Implementation of PDSCH Receiver and CSI-RS for 5G-NR

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This Thesis entitled Implementation of PDSCH Receiver and CSI-RS for 5G-NR by Gautam Kumar is approved for the degree of Master of Technology from IIT Hyderabad

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Dedication

To my IIT-H Friends and Family

Abstract

PDSCH (Physical Downlink Shared Channel) is the data-bearing channel in 5G-NR. In order to decode data, it needs DCI (downlink control Information) from PDCCH (Physical Downlink Control Channel).

PDSCH uses LDPC(Low-Density Parity Check) code for encoding the data which is an error-correcting code. One of the main blocks of PDSCH is Rate Matching and scrambling followed by modulation. NR supports modulation up-to 256 QAM (Quadrature Amplitude Multiplexing).

AWGN and TDLC channel Model (delay spread) as defined in 3GPP specifications are used for the simulation purpose. The Channel estimator used for PDSCH is Least square followed by tone-averaging and linear interpolation in time.

The block error rate performance highly depends on the channel quality between the base station and the receiver. For acquiring the channel quality, NR specifies a special type of cell-specific reference signal which can be configured for transmission on up-to 32 antenna ports. The CSI-RS resources are code, frequency and time division multiplexed. After passing through the channel the CSI receiver estimates the channel, and finds the suitable rank, the precoding matrix to be used and the MCS and feeds it back to the transmitter which is free to use the recommendation give by UE or follow its own. In either case, it signals the parameters used in the base station back to UE.

Contents

Chapter 1

Evolution of 5G

1.1 Generations of Wireless Communications

First Generation

Evolved based on analog transmission and communication systems based on this could support voice services Only.

Second Generation

The digital transmission was the base for 2G allowing not only the voice services but also limited data services. DAMPS, GSM are some of the second-generation technologies.

Third Generation

As is popular with the name 3G was introduced in early 21^{st} century.It powered high-speed wireless internet access. Earlier generations were designed to operate in paired spectrum involving FDD, but with the evolution of 3G saw the introduction of an unpaired spectrum in wireless communication based on TDD.

Fourth Generation

In the current era of 4^{th} generation or more popularly known as LTE, operation in the unpaired & paired spectrum is supported. It delivers comprehensive performance and improved mobile - broadband experience in terms of data rates with the help of transmission using OFDM (Orthogonal Frequency Division Multiplexing).

Fifth Generation

5G often coined as NR (New Radio-an indication that unlike LTE is not limited to preserve backward adaptability) is an assemblage of technology from Physical layer to Core Network that achieves mainly three idiosyncratic types of services:

1. eMBB(Enhanced Mobile Broadband)

- Better User Experience in terms of data rates.
- Higher Data Volumes.

2. mMTC(Massive Machine-type Communication)
   - Long battery life
   - Low device complexity
   - Improved link budget
3. URLLC(Ultra-reliable low latency Communication)
   - Low Latency
   - Acutely high reliability & Availability
   - Low packet data error rate

