project Report

submitted by

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THESIS CERTIFICATE

This is to certify that the thesis titled **Link Level Physical layer implementation of nrPUSCH DM-RS(Transmitter and Receiver), nrPUSCH PT-RS(Transmitter), nrPUCCH DM-RS(Transmitter), PUCCH-DMRS on MATLAB**, submitted by **Kshitija Sunil Rangrej**, to the Indian Institute of Technology, Madras, for the award of the degree of **Master of Technology**, is a bona fide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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ABSTRACT

5G New Radio (5G-NR) is an emerging radio access technology, which has been standardised to meet requirements of the future wireless networks. Future wireless networks are about significantly wider range of use cases such as massive-MIMO, AR-VR applications, remote control of robotics, etc. This project implements nrPUSCH-DMRS(Demodulation Reference Signal), nrPUSCH-PTRS(Phase Tracking Signal), nr-PUCCH DM-RS as defined in the release 15 of the 3GPP standards 38.211, 38.212, 38.213, 38.214 and 38.331, consisting of both transmitter and receiver links on physical layer level using MATLAB software. This project report describes briefly about 5G numerology followed by PUSCH DMRS, PTRS configurations scheduled by higher layer parameters (MAC & RRC). Later chapters describe about sequence generation, precoding and mapping of DM-RS, PT-RS in PUSCH and similarly for DM-RS in PUCCH grids. Lastly results have been presented, which has been verified with the outputs obtained from SystemVue and MATLAB 5G Toolbox. The last chapter gives detailed description of DM-RS receiver architecture, focusing on channel estimation using DM-RS. Finally, the project report concludes with code structure.

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ABBREVIATIONS

IITM	Indian Institute of Technology, Madras
5G	5th Generation
NR	New Radio
3GPP	3rd Generation Partnership project
UE	User Equipment
OFDM	Orthogonal Frequency Division Multiplexing
PUSCH	Physical Uplink Shared Channel
DMRS	Demodulation Reference Signal
PTRS	Phase Tracking Reference Signal
PUCCH	Physical Uplink Control Channel
MAC	Medium Access Control
RRC	Radio Resource Control
BWP	Bandwidth Part
PRB	Physical Resource Block
DCI	Downlink Control Information
SRS	Sounding Reference Signal

NOTATION

$a_{k,l}^{(p,\mu)}$	Value of resource element
$c(n)$	PN sequence
l	OFDM symbol index relative to a reference
μ	Subcarrier spacing configuration
M_{SC}^{PUSCH}	Scheduled bandwidth for uplink transmission, as number of subcarriers
M_{RB}^{PUSCH}	Scheduled bandwidth for uplink transmission,as number of resource blocks
ν	Number of transmission layers
$N_{BWP,i}^{start}$	Size of bandwidth part i
$N_{grid,x}^{size,\mu}$	The size of the resource grid
N_{group}^{PTRS}	The number of PT-RS groups
N_{samp}^{group}	Number of samples per PT-RS group;
N_{ID}^{cell}	Physical layer cell identity
N_{SC}^{RB}	Flight path in degrees
$N_{slot}^{subframe,\mu}$	Number of slots per subframe for subcarrier
$N_{slot}^{frame,\mu}$	Number of slots per frame
N_{symb}^{slot}	Number of symbols per slot
n_{PRB}	Physical resource block number
n_{RNTI}	Radio network temporary identifier
$n_{s,f}^{\mu}$	Slot number within a frame
$r_{u,v}^{(\alpha,\delta)}$	Low-PAPR sequence;
W	Precoding matrix for spatial multiplexing

CHAPTER 1

INTRODUCTION

What makes 5G so different from 4G? Simply said, 5G is smarter, faster and more efficient than 4G. Low latency (URLLC), eMBB(enhanced Mobile BroadBand), mmTC (Massive Machine Type Communication) are key differentiators between 4G and 5G. Latency is the time duration from the moment information is requested by a device until the moment the base station caters that request by the device. Reduced latency leads to newer time-critical use cases such as remotely controlled medical bots to perform successful medical surgeries, automatic vehicule driving, e-sports, etc. Increased data rates have made it possible to use your mobile device's connection as a replacement to your cable modem and/or Wi-Fi. Theoretically 5G will support downlink speeds of upto 10Gbps and uplink speeds of upto 1Gbps. These newer capabilities have been possible due to meticulous planning and flexibility introduced in 5G in comparison to 4G. Few of them are :

1. Support for multiple Numerology, including subcarrier spacing
2. Front-loaded DMRS, leading to parallel processing of data as oppsed to waiting for the whole subframe to be received.

CHAPTER 2

PUSCH DM-RS Transmitter

2.1 DM-RS Use Case

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, transmission durations 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.

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. It is not possible to interpolate between slots, or in general different transmission occasions, as different slots may be transmitted to different devices and/or in different beam directions.

2.2 Scheduling and Transmission

In uplink, there are two types of CG configurations, Type 1 and Type 2. In Type 1, the UL grant is configured by RRC and, once configured, it is always active. Type 2 CG is first configured by RRC, but it has to be additionally activated by PDCCH(DCI 0-0 and 0-1)scrambled with CS-RNTI before it can be utilized. Once not required, it may be dynamically deactivated via PDCCH, but the UE keeps its configuration, so that it can be activated quickly when needed again. The UE also confirms the reception of the L1 activation/deactivation by sending a configured grant confirmation MAC CE to the network.

Fields of DCI 0-0.

Resource information :

[CFI] Carrier indicator (0 or 3 bit). This field is present if cross-carrier scheduling is configured and is used to indicate the component carrier the DCI relates to. The carrier indicator is not present in DCI format 0-0.

[UL/SUL] UL/SUL indicator (0 or 1 bit), used to indicate whether the grant relates to the supplementary uplink or the ordinary uplink. Only present if a supplementary uplink is configured as part of the system information.Aim of SUL is to extend uplink coverage, that is, to provide higher uplink data rates in power-limited situations, by utilizing the lower path loss at lower frequencies and also can also be used to reduce latency.

[BWP indicator] Bandwidth-part indicator (0-2 bit),, this field is used to switch the active bandwidth part. It can either point to the current active bandwidth part, or to another bandwidth part to activate one of up to four bandwidth parts configures by higher-layer signaling. Not present in DCI format 0-0.

[Frequency domain allocation] Frequency-domain resource allocation. This field indicates the resource blocks on one component carrier upon which the device should transmit the PUSCH. The size of the field depends on the size of the bandwidth and on the resource allocation type, type 0 only, type 1 only, or dynamic switching between the two.Format 0-0 supports resource allocation type 1 only.Type 0 is a bitmap-based allocation scheme.The most flexible way of indicating the set of resource blocks the device is supposed to receive the downlink transmission upon is to include a bitmap with size equal to the number of resource blocks in the bandwidth part. This would allow for an arbitrary combination of resource blocks to be scheduled for transmission to the device.Resource allocation type 1 does not rely on a bitmap. Instead, it encodes the resource allocation as a start position and length of the resource-block allocation.This type 1 Supports only frequency-contiguous allocations, thereby reducing the number of bits required for signaling the resource-block allocation.Both resource-allocation types refer to virtual resource blocks.

[Time-domain allocation] Time-domain resource allocation (0-4 bit). This field used as an index into an RRC-configured table from which the time-domain allocation is obtained.Whereas each row of table contains A slot offset,the first OFDM symbol in the slot where the data are transmitted, The duration of the transmission in number of OFDM symbols in the slot.The time-domain allocation for the data to be transmitted is dynamically signaled in the DCI, which is useful as the part of a slot available for uplink transmission may vary from slot to slot as a result of the use of dynamic TDD or the amount of resources used for uplink controls signaling.

[Frequency hopping] Frequency-hopping flag (0 or 1 bit), used to handle frequency hopping for resource allocation type 1.

Transport-block-related:

[MCS] Modulation-and-coding scheme (5 bit), used to provide the device with information about the modulation scheme, the code rate, and the transport block size.

[NDI] New-data indicator (1 bit), used to indicate whether the grant relates to retransmission of a transport block or transmission of a new transport block.

[RV] Redundancy version (2 bit).

Multi-antenna-related :

[DM-RS sequence initialization]DMRS sequence initialization (1 bit), used to select between two preconfigured initialization values for the DM-RS sequence. **[Antenna ports]**Antenna ports (2-5 bit), indicating the antenna ports upon which the data are transmitted as well as antenna ports scheduled for other users

[SRI]SRS resource indicator used to determine the antenna ports and uplink transmission beam to use for PUSCH transmission.The number of bits depends on the number of SRS groups configured and whether codebook-based or non-codebook-based precoding is used.

[Precoding information] Precoding information (0-6 bit), used to select the precoding matrix W and the number of layers for codebook-based precoding.The number of bits depends on the number of antenna ports and the maximum rank supported by the device.

[PTRS-DMRS association] PTRS-DMRS association (0 or 2 bit), used to indicate the association between the DM-RS and PT-RS ports.

Power control :

[PUSCH power control]PUSCH power control (2 bit), used to adjust the PUSCH transmission power

[Beta offset]Beta offset (0 or 2 bit), used to control the amount of resources used by UCI on PUSCH in case dynamic beta offset signaling is configured for DCI format 0-1.

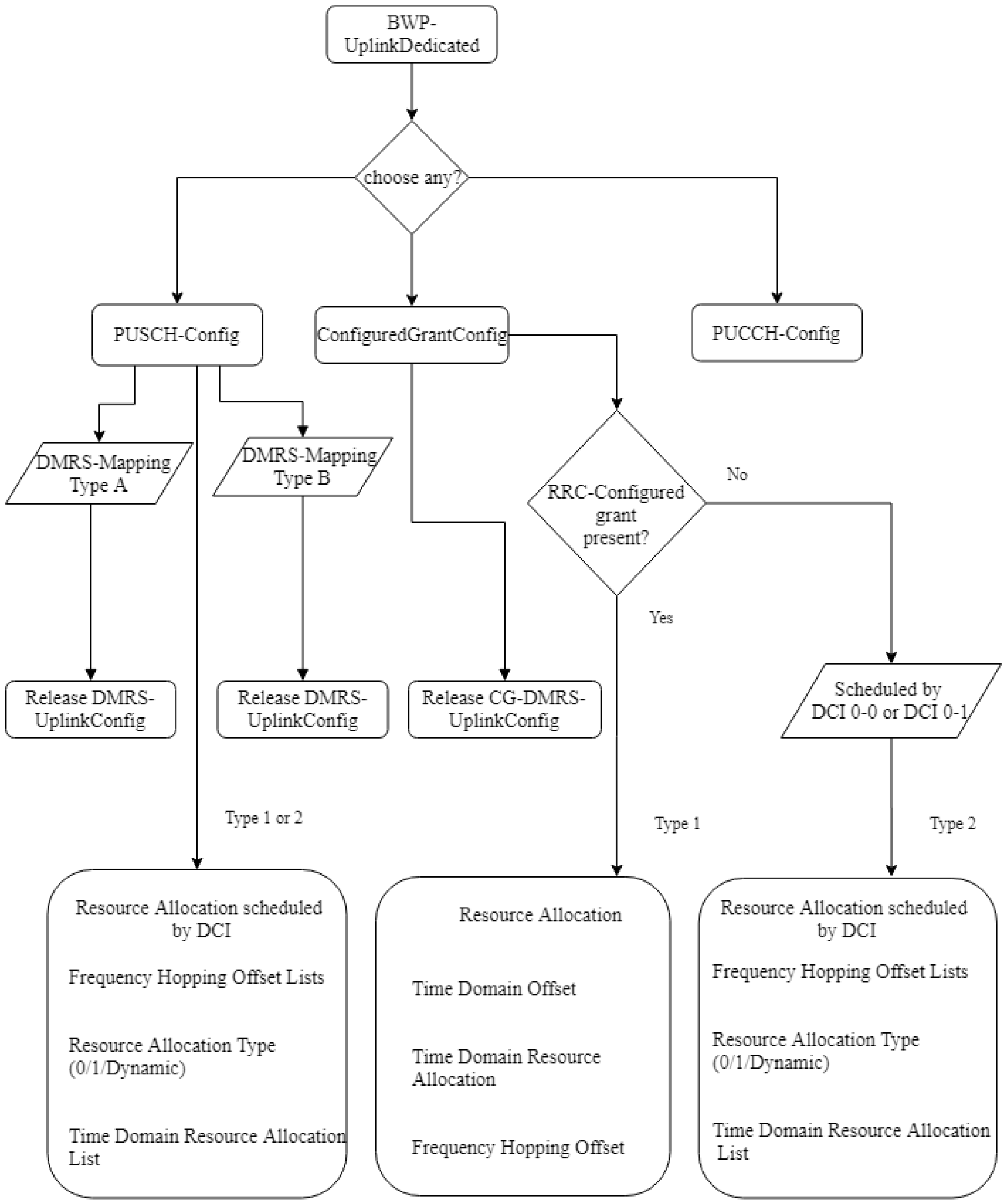

Figure 2.1: UL-SCH DM-RS transmission flow.