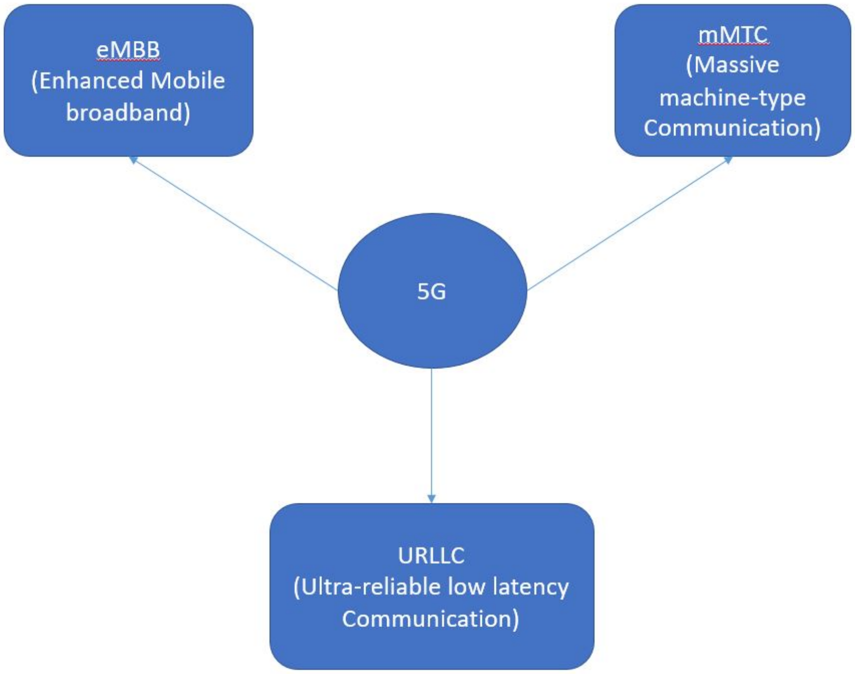


Figure 1.1: Use Cases

Chapter 2

Overview of NR

2.1 Benefits of 5g over LTE

1. The NR's ultra-thin design enhances the energy performance of the network and help in reducing interference.
2. Low latency which improves performance.
3. Spectrum Flexibility with the high-frequency operation.
4. NR does not rely upon CRS for channel estimation enabling efficient multi-antenna transmission and beam-forming.

2.2 Transmission Scheme & Bandwidth parts

Transmission Scheme

OFDM is used as a waveform in NR as it easily exploits frequency and time domain and is also robust to time dispersion.LTE uses DFT-precoded OFDM for uplink transmission whereas in NR for the uplink transmission non-DFT-precoded OFDM is used due to its simplicity in the implementing state of the art and simple receivers. However, NR also supports complementary DFT-precoded OFDM.

Bandwidth parts

NR due to its huge bandwidth support does not assume that the device will use the full carrier bandwidth. So NR uses the receiver bandwidth adaptation in cases when there are large data to be received the receiver uses the full carrier bandwidth and for monitoring control channels the receiver uses narrower bandwidth. To efficiently handle this aspect the NR uses Bandwidth parts(BWPs) which is a collection of contiguous resource blocks.

2.3 Numerologies & Frame Structure

In NR the numerology varies from 15Khz to 240Khz which in turn changes the length of the cyclic prefix. If the subcarrier spacing is less then there will be longer cyclic prefix but it comes with overhead. In turn, if the subcarrier spacing is more than the length of the cyclic prefix will be less but then the advantage is it can effectively nullify the phase-noise which occurs at frequencies which are relatively higher. In selecting between longer or shorter cyclic prefix length there is a trade-off between overhead relative sensitivity to phase noise & doppler.

The system frame number (SFN) helps in identifying the radio frame. One Radio frame is comprised of ten 1-ms subframes. The subframe is further subdivided into slot depending upon the numerology. For Example: If the numerology μ is 2 then the corresponding subcarrier spacing will be $2^{\mu} \times 15KHz$ =60 KHz and the number of slots per subframe will be 2^{μ} =4. However N_{symbol}^{slot} is constant equal to 10.The no. of symbols in one sub-frame for our case will be $N_{slots}^{\mu,subframe} \times N_{symbol}^{slot}$ to 4×10=40.

We can infer that as the sub-carrier spacing increases the CP length shrivels thus making it infeasible to deploy in many situations. In an attempt to achieve low latency in an efficient way NR supports mini slot transmission (transmission is done in only a fraction of a time slot). Just to mention such transmission preempt the ongoing slot-based regular transmission to make room for the transmission which requires low latency. Such mini slot transmission has the advantage also in transmission in unlicensed spectra where a base station eNb starts transmitting as soon as its the radio channel is vacant, a procedure coined as ”listen-before-talk”. In the figures below we show the frame structure for all numerologies supported by NR.

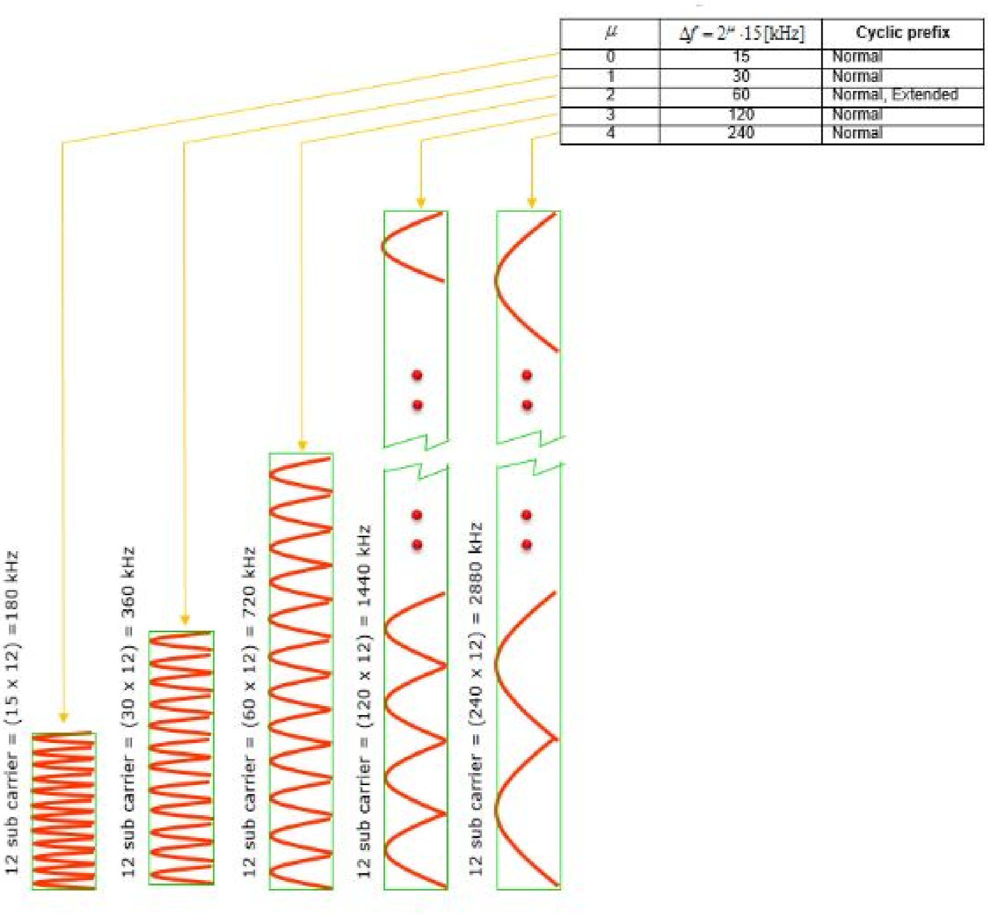
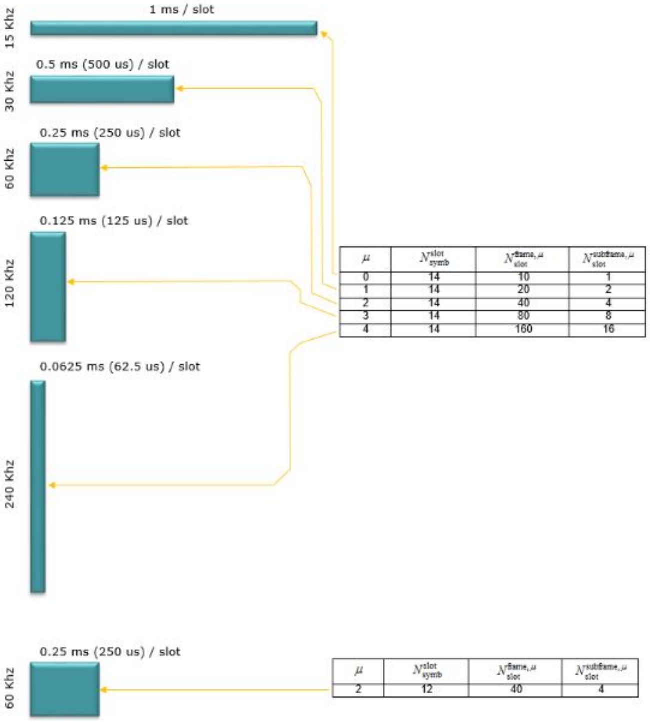