2.3 Sequence Generation and Transform Precoding

Reference signals should preferably have small power variations in the frequency domain to allow for a similar channel-estimation quality for all frequencies spanned by the reference signal. Note that this is equivalent to a well-focused time-domain auto-correlation of the transmitted reference signal. For OFDM-based modulation, a pseudo-random sequence is used, more specifically a 31-length Gold sequence, which fulfills the requirements on a well-focused auto-correlation.On the other hand for DFT-based modulation,Low PAPR sequence is used.

The sequence is generated across all the common resource blocks (CRBs) in the frequency domain but transmitted only in the resource blocks used for data transmission as there is no reason for estimating the channel outside the frequency region used for transmission. Generating the reference signal sequence across all the resource blocks ensures that the same underlying sequence is used for multiple devices scheduled on overlapping time-frequency resources in the case of multi-user MIMO. If the underlying pseudo-random sequence would differ between different co-scheduled devices, the resulting reference signals would not be orthogonal.The pseudo-random sequence is generated using a configurable identity, similar to the virtual cell ID in LTE. If no identity has been configured, it defaults to the physical-layer cell identity.the underlying pseudo-random sequence is mapped to every second subcarrier in the frequency domain in the OFDM symbol used for reference signal transmission.

2.4 Mapping to Grid

The different time-domain allocations for DM-RS are illustrated in (put Fig.No.), including both single-symbol and double-symbol DM-RS.The purpose of the double-symbol DM-RS is primarily to provide a larger number of antenna ports than what is possible with a single-symbol structure.Note that the time-domain location of the DM-RS depends on the scheduled data duration. Multiple orthogonal reference signals can be created in each DM-RS occasion.The different reference signals are separated in the frequency and code domains,and, in the case of a double-symbol DM-RS, additionally in the time domain.

Two different types of demodulation reference signals can be configured, type 1 and type 2, differing in the mapping in the frequency domain and the maximum number of orthogonal reference signals.

Configuration Type 1 : Provides up to four orthogonal signals using a single-symbol DM-RS and up to eight orthogonal reference signals using a double-symbol DM-RS.

Configuration Type 2 : Provides up to six orthogonal signals using a single-symbol DM-RS and up to twelve orthogonal reference signals using a double-symbol DM-RS.

Two main time-domain structures are supported, differencing in the location of the first DM-RS symbol:

Mapping Type A : where the first DM-RS is located in symbol 2 or 3 of the slot and the DM-RS 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.

Mapping Type B : where the first DM-RS is located in the first symbol of the data allocation, that is, the DM-RS 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.The mapping type for the PUSCH is semi-statically configured.

NR Uplink Supports up to 4 layers for CP-OFDM and 1 layer for DFT-OFDM.0 series ports are reserved for PUSCH transmission.

2.5 Multi-Antenna Precoding

Precoding matrix selection depends on transmission configuration,TPMI and SRS ports in use.And Selection of PUSCH transmission configuration is based on , assumption that, to what extent the detailed uplink channel conditions can be estimated by the device based on downlink . Uplink precoding is transparent to the receiver in the sense that receiver-side demodulation can be carried out without knowledge of the exact precoding applied at the transmitter (device) side.

Codebook-based precoding :In the uplink direction,in the case of codebook-based precoding, the scheduling grant includes information about a precoder, that is the device is assumed to use the precoder provided by the network.

Non-Codebook based precoding:Non-codebook-based precoding is based on device measurements and precoder indications to the network.Non-codebook-based precoding is thus based on an assumption of channel reciprocity, that is, that the device can acquire detailed knowledge of the uplink channel based on downlink measurements. Each column of a precoder matrix W can be seen as defining a digital "beam" for the corresponding layer. The device selection of precoder for N_L layers can thus be seen as the selection of N_L different beam directions where each beam corresponds to one possible layer. NR non-codebook-based precoding includes an additional step where the network can modify the device-selected precoder, in practice remove some "beams," or equivalently some columns, from the selected precoder. To enable this, the device applies the selected precoder to a set of configured SRSs, with one SRS transmitted on each layer or "beam" defined by the precode.Based on measurements on the received SRS, the network can then decide to modify the device-selected precoder for each scheduled PUSCH transmission. This is done by indicating a subset of the configured SRSs within the SRS resource indicator (SRI) included in the scheduling grant.The device then carries out the scheduled PUSCH transmission using a reduced precoder matrix where only the columns corresponding to the SRSs indicated within the SRI are included. Note that the SRI then also implicitly defines the number of layers to be transmitted. It should be noted that the device indication of precoder selection is not done for each scheduled transmission. The uplink SRS transmission indicating device precoder selection can take place periodically (periodic or semi persistent SRS) or on demand (aperiodic SRS).In contrast, the network indication of precoder, that is in practice the network indication of the subset of beams of the device precoder, is then done for each scheduled PUSCH transmission.Fig. 2.2 shows Multi-port mapping flow.

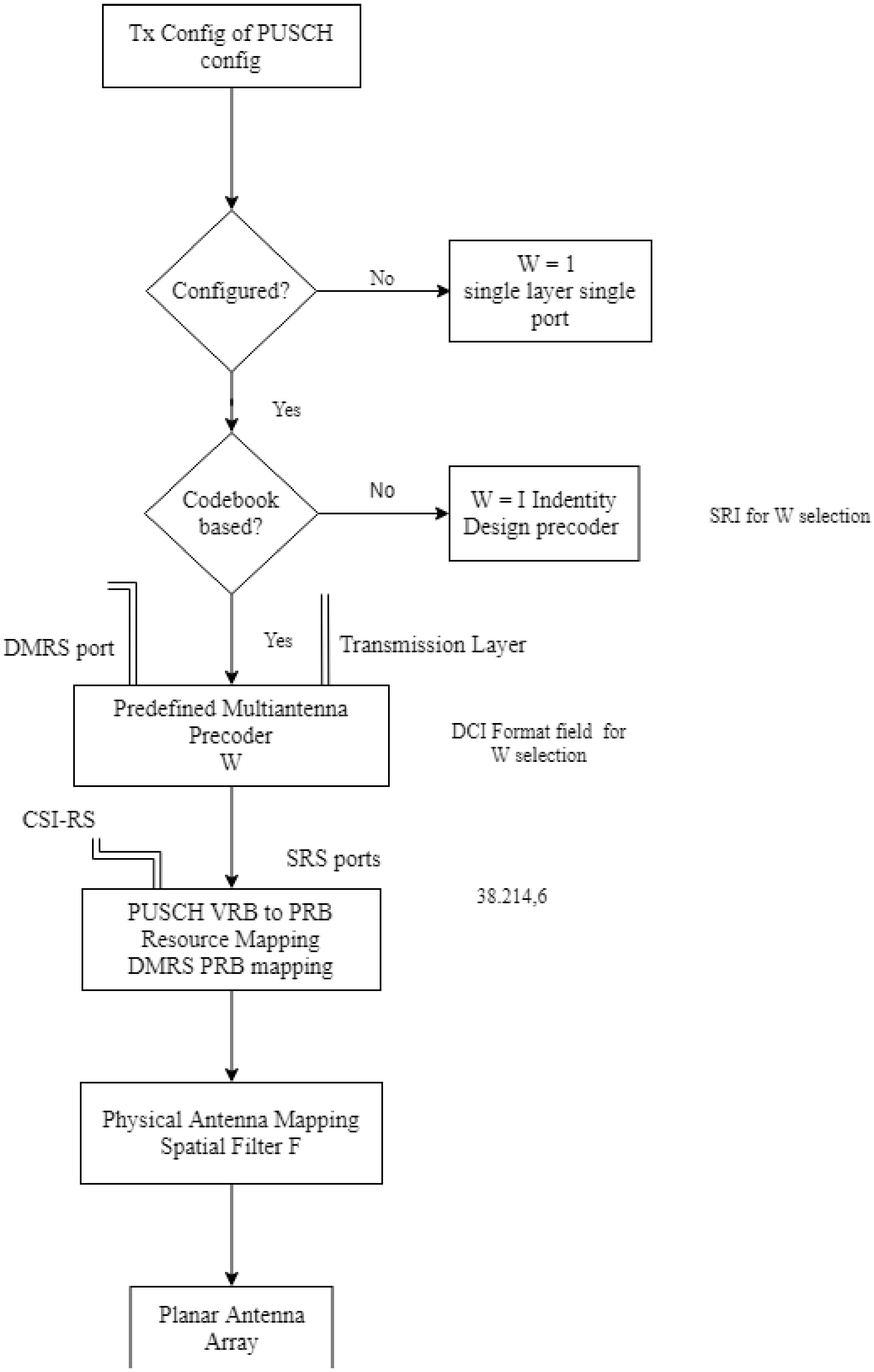

Figure 2.2: Multi-port mapping flow.

2.6 CDM

CDM stands for code division multiplexing. As the name suggests, it's used to bring orthogonality between codes formed from a common base sequence. In the case of 5G there are 3 possible ways of enforcing orthogonality. They are as follows;

- Dispersing symbols over OFDM symbols within a slot.
- Using different subcarrier.
- Using codes in same RE.

One important aspect of cellular communication is estimating the channel before data decoding is started.So the DMRS symbols used as pilot signal to estimate channel at receiver is called as front-loaded DMRS.The reason being as highlighted in the previous sentence, since it's the first thing the receiver will look for and process and then do further processing. By referring to tables mentioned in the 3GPP TS 38.211 under PUSCH DMRS section, another table can be concluded and is mentioned in (include table).Now the term CDMGroup refers to a set of DMRS ports , such that the locations of DMRS symbols in a time-frequency grid are the same but the symbols are orthogonal to each other in the coding sense.Further based on how the PUSCH transmission is scheduled, the number of CDMGroup may or may not be mentioned, and if mentioned, it also specifies which DMRS port to select among the specified CDM Group.Adding to this,DMRS ports mentioned with CDM group without data ,has DMRS symbols along with device specific data,remaining ports in the CDM group have no data. The scheduling decision also contains information for the device which reference signals (more specifically, which CDM groups) that are intended for other devices. The scheduled device maps the data around both its own reference signals as well as the reference signals intended for another device. This allows for a dynamic change of the number of co scheduled devices in the case of multi-user MIMO. In the case of spatial multiplexing (also known as single-user MIMO) of multiple layers for the same device, the same approach is used—each layer leaves resource elements corresponding to another CDM group intended for the same device unused. This is to avoid interlayer interference for the reference signals.

2.7 Grids

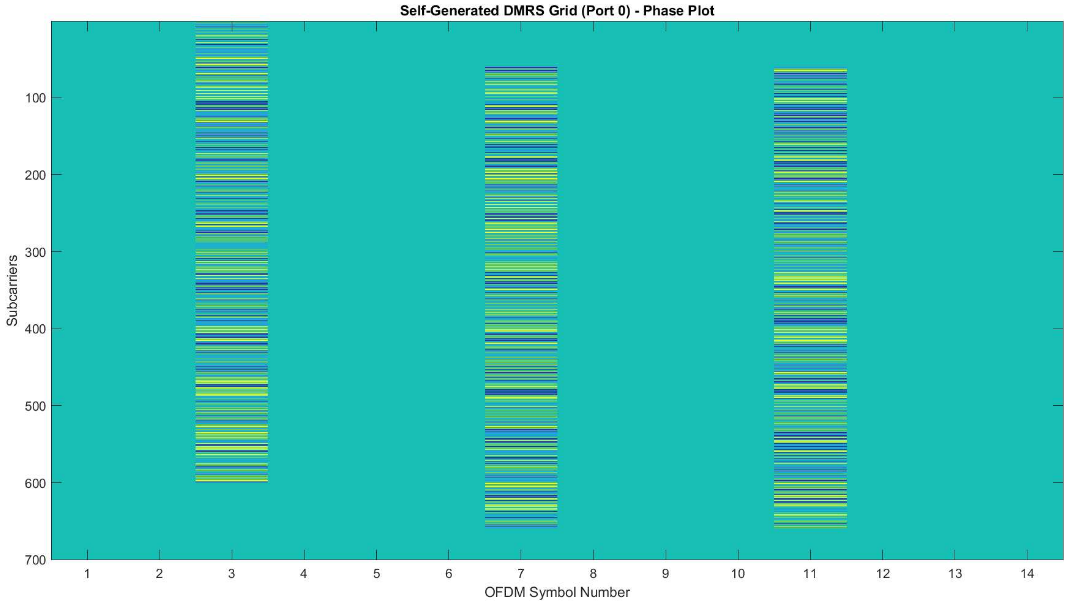

Figure 2.3: Configuration 1

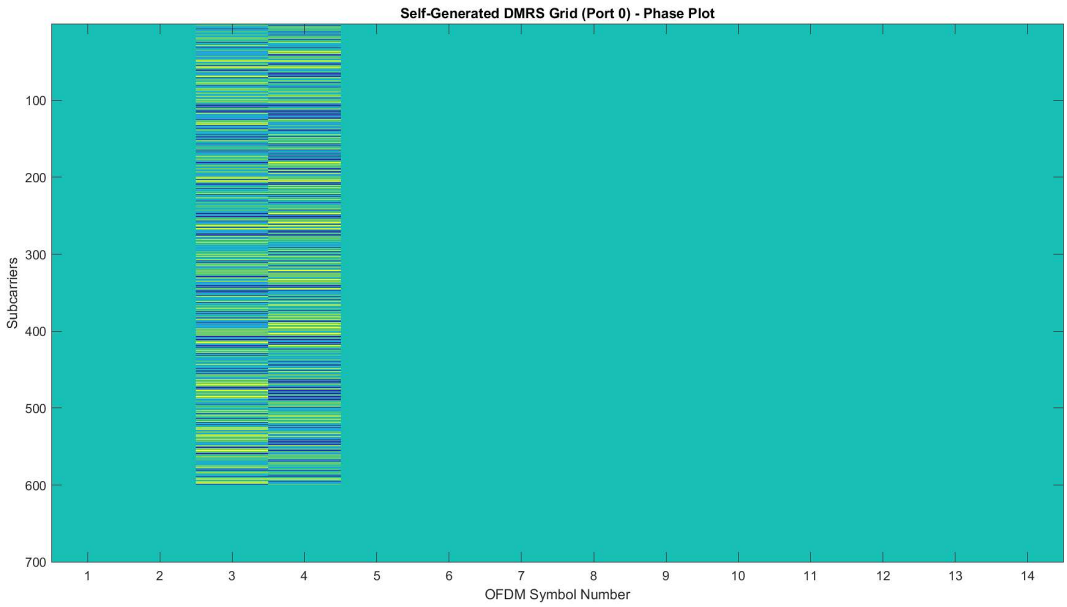

Figure 2.4: Configuration 2

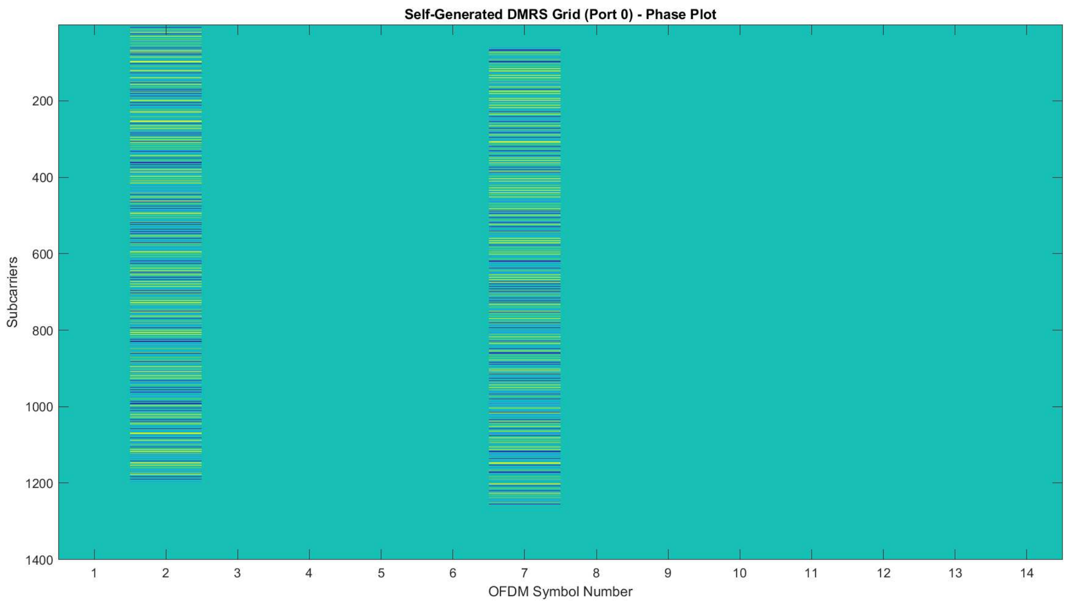

Figure 2.5: Configuration 3

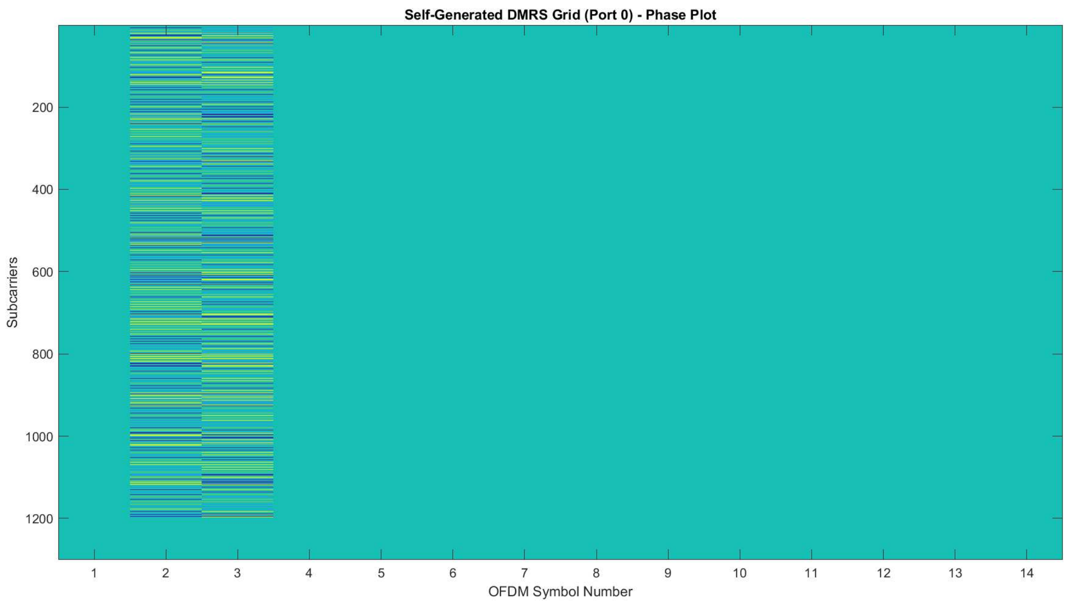

Figure 2.6: Configuration 4

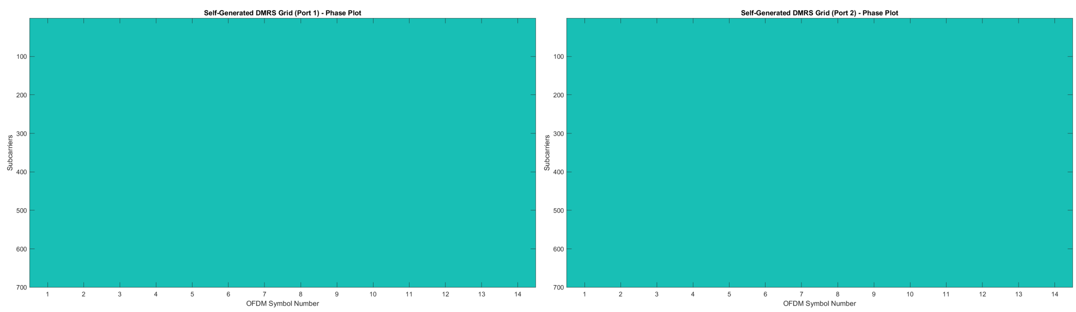

Figure 2.7: Configuration 5 port 1 and port 2

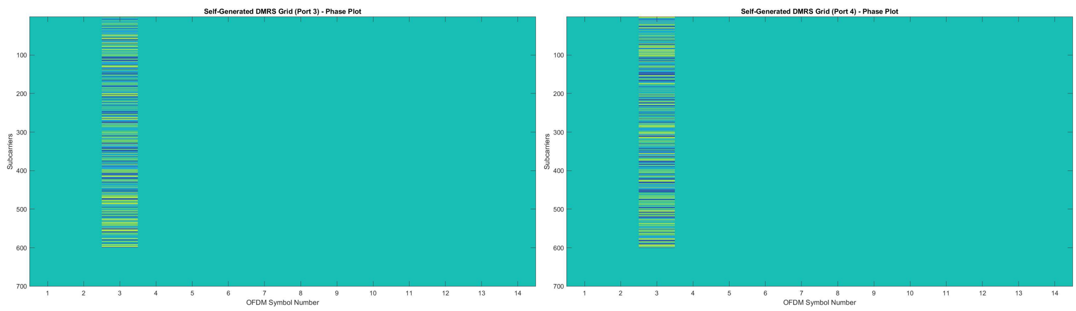

Figure 2.8: Configuration 5 port 3 and port 4

CHAPTER 3

PUSCH PT-RS Transmitter

3.1 PT-RS Use Case

Phase noise caused by lossy component or active devices of local oscillators, is potentially detrimental to 5G, when bandwidth efficient and high order modulation schemes are employed. At carrier frequency above 6 GHz, phase noise becomes significant and could lead to great performance degradation if not considered properly. Therefore, it is necessary to study phase noise influence and mitigation methods, as 5G will use high-frequency signals in the mmW band. One way to estimate phase noise is to design appropriate PT-RS for all the OFDM symbols. Phase-tracking reference signals (PT-RS) can be seen as an extension to DM-RS, intended for tracking phase variations across the transmission duration, for example, one slot. Since the main purpose is to track phase noise, the PT-RS needs to be dense in time but can be sparse in frequency.