Figure 2.1: Bandwidth occupied by a resource grid in various numerologies



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

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

Figure 2.2: Time duration of Slots in various numerologies

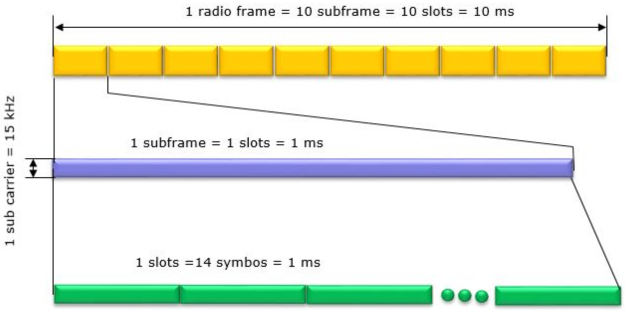


Figure 2.3: Frame Structure for Numerology 0

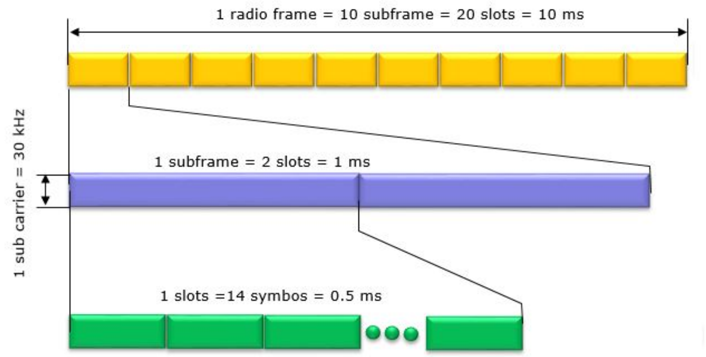


Figure 2.4: Frame Structure for Numerology 1

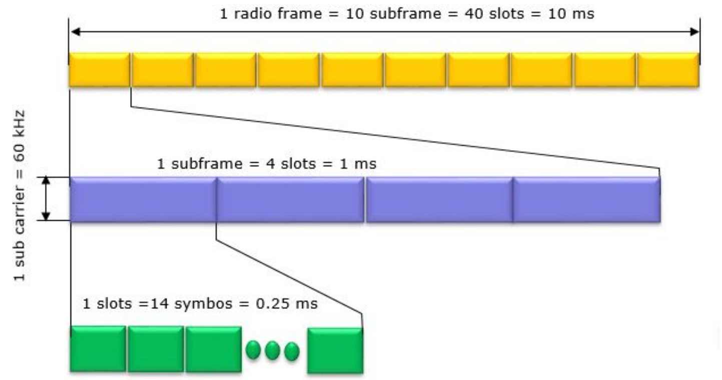


Figure 2.5: Frame Structure for Numerology 2

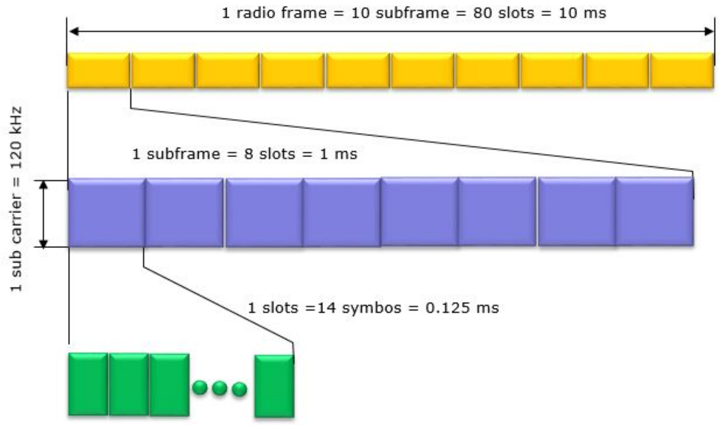


Figure 2.6: Frame Structure for Numerology 3

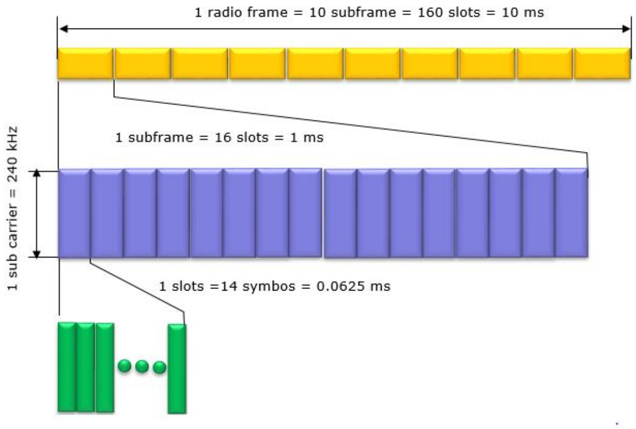


Figure 2.7: Frame Structure for Numerology 4

2.4 Duplex Mode in 5G

The duplex mode to be used for data transmission mainly depends on spectrum allocation. For example, if we are operating in lower frequency bands then allocation will be paired that is frequency division duplex. Contrary to it for higher frequency bands unpaired spectrum allocation is used, named as time division duplex. Contrary to LTE which depends on two different frame structures, NR has the cushion to operate in both unpaired and paired spectrum using the same frame arrangement. IN NR we also have dynamic TDD in which there is changing distribution and redistribution of the resources in time between uplink and downlink transmission directions. For example: If we are in a cell all alone and need to play a large file say video/audio then only and a few resources will be used in uplink whereas a maximum of the resources will be used for downlink.

2.4.1 Time Division Duplexing (TDD)

- In this One carrier frequency is used for UL and DL transmission but they are separated in time.