3.2 Scheduling and Transmission

The PT-RS only occurs in combination with DM-RS and only if the network has configured the PT-RS to be present. DCI 0-1 fields information:
[PTRS-DMRS association] If PTRS-UplinkConfig is not configured and transformPrecoder is disabled, or if transformPrecoder is enabled, or if maxRank is one,there is no DMRS-PTRS association.
Otherwise, (2 bit) to indicate the association between PTRS port(s) and DMRS port(s) for transmission of one PT-RS port and two PT-RS ports. Fig. 3.1 shows PT-RS transmission and mapping

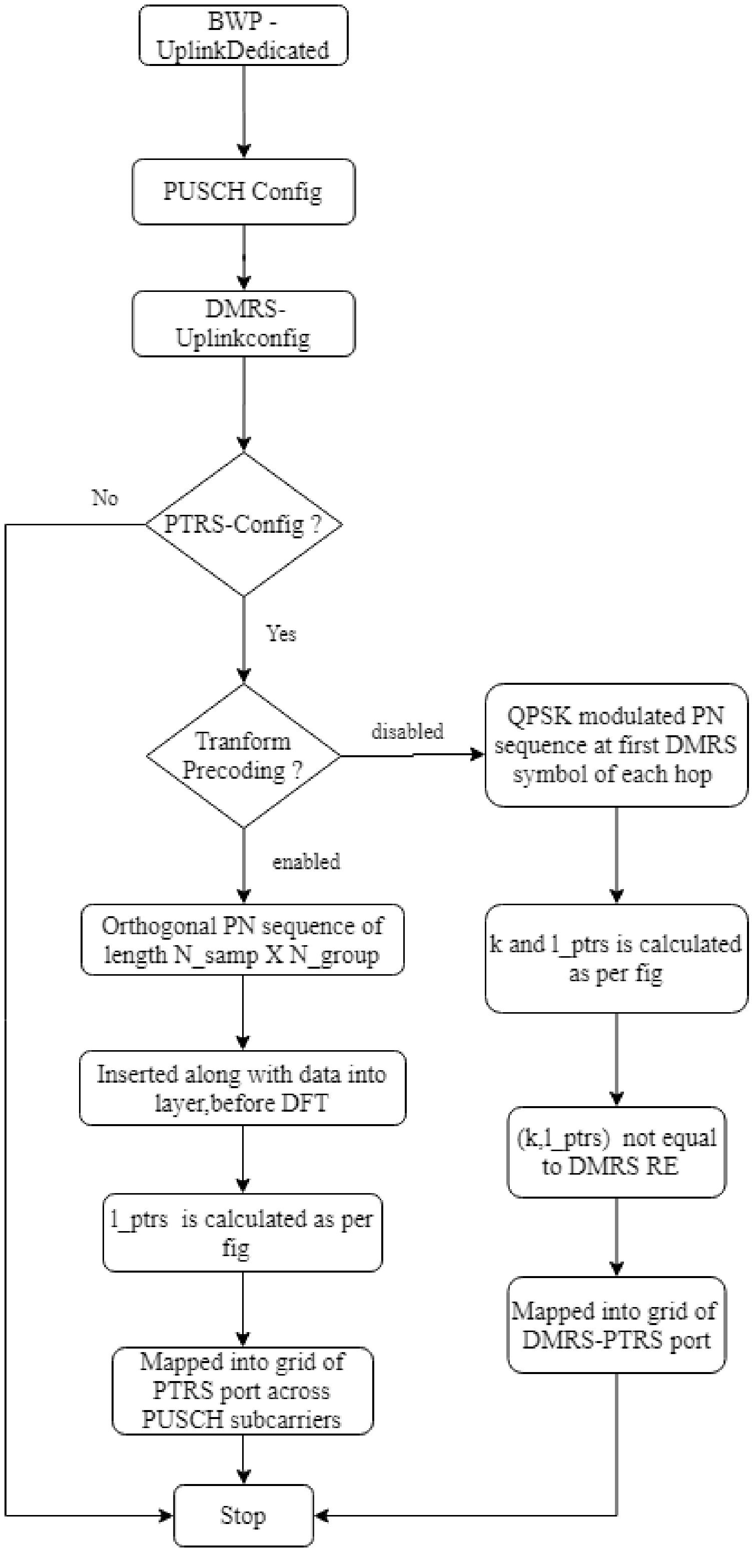

Figure 3.1: PT-RS Scheduling and Transmission within PUSCH transmission

3.3 Precoding and Mapping to Grid

For OFDM, the first reference symbol (prior to applying any orthogonal sequence) in the PUSCH allocation is repeated every L^{th} OFDM symbol,starting with the first OFDM symbol in the allocation. The repetition counter is reset at each DM-RS occasion as there is no need for PT-RS immediately after a DM-RS. The density in the time-domain is linked to the scheduled MCS in a configurable way. In the frequency domain, phase-tracking reference signals are transmitted in every second or fourth resource block, resulting in a sparse frequency domain structure. The density in the frequency domain is linked to the scheduled transmission bandwidth such that the higher the bandwidth, the lower the PT-RS density in the frequency domain. For the smallest bandwidths, no PT-RS is transmitted.

To reduce the risk of collisions between phase-tracking reference signals associated with different devices scheduled on overlapping frequency-domain resources, the subcarrier number and the resource blocks used for PT-RS transmission are determined by the C-RNTI of the device. For DFT-precoded OFDM in the uplink, the samples representing the phase tracking reference signal are inserted prior to DFT precoding. The time domain mapping follows the same principles as the pure OFDM case. Fig. 3.1 gives overview of Mapping of PTRS into resource grid of PT-RS port. The antenna port used for PT-RS transmission is given by the lowest numbered antenna port in the DM-RS antenna port group.Since there is DMRS-PTRS association. Fig. 3.2 shows a figure of how to calculate PTRS time indices.

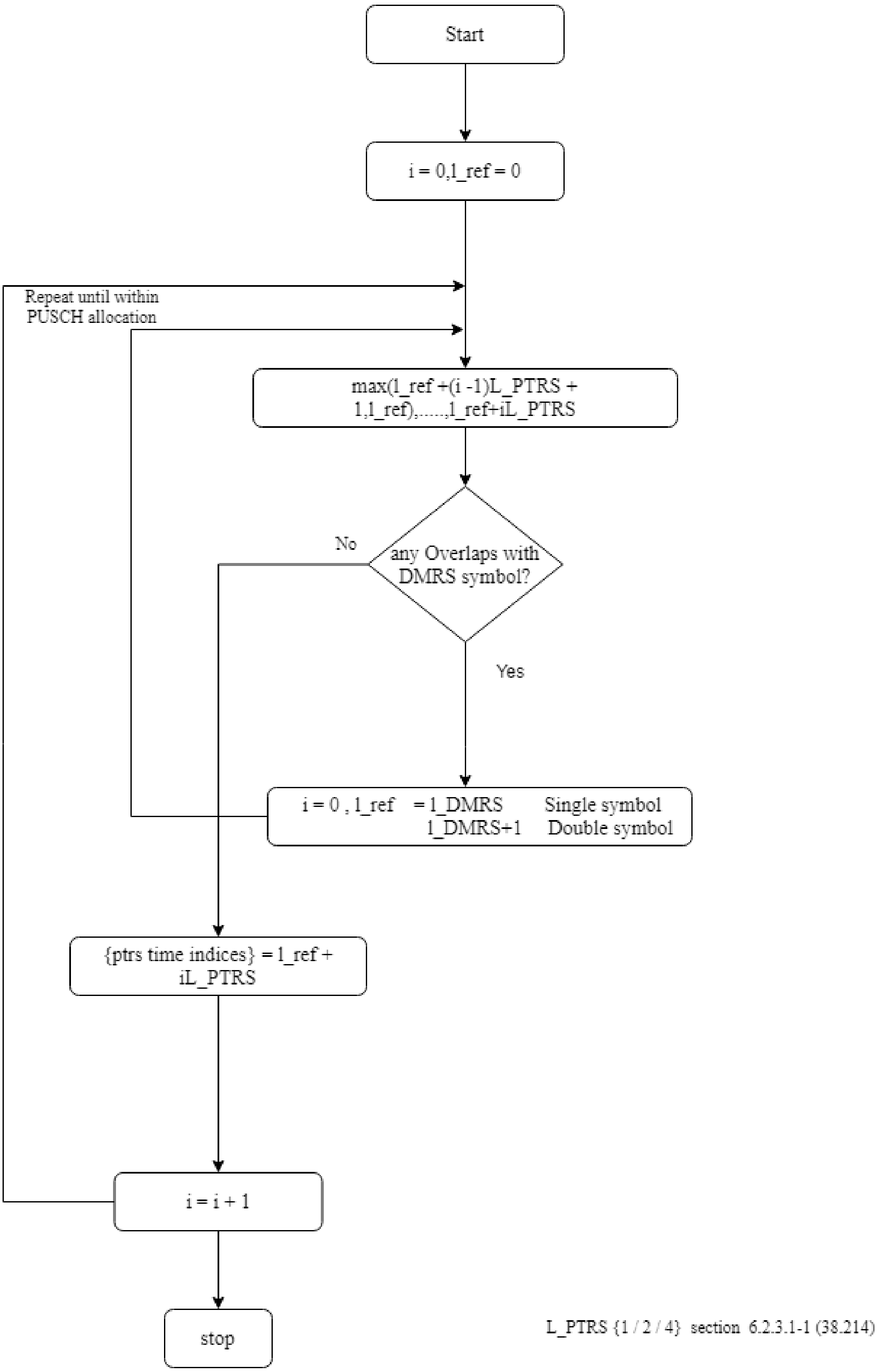

Figure 3.2: PTRS time domain indices calculation.

CHAPTER 4

PUCCH DM-RS Transmitter

The Physical Uplink Control Channel (PUCCH) is used by the device to send hybrid-ARQ acknowledgments, indicating to the gNB whether the downlink transport block(s) was successfully received or not, to send channel-state reports aiding downlink channel-dependent scheduling, and for requesting resources to transmit uplink data upon.

4.1 Scheduling and Transmission

DCI 1-1 fields

PUCCH-related information:

PUCCH power control (2 bit), used to adjust the PUCCH transmission power.

PUCCH resource indicator (3 bit), used to select the PUCCH resource from a set of configured resources. Fig. 4.1 shows a figure of PUCCH Scheduling and Transmission. There are several different PUCCH formats, depending on the amount of information and the duration of the PUCCH transmission. The short PUCCH is transmitted in the last one or two symbols of a slot and can support very fast feedback of hybrid-ARQ acknowledgments in order to realize so-called self-contained slots where the delay from the end of the data transmission to the reception of the acknowledgment from the device is in the order of an OFDM symbol, corresponding to a few tens of microseconds depending on the numerology used. Periodic reporting with certain configured periodicity is always done on the PUCCH physical channel. Thus, in the case of periodic reporting, the resource configuration also includes information about a periodically available PUCCH resource to be used for the reporting. Similar to periodic reporting, semi-persistent reporting can be done on a periodically assigned PUCCH resource.(No DMRS signal for PUCCH format 0 due to its short duration and also is placed mostly at end of PUCCH duration.CONFIRM THIS?)

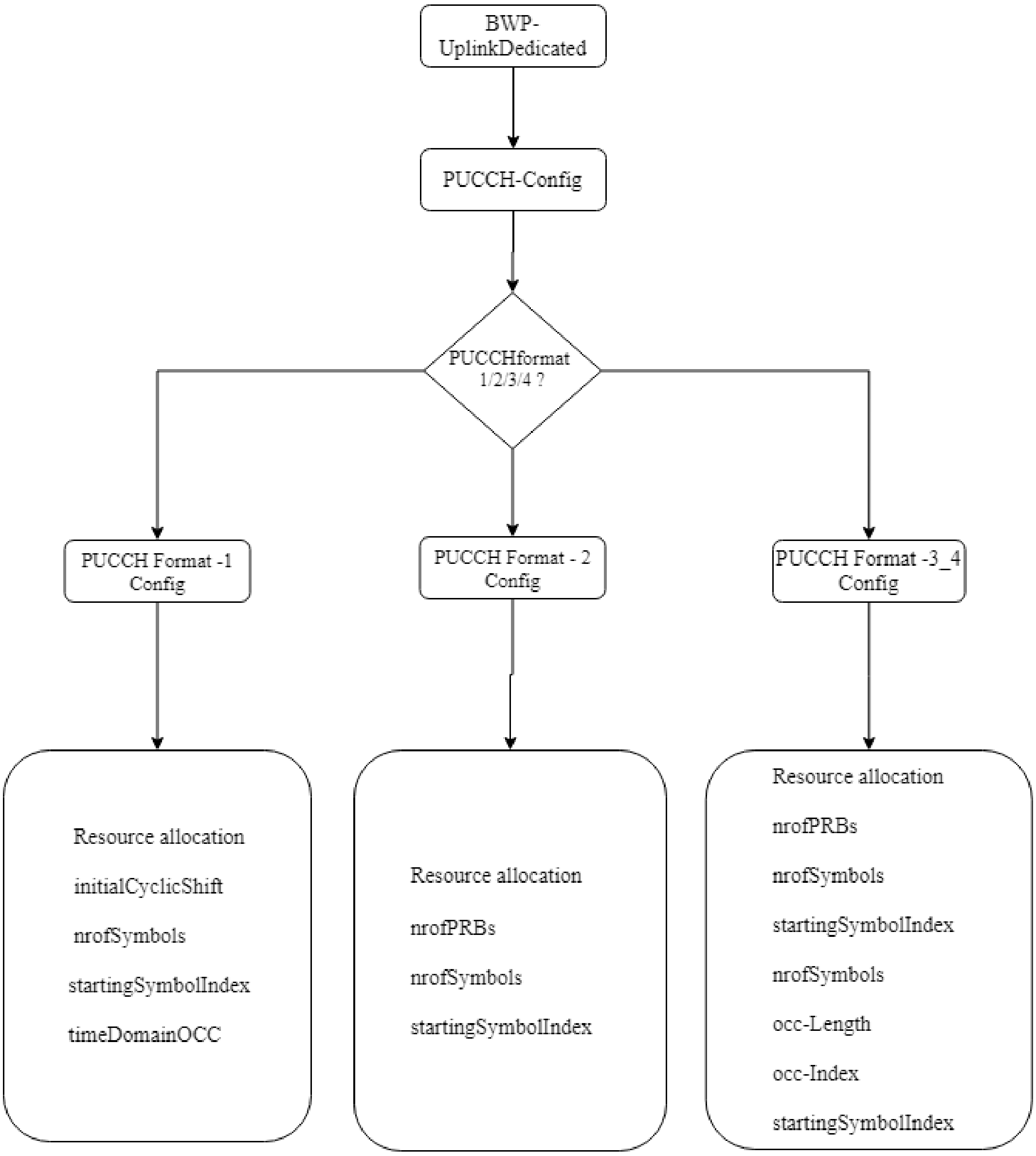

Figure 4.1: PUCCH Scheduling and Transmission

4.2 Format 1

Sequence generation: PUCCH Format 1 DM-RS symbol has been generated from Low Peak to Average Power Ratio sequence.Multiple Low PAPR sequences are defined from a single base sequence through different values of cyclic shifts.These low PAPR sequences were being multiplied by unit magnitude orthogonal sequences, only differ with phases. The length of set of orthogonal sequence varies with PUCCH transmission duration which ranges between 4 and 14.Finally generated orthogonal low PAPR sequences shall be multiplied with the amplitude scaling factor in order to conform to the transmit.

Mapping: Allocation of DM-RS symbols into grid of antenna port 2000,has been at the even OFDM symbol indices from starting symbol of transmission,in a slot and within the resource blocks assigned for PUCCH transmission.

Intra-slot frequency hopping shall be assumed when the higher-layer parameter intraSlotFrequencyHopping is provided, regardless of whether the frequency-hop distance is zero or not,otherwise no intra-slot frequency hopping shall be assumed. Frequency allocation is in contiguous PRBs whereas number of PRBs in each hop of Format 1 varies with duration of PUCCH Format 1.For long PUCCH over multiple slots, the intra and inter slot frequency hopping cannot be enabled at the same time for a device.

4.3 Format 2

Sequence generation : PUCCH format 2 DM-RS symbols have been generated from pseudo random sequence. The pseudo random sequence has been generated by 31 length gold sequence generator which is initialized per symbol per slot of scheduled device. These sequences have been further modulated by QPSK modulation.These modulated symbols shall be multiplied with the amplitude scaling factor in order to conform to the transmit power.No additional DMRS symbols are required for this format.

Mapping : Allocation of DM-RS symbols into the resource grid of antenna port 2000 has been done relative to subcarrier 0 of common resource block 0. Symbols has been dispersed in subcarriers of multiples of three, within the resource blocks assigned for

PUCCH transmission,per symbol fashion.Likewise has been done for all the symbols in PUCCH transmission duration.
PUCCH Format 2 does not have inter slot frequency hopping.Thus only intra slot frequency hopping can be enabled as per requirement of device.

4.4 Format 3

Sequence generation : PUCCH format 3 DM-RS symbols have been generated by cyclically shifted low PAPR sequence.Where cyclic shift varies with the symbol number and slot number.That is sequence has been generated per symbol per slot basis.Initial cyclic shift of format 3 is always 0 and independent on orthogonal sequence index.Low PAPR sequence generation needs to know whether sequence group hopping is enabled or disabled.
Mapping : Time indices of DM-RS symbols are fixed with respect to PUCCH length (i.e. duration of PUCCH duration) but at the same time depends on Additional DM-RS symbol,intra slot hopping enable or disable.Additional DM-RS field indicates number of DM-RS symbols shall be required by device. Allocation of DM-RS symbols into the resource grid of antenna port 2000 has been done relative to subcarrier 0 of lowest numbered resource block assigned for PUCCH transmission. In frequency that is subcarrier first and symbol later fashion.

4.5 Format 4

Sequence generation : PUCCH format 4 DM-RS symbol generation is similar to PUCCH format 3 but the slightly differs with initial cyclic shift. Initial cyclic shift varies with orthogonal sequence index which ranges between 0 and 4 and also depends on orthogonal sequence length(OCC-length).
Mapping : Time indices of DM-RS symbols are fixed with respect to PUCCH length (i.e. duration of PUCCH duration) but at the same time depends on Additional-DMRS symbol,intra slot hopping enable or disable. Allocation of DM-RS symbols into the resource grid of antenna port 2000 has been done relative to subcarrier 0 of lowest numbered resource block assigned for PUCCH transmission.In frequency that is subcarrier

first and time later fashion.