- There is a chance to provide a guard interval where no transmission occurs which helps in switching between UL and DL transmissions.

2.4.2 Frequency Division Duplex (FDD)

- For DL and UL transmission different carrier frequency is used but they enjoy the full set of slots in a frame.
- The isolation between the UL and DL is achieved by using transmission and reception filters.

2.4.3 Half Duplex FDD

- UL and DL transmissions are separated both in time and frequency.
- The device is incapable of concurrent reception and transmission.

Chapter 3

Physical Layer

The Physical layer is responsible for modulation, multiple antenna processing, coding, and mapping of the signal to the correct frequency-time resource. The mapping of the physical channel to the transport channel is also handled by it. It is a sort of service provider to the MAC layer in the form of transport channels.

3.1 Physical channel

This corresponds to the collection of time-frequency resources utilized for the broadcast of the given transport channel, which is mapped to their own physical channels. There are some physical channels that don't have their own transport channel and popularly known as L1/L2 channels are used for downlink control information(DCI) and uplink control information(UCI).

The physical Channel types defined for NR are as follows:

1. The Physical Downlink Shared Channel (PDSCH).
2. The Physical Broadcast Channel (PBCH).
3. The Physical Downlink Control Channel(PDCCH).
4. The Physical Uplink Shared Channel (PUSCH).
5. The Physical Uplink Control Channel(PUCCH).
6. The Physical Random-Access Channel(PRACH).