4.6 Grids

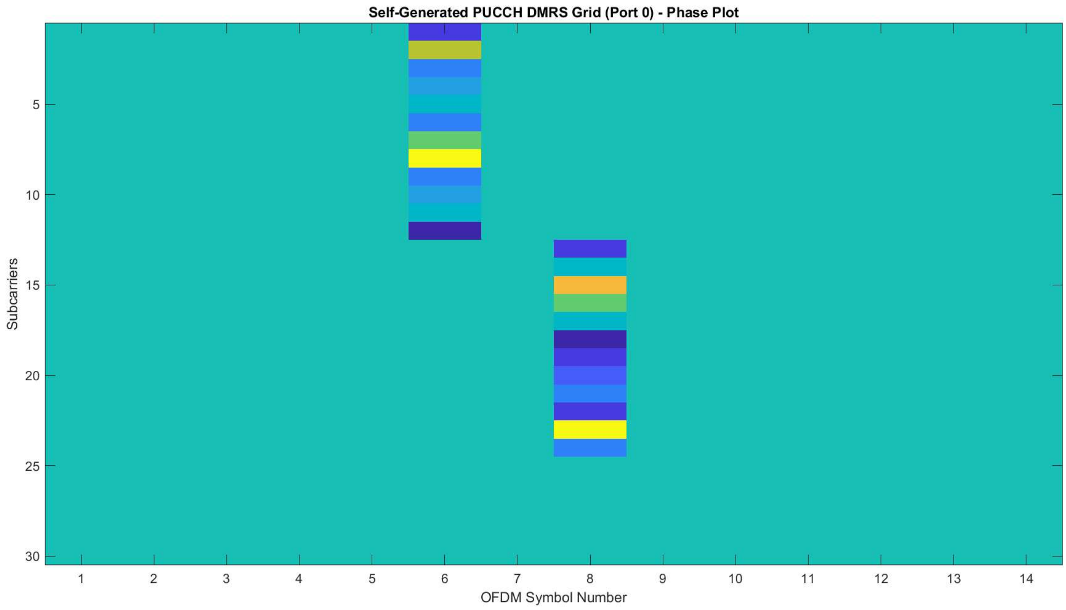

Figure 4.2: PUCCH Format 1 DM-RS

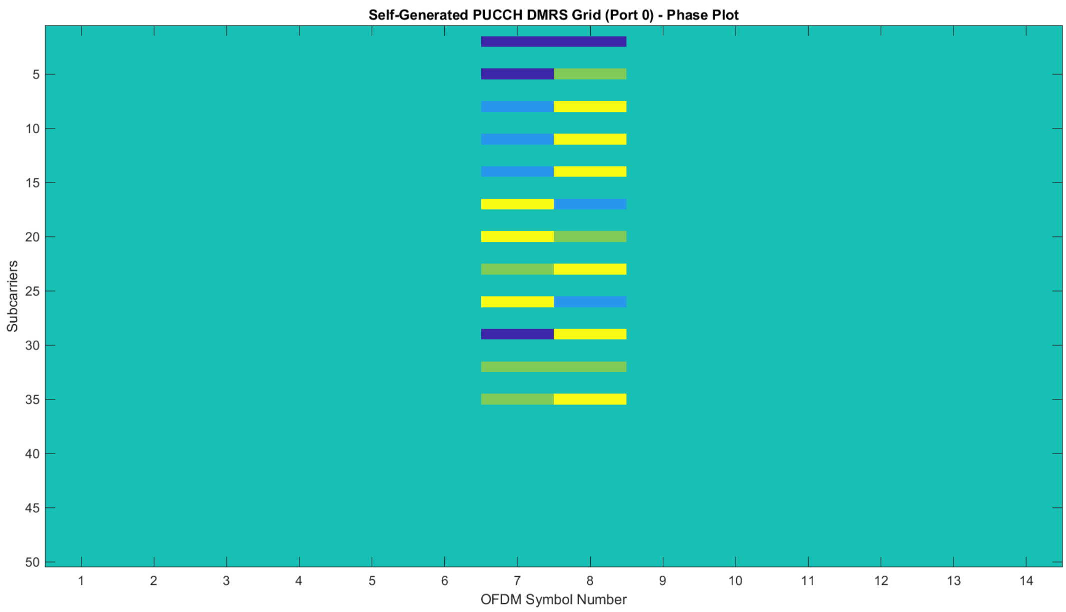

Figure 4.3: PUCCH Format 2 DM-RS

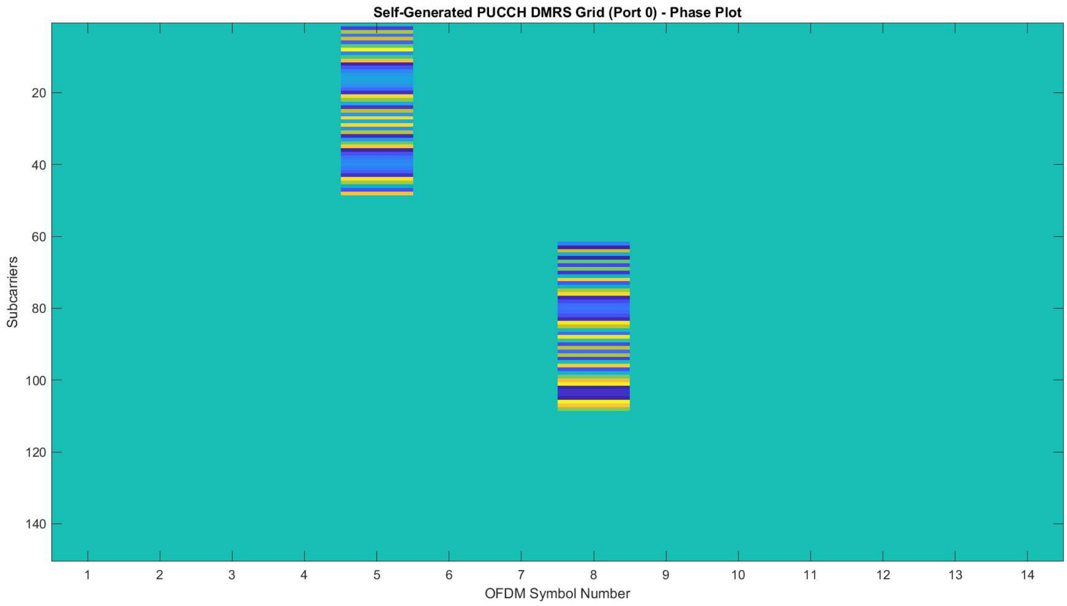

Figure 4.4: PUCCH Format 3 DM-RS

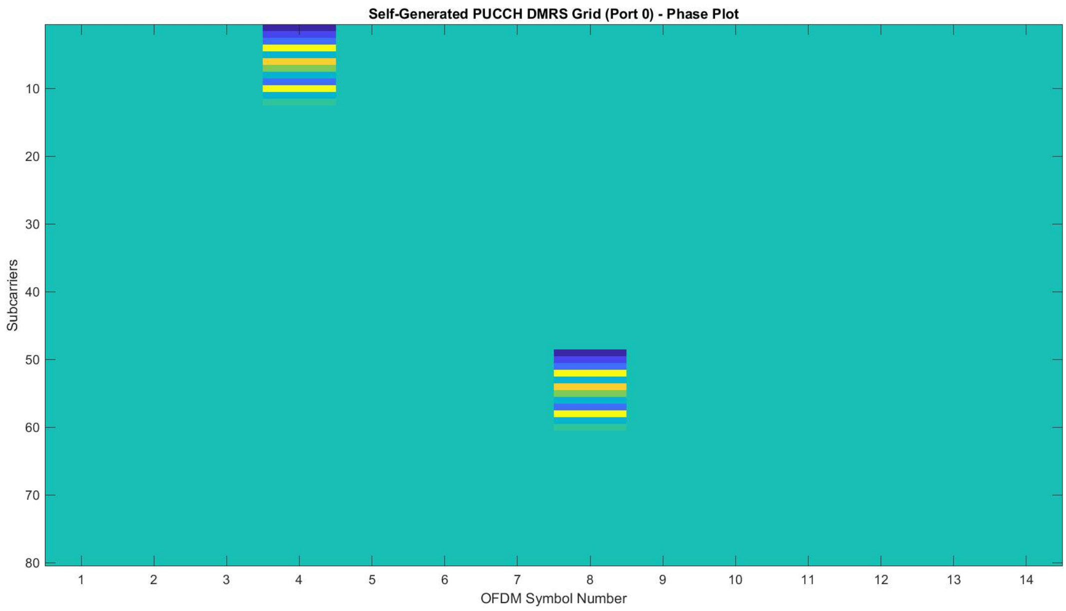

Figure 4.5: PUCCH Format 4 DM-RS

CHAPTER 5

PUSCH DM-RS Transceiver

Determination of the DMRS structure is strongly related to the channel characteristics because the main purpose of DMRS is to estimate the channel coefficient for coherent detection.More specifically, if the channel fluctuates more severely in the frequency domain (i.e., having shorter channel coherence bandwidth), the DMRS density in the frequency-domain should be increased.Whereas the effect of reducing DMRS density in the frequency domain can be advantageous in enhancing spectral efficiency. The spectrum efficiency provides a measure of how the proposed DMRS design helps efficiently utilize the available bandwidth. Similarly,if the channel varies faster (i.e., having shorter channel coherence time), denser DMRS allocation in the time-domain is needed.There is a trade off between the channel estimation accuracy and DMRS overhead.Since any useful data cannot be transmitted by DMRS, allocating DMRS with a proper density is required in order to maximize throughput.
The front-loaded RS structure is particularly advantageous in decoding latency reduction for low mobility scenarios where channel coherence time is longer than the time period of front-loaded RSs. However, allocating only the front loaded DM-RS can degrade the link performance when the UE speed becomes higher (i.e., channel coherence time becomes shorter). Although the channel information in the data region can be obtained by interpolation, the channel information accuracy severely degrades with higher mobility.So selecting channel model for different scenarios and corresponding DM-RS structure is particularly important for simulations

CP : the guard interval, which is chosen to be grater than the delay spread and contains the cyclically extended part of the OFDM symbol for eliminating inter-carrier interference, is inserted to avoid inter-symbol interference.

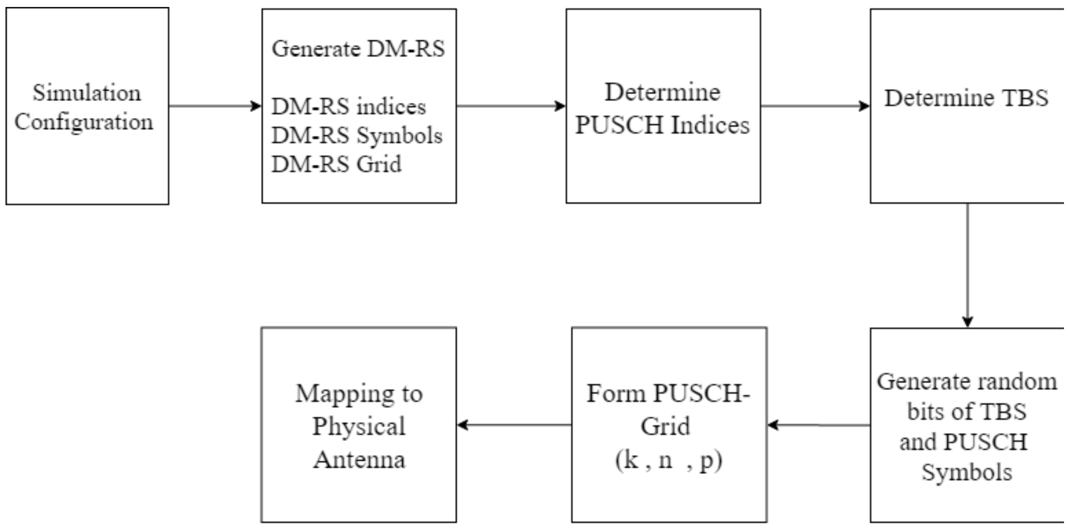

Figure 5.1: Transmitter

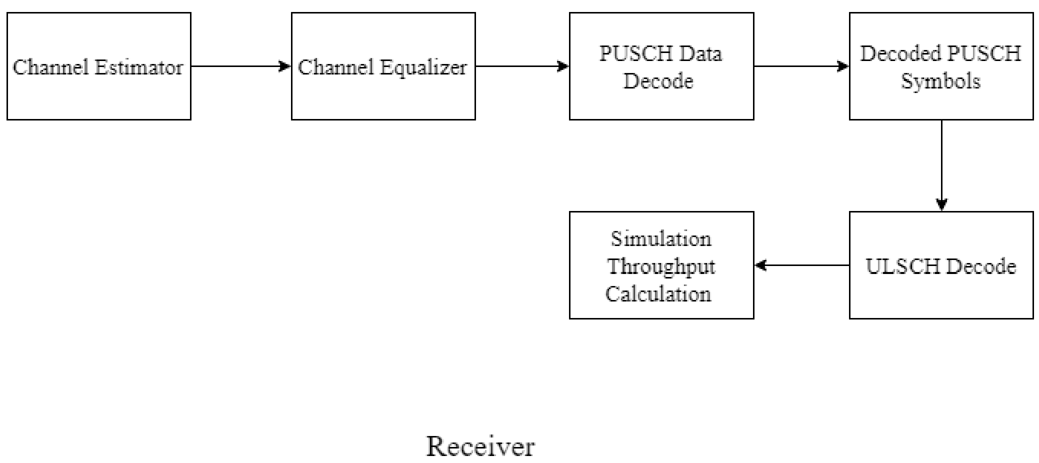

Figure 5.2: Receiver

5.1 Channel Model

A channel is depicted as a physical medium in the radio sign structure, the source to that of the sink. A numerical portrayal to move attributes in the physical medium characterizes the channel model. These channel models are figured through perception of the characters of the sign got. In the thesis i've used TDL models for simplified evaluations, e.g., for Non -MIMO evaluations And also CDL channel Model for MIMO.TDL models are defined for the full frequency range from 0.5 GHz to 100 GHz with a maximum bandwidth of 2 GHz. Three TDL models, namely TDL-A, TDL-B and TDL-C, are constructed to represent three different channel profiles for NLOS while TDL-D and TDL-E are constructed for LOS. The Doppler spectrum for each tap is characterized by a classical (Jakes) spectrum shape and a maximum Doppler shift. Due to the presence of a LOS path, the first tap in TDL-D and TDL-E follows a Ricean fading distribution. For those taps the Doppler spectrum additionally contains a peak at the Doppler shift $fS = 0.7fD$ with an amplitude such that the resulting fading distribution has the specified K-factor. Each TDL model can be scaled in delay so that the model achieves a desired RMS delay spread.

5.2 Receiver

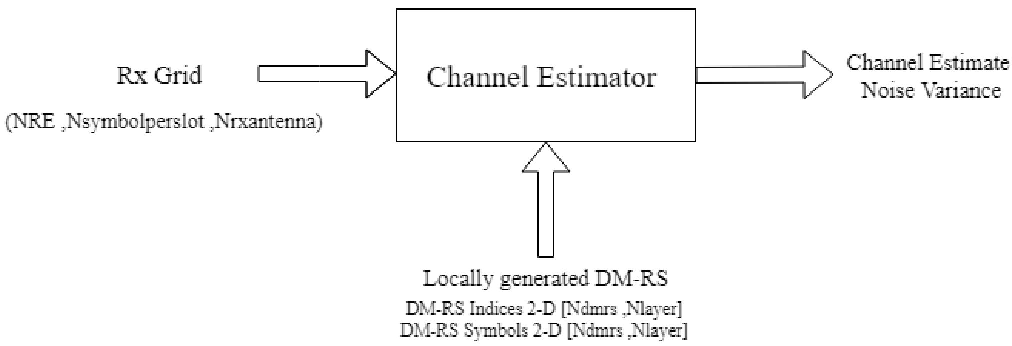

Figure 5.3: Channel Estimator Block diagram

The channel estimation procedure is intended to portray the physical medium and its impact on an information arrangement, and the fundamental point of this will be to limit the mean square blunder having less multifaceted nature. Let's take an overview of the receiver side, the major functional blocks and the corresponding processes are Passing

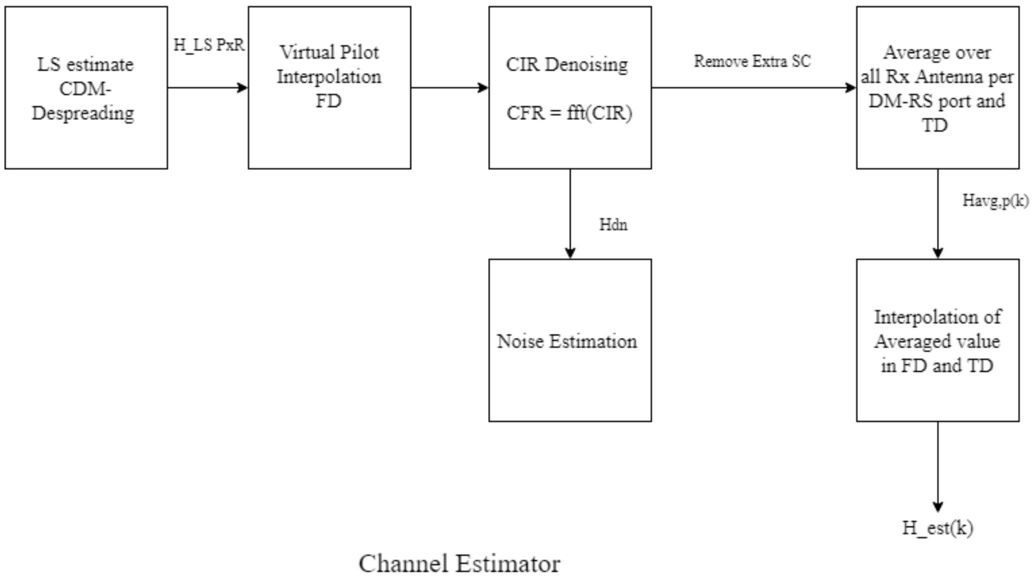

Figure 5.4: Channel Estimator Block diagram

the txwaveform through a fading channel. The 3GPP specifies the channel models to be used for simulations. The channel Models are CDL or TDL, where CDL stands for “Clustered Delay Line” and TDL stands for “Tapped Delay Line”. The fading channel simulates channel delay and multipath fading. More details will be discussed in the later slides. Noise addition at the receiver end. The noise here is additive white gaussian with zero mean. The variance is calculated from the SNR. After this the actual process of demodulating the received waveform begins. The first step is to estimate the timing, that is from where the slot is beginning, the timingEstimate block returns a timingoffset, from that index on wards the rxwaveform entries will be considered further. Now, OFDM-De-Modulation. This is just the reverse process of what is done at the transmitter side. Firstly the cyclic prefix (CP) is removed followed by N point FFT. The samples now are in the frequency domain. The output of the ofdm de-modulation block is referred by rxGrid and now, will be passed to the channel estimator block. In short this block takes locally generated reference DMRS symbols and indices using the same configuration as set for the simulation and then does a Least Square estimation, to estimate channel frequency response and also the noise variance. More on this block will be discussed later. Then the estimated Channel response is used to equalize the received grid (rxGrid) , which is followed by decoding of the pusch symbols , and then ULSCH decoding, and then finally BER calculation is performed. Now, I will further discuss each of the blocks in detail.and also highlight the importance, role, and short description on how it's programmed.

AWGN Noise This block simulates noise addition that happens at the receiver front end, due to the receiver side electronics. It's well known to be modelled as additive white gaussian, with zero (0) mean and variance that is calculated from the simulation parameter SNR (signal to noise ratio). The complex noise is randomly generated using MATLAB's "rand-n" function. You can see in the slide the mathematical expression to calculate the noise variance. This variance is calculated per resource element (RE). To quickly summarize, until this point in the transceiver simulation, we have successfully generated the transmit waveform (txwaveform) and passed through a channel followed by noise addition, and now the reverse of what has done for generating the transmit waveform (txwaveform) is performed. So the first block in the series of blocks that will finally result in decoding of pusch symbols is the ofdm demodulation block. Even before beginning to demodulate, it's important to first estimate the slot boundary, since the channel introduces delay. Hence the timing estimate block.

Timing Estimate As you can see from the block diagram shown here, the input to the timing estimate block is the rxwaveform, and the reference dmrs symbols and indices. This block typically performs a correlation between received waveform and the reference symbol, per receive antenna, and then stores the index of the maximum value of the correlated vector, which is the timing peak. The index is the offset from where the slot begins. This timingoffset is calculated for each of the receive antennas.

OFDM Demodulation To reiterate, the first step is cyclic prefix removal, followed by N point fast fourier transform (fft). The output from this block is the received grid (rxGrid) whose dimensions are "NRE" cross "Number of symbols in a slot" cross "number of receive antennas". The importance of cyclic prefix has been highlighted earlier. The channel estimation step is the most prominent step in all of the blocks in a link level simulation. It's a huge block and for better understanding , I have created a more detailed block diagram of processes performed inside the channel estimator block and can be seen here on the screen.

Channel Estimation A quick overview of the functional block diagram, is firstly the the least squares estimate of the channel is calculated with the help of reference symbols which also includes FDM and or TDM despreading, followed by virtual pilot creation, and then the channel estimate interpolation at the relevant frequency indices. After this it is channel denoising, where the channel impulse response is smoothened by a raised cosine window. A copy of the channel estimate before it is denoised is stored, and then the variance between the samples of LS channel estimates and denoised channel estimate is calculated, which is the noise variance. This is then followed by first averaging in frequency and then interpolation of channel frequency response at non-reference symbol subcarriers. Finally the same is performed in time.

Channel Least Square Estimate The least square estimate is a computationally low-complexity estimator. In implementation the process is not so straight forward. We have a rxGrid of dimension "N-RE cross N-ofdm symbol-per slot cross number of rx antennas", whereas the channel estimates to be generated should be of dimension " N-RE cross N-ofdm symbol-per slot cross number of rx antennas cross number of dmrs ports". The estimator estimates the overall channel including the effect of dmrs port grids mapped to physical antennas, where it is multiplied by spatial filter F. A loop is run for each dmrs port, within which another loop is run for each received antenna, within which LS estimates are computed as per the equation discussed earlier. Another important step is the FDM despreading. The despreading is done in an averaging sense, for all the reference symbols in the subcarriers of an OFDM symbol,FD-CDM length number of subcarriers are grouped and averaged over sub-carriers within the group. and then the channel estimate is replaced by this averaged value. After this stage we have channel estimates for all the reference subcarriers in ofdm symbols containing these reference symbols. The dimension of this estimated channel response is dimension " N-RE cross N-ofdm symbol-per slot cross number of rx antennas cross number of dmrs ports". The final stage in this sub-block is to perform TDM despreading. This is similar to how FDM desprading is done, where TDMLength samples are grouped together.

VP interpolation and CIR denoising The next step is virtual pilot interpolation and hence estimation of channel estimates at the virtual pilot indices, which are later used to interpolate channel frequency response at remaining non - reference indices of the channel estimate grid.The reason for doing so is to be able to estimate channel frequency response at lower and higher edges of the frequency bandwidth. The already present reference pilot symbols aid in estimating CFR at subcarriers present in between, the sub-carriers containing pilot symbols. The broad steps involved are First creation of virtual pilot interpolators at the low frequency and high-frequency edges. For this we have added extra subcarriers. These interpolators are used to create virtual pilots. The interpolator uses reference symbols that are closer to it in the euclidean distance sense from the whole grid. Second step is to calculate the virtual pilot indices for each reference symbol containing OFDM symbol, for each port and receive antenna. In these indices with the help of virtual pilot interpolators, virtual pilots will be calculated linearly Lastly the channel estimates will be interpolated in the frequency using the 'spline' method for all the relevant frequency sub-carriers. Now, the least square estimate channel impulse response will be denoised using a raised cosine window in the time domain. As you can see on the screen, the estimated channel frequency response is first transformed to channel impulse response by performing ifft and then element wise multiplication with the raised cosine window. It is assumed that the channel impulse response is of finite length and the cyclic prefix considered is at least the length of the channel impulse response. The raised cosine window truncates and smoothly thresholds the channel impulse response, thus results in denoising. This is again transformed to channel frequency response. Finally the noise variance is calculated by measuring the variance between the original LS estimates and the denoised channel frequency response.

Averaging and Interpolation The final sub block is the averaging and interpolation, first in frequency and then in time direction. The central averaging is done to further reduce the noise. The window length is an odd number, to maintain symmetry, that is take an equal number of samples before and after the sample which is going to be replaced by the averaged value. Firstly the averaging is done in the frequency direction followed by interpolation of channel frequency response at non-reference subcarrier indices using the 'spline' method.

Channel Equalization Channel equalization is the next very important step, this step is responsible for reversing the effect of channel and noise in the received symbols. For the SISO case the steps involved are very straightforward, the csi is calculated by the expression shown on the screen, and the received symbols grid is scaled down by this calculated csi and multiplied by the conjugate of the estimated channel frequency response, this kind of equalization is referred to as MMSE equalization. Here the ".*" represents element-wise multiplication. The csi is later used for other purposes too. For the non-SISO cases, the steps are more involved as compared to the former case. The process is the same, the difference is, it's performed per RE for all ports and receive antennas.

Throughput and BER results The throughput here is the percentage of successful transport block transmissions for each SNR. The BER is the average number of error bits received. This is also calculated per SNR. The simulation has been run for 2 frames for each SNR point,