3.1.1 The Physical Downlink Shared Channel

This is the main channel used for data transmission, paging information, some parts of system information and also random-access response message. It decodes DCI from PDCCH which provides necessary information to decode data in PDSCH. Within each TTI one or two transport blocks of variable size comes to the physical layer and is transmitted over the radio interface. Then we attach the CRC (Cyclic Redundancy check) for error detection purpose to each transport block followed by LDPC(Low-density Parity-check code) an error correcting code. The processes which follow are

Rate matching which helps to adapt the number of coded bits to the total number of the scheduled resource.

This follows the important process of scrambling which is done to randomize the interference helping the decoder at the receiver to decode in an efficient way. The scrambling sequence depends on the physical layer cell id. After the scrambling, we go for modulation. The modulated symbols are then mapped to the actual physical resources. After the mapping, we go for IFFT and CP insertion at each of the transmitter antennae of the downlink. The IFFT size we can use is variable ie 2048,4096 etc. The length of CP added to the different symbols are also different, i.e for the First and Seventh symbols of each slot its length is 288 and for the other symbols, the length is 320.

3.1.2 The Physical Broadcast Channel

This carries the main part of the information necessary to access the network.PBCH carries system information for UE's. A 5g compatible device must decode the PBCH data in-order to get access to the Cell.PBCH is mainly of the following things:

- Downlink System BW
- Timing information
- SS burst periodicity
- System frame number (SFN)

NR supports only one antenna port based transmission for PBCH data in order to avoid blind decoding.

3.1.3 The Physical Downlink Control Channel

As from the name it is clear this channel's functionality is to provide scheduling decisions necessary for the reception of PDSCH and also scheduling grants which enables transmission on PUSCH. Unlike LTE where the control channels were always distributed across the full system bandwidth thus introducing inter-cell interference, NR's PDCCH is designed specifically to be transmitted in a CORESET(control resource set) with its own demodulation reference signals enabling better beamforming of the control channel.

CORESET

A set of physical resources which has varying time and frequency domain length. In time domain it may occupy 1,2,3 OFDM symbols whereas in frequency domain it is in a multiple of one resource block(12 subcarriers).

3.1.4 The Physical Uplink shared Channel

It is the uplink equivalent to PDSCH. There is at most one PUSCH per uplink component carrier per device. The physical layer processing for both uplink and downlink shared channel is the same. It mainly carries the UCI, CSI feedback, HARQ feedback, and various scheduling request. It can handle a low payload than the PUSCH. Unlike the PUCCH in LTE where it is located at the cell edges with fixed timing and duration in NR, we have flexibility in doing so. The PUCCH is designed based on 5 formats: PUCCH formats 0,2 which uses 1 or 2 OFDM symbols in time the PUCCH formats 1,3,4 can use 4 to 14 OFDM symbols.

3.1.5 The Physical Random-Access Channel

This is used for random access. The main purpose of PRACH is to achieve the synchronization between gNB and the UE(user equipment). The downlink synchronization signal is broadcast for all time within a specific interval. It also helps gNB to adjust the timings of the UE in uplink directions.

3.2 Reference Signals

These are the predefined signals which occupy particular positions those resource elements (RE's) in the resource grid. Unlike LTE which heavily depended on CRS for channel estimation, coherent demodulation and channel quality estimation for CSI reporting the NR in line with its attempt to have ultra lean design transmission uses various different reference signals for different functionalities. The reference signals of NR include:

3.2.1 Demodulation Reference Signals

It is mainly used for channel estimation at the device for serving the purpose of coherent demodulation. These reference signals are present in every resource block of the Ul and DL transmission.