5.3 SNR vs BER curves

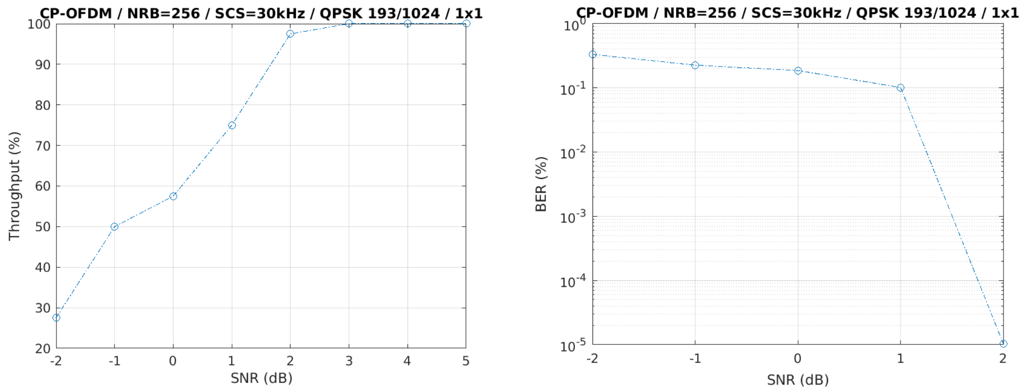

Figure 5.5: For UE - 1 Configuration

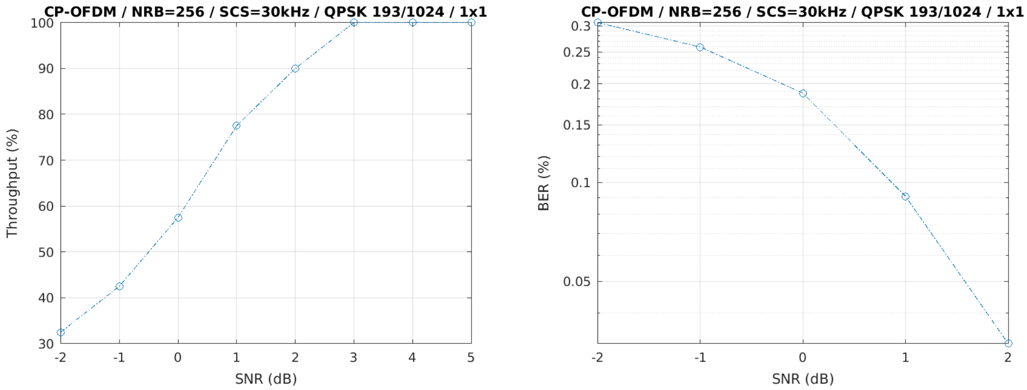

Figure 5.6: For UE - 2 Configuration

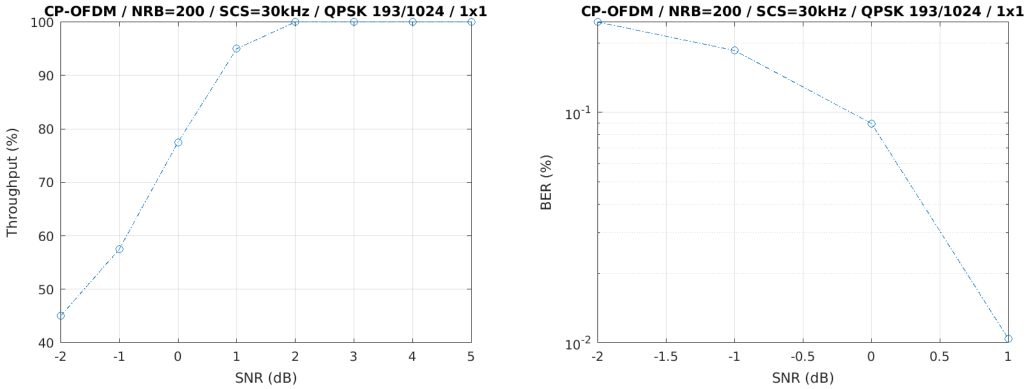

Figure 5.7: For UE - 3 Configuration

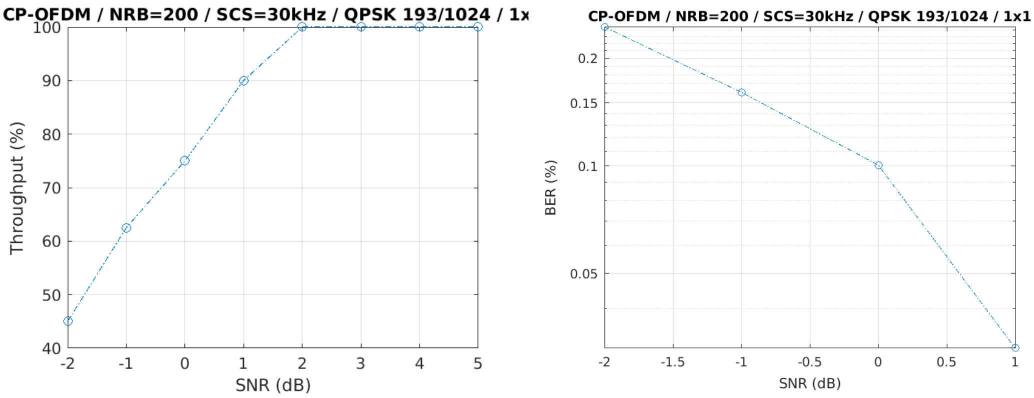

Figure 5.8: For UE - 4 Configuration

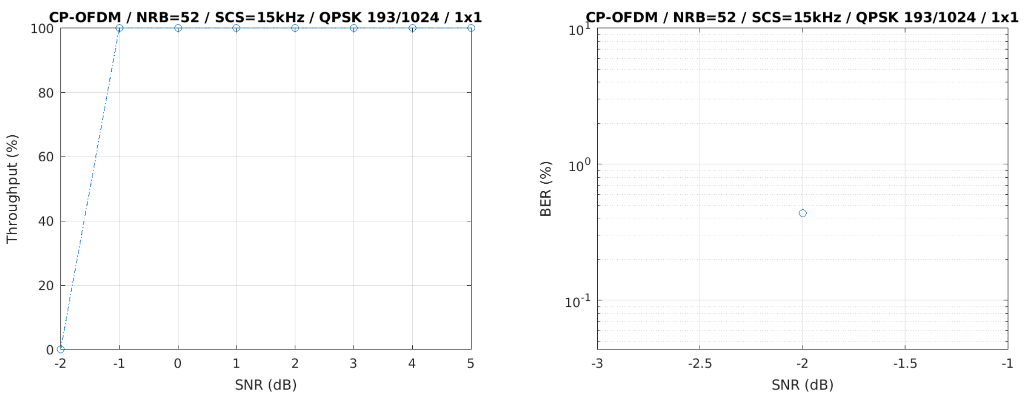

Figure 5.9: For UE - 5 Configuration

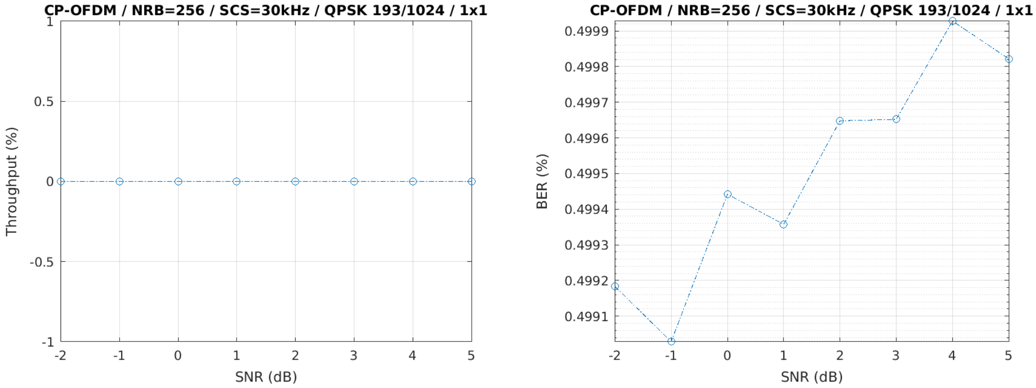

Figure 5.10: For UE - 6 Configuration

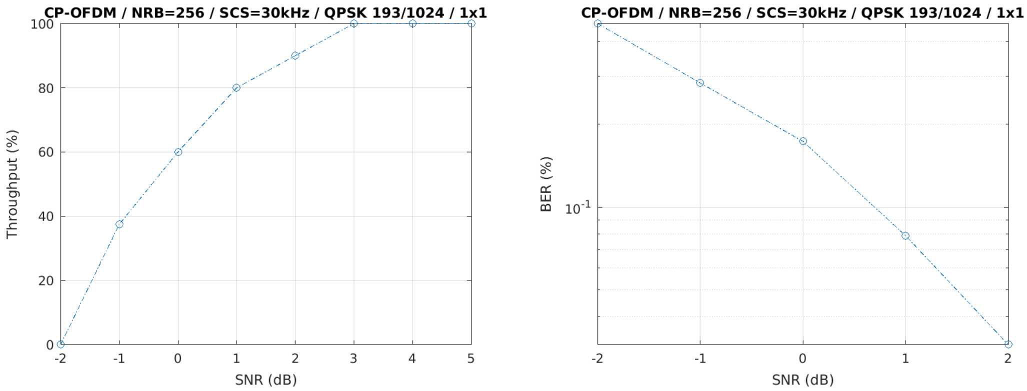

Figure 5.11: For UE - 7 Configuration

CHAPTER 6

Equations

- Low PAPR Sequence $r(n) = r_{u,v}^{\alpha,\delta}(n)\ n = 0, 1, 2...M_{sc}^{PUSCH}/2^{\delta} - 1$
- Gold Sequence: $r(n) = \frac{1}{\sqrt{2}}((1 - 2c(2n)) + j(1 - 2c(2n + 1))$
  $c_{ini} = (2^{17}(N_{sym}^{slot} n_{s,f}^{\mu} + l + 1)(2N_{ID}^{n_{SCID}}) + 2N_{ID}^{n_{SCID}} + n_{SCID}) mod 2^{31}$
- Mapping to PRB :Configuration Type 1 $\tilde{a}_{k,l}^{(p_j,\mu)} = w_f(k')w_t(l')r(2n + k')$
  $$k = \begin{cases} 4n + 2k' + \Delta & \text{Configuration Type 1} \\ 6n + k' + \Delta & \text{Configuration Type 2} \end{cases}.$$
  $k' = 0, 1$
  $l = \bar{l} + l'$
  $n = 0, 1, ...$
  $j = 0, 1, ..\nu - 1$ Configuration Type 2 : $\tilde{a}_{k,l}^{(p_0,\mu)} = w_f(k')w_t(l')r(2n + k')$
  $$k = \begin{cases} 4n + 2k' + \Delta & \text{Configuration Type 1} \\ 6n + k' + \Delta & \text{Configuration Type 2} \end{cases}.$$
  $k' = 0, 1$
  $l = \bar{l} + l'$
  $n = 0, 1, ...$
- PUSCH Precoding : $\begin{bmatrix} a_{k,l}^{(p_0,\mu)} \\ . \\ a_{k,l}^{(p_{\rho-1},\mu)} \end{bmatrix} = \beta_{PUSCH}^{DMRS} W \begin{bmatrix} a_{k,l}^{(\tilde{p}_0,\mu)} \\ . \\ a_{k,l}^{(\tilde{p}_{\nu-1},\mu)} \end{bmatrix}$
- PUSCH PT-RS $r^{(p_j)}(m) = \begin{cases} r(m) & \text{for j = j' or j=j''} \\ 0 & \text{otherwise} \end{cases}$
  $r_m(m') = W(k')\frac{e^{j\frac{\pi}{2}(m mod 2)}}{\sqrt{2}}[(1 - 2c(m')) + j(1 - 2c(m'))]$
  $m' = N_{samp}^{group} s' + k'$
  $s' = 0, 1, ...N_{PT-RS}^{group}$
  $k' = 0, 1, .N_{samp}^{group} - 1$
  $c_{ini} = (2^{17}(14^{slot} n_{s,f}^{\mu} + l + 1)(2N_{ID} + 1) + 2N_{ID}) mod 2^{31}$
  $$\begin{bmatrix} a_{k,l}^{(p_0,\mu)} \\ . \\ a_{k,l}^{(p_{\rho-1},\mu)} \end{bmatrix} = \beta_{PUSCH}^{DMRS} W \begin{bmatrix} a^{(\tilde{p}_0,\mu)}(2n + k') \\ . \\ a^{(\tilde{p}_{\nu-1},\mu)}(2n + k') \end{bmatrix}$$
  $$k = \begin{cases} 4n + 2k' + \Delta & \text{Configuration Type 1} \\ 6n + k' + \Delta & \text{Configuration Type 2} \end{cases}.$$

APPENDIX A

Code Details

The code is in

```
git@172.16.1.10:aniruddh/5g_matlab_sim.git
```

repository in the *uplink_dmrs* branch.

REFERENCES

1. TS 38.211 NR; Physical channels and modulation
2. TS 38.212 NR; Multiplexing and channel coding
3. TS 38.214 NR; Physical layer procedures for data
4. TS 38.331 NR; Radio Resource Control (RRC); Protocol specification
5. TS 38.900 Study on channel model for frequency spectrum above 6 GHz