3.2.2 Phase Tracking reference Signals

PTRS as is abbreviated as is mainly used for compensating the phase noise. It is sparser in frequency and denser in time as compared to DMRS.

3.2.3 Channel State Information reference Signals

CSI-RS is used by the device to acquire information about the downlink channel. It is decoded by the device and sent as the feedback to the base station as part of reports via PUSCH and PUCCH. The base station then understands the channel quality between a link and change various parameters like the number of transmission layers, modulation and coding scheme and the pre-coding matrix to be used to map the number of transmit antenna to the transmitted no of layers.

3.2.4 Tracking Reference signals

It is intended to help the device in time and frequency tracking.

3.2.5 Sounding Reference Signal

This is the reference signal in the uplink direction transmitted by the device and used to get the info about the channel estimation at the base station.

Chapter 4

PDSCH Transmitter and Receiver

PDSCH is the main data-carrying channel. The receiver needs the DCI transported on PDCCH in order to decode the PDSCH data.

First, the SS Block and PBCH help in locking and making synchronization with the base station. After that, the data transmitted on PDCCH is decoded at the receiver which provides DCI which is needed by the receiver in order to decode the actual data.

Here is a brief overview of the flow of the transmitter and the receiver chain of the PDSCH is presented[2].

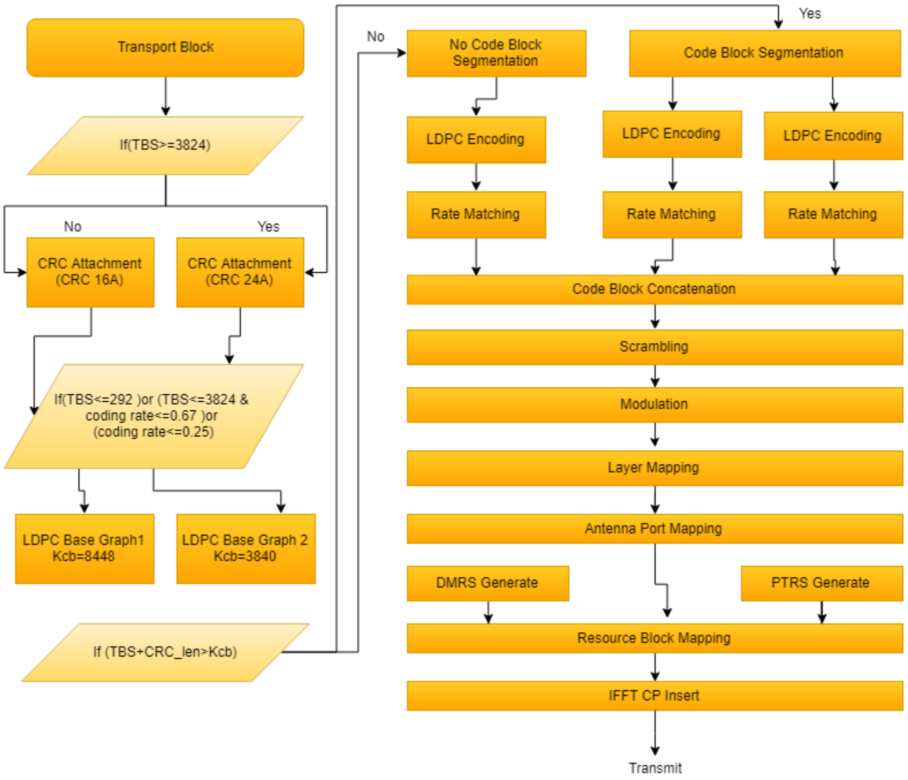


Figure 4.1: Block Diagram of PDSCH transmitter

4.1 PDSCH Transmitter

4.1.1 Transport block Generation and CRC attachment

The data at the transport block level is coming from the higher layer. For the simulation purpose, the data is generated in MatLab using the random generator randn function. The length of the transport block data depends on many factors:

- Amount of data to be transmitted.
- The no of scheduled resources.
- The channel quality.

After the transport block-level data comes in, the transport-level CRC is attached to the block of data. The CRC attachment is done in a way that it is encoded in a systematic form in GF2.CRC stands for cyclic redundancy check which is an error detecting code. In NR different CRC polynomials of different lengths are defined viz CRC 24A, CRC 24B, CRC 16.

The CRC polynomial to be used for calculation of parity bits depends on the transport block length as shown in the flow diagram.

4.1.2 LDPC base Graph Selection

After attaching of CRC at the transport block-level, depending on the coding rate, the transport block length and the CRC polynomial length, LDPC base graph selection is done which will be used to generate different parity matrix for encoding the data prior to rate matching block. Needless to say that the LDPC is an error correction code used in NR. In LTE we use the turbo code but the performance of the LDPC code is optimum.

4.1.3 Code Block Segmentation and CRC attachment

After the CRC attachment at the transport block-level, the data goes through this block. If the data length after the previous CRC attachment exceeds a given constant value (determined by LDPC base graph 1 or 2) the data is segmented into more than 1 resource block. The segmentation is done because of the limitation of the LDPC encoder to code a large block length of data. If the input data length to the LDPC is lesser, then the LDPC coding is extremely fast ensuring the low latency promised in NR. After the segmentation, the length of each code block is the same and then again CRC is attached at this level. The purpose of attaching two different CRC's is to ensure and fasten the receiver processing. For example: If at the receiver end a code block is unable to pass the CRC check function then the whole transport block is rejected and the same is fed back to the transmitter which then retransmits the total block depending on the redundancy version.

4.1.4 LDPC coding and Rate Matching

Each code block data goes for LDPC coding separately. The LDPC coding is done based on the chosen base graph and the code block data coming in. LDPC stands for low-density parity-check code which is an error-correcting code. Before LDPC coding the data at the code block level is processed and the filler bit is removed as the LDPC should not encode the filler bit appended at the code block segmentation level[3].

After the LDPC coding, we again append the filler bits which we have undone during the processing of the data for LDPC encoding. The LDPC coded data goes for the rate matching. The rate matching is done to ensure that we are sending the correct data and not sending the repeated data. Rate matching consist of two important steps:

- Bit Selection: It is done by writing the LDPC encoded data in a circular buffer and then reading the data depending on the redundancy version.
- Bit Interleaving: After bit selection, the data is written in rows where the number of rows is determined by the modulation order used in NR. Then the data is reading column-wise that is the first element of each row is read and then the second element of other rows follow.

4.1.5 Code Block Concatenation

After the rate matching the data goes for code block concatenation. In this block, the data from each of the rate matched block comes and concatenated in a serial manner. Code block segmentation was done to ease the process of LDPC encoding which has difficulty working on larger block lengths. After the LDPC encoding is done there is no point of keeping the data in the previous form and thus concatenation follows.

4.1.6 Scrambling and Modulation

After the code block concatenation, the data passes through the scrambling block. The purpose of this block is for interference randomization which helps the decoder to effectively decode the data as the received signal strength of two adjacent base stations can be approximately equal. So by using different scrambling codes that depend on the Physical Cell layer ID which is unique in a cell the beam is randomized effectively suppressing or nullifying the effects of inter-cell interference. The intercell interference can now be treated just like noise and at the receiver, the processing is done accordingly.

After the scrambling, the data passes through the modulation block. In NR the specifications define modulation order up to 256 QAM all the way starting from the BPSK modulation scheme. For our simulation purpose, we have used up to 16 QAM constellation.

4.1.7 Mapping to Physical Resources

After the modulation, the data is in the form of symbols. These symbols need to be mapped to physical resources. In the mapping block, we have Layer mapping, virtual resource block mapping, and physical resource block mapping. In PDSCH there is one to one correspondence between layer mapping and antenna mapping.

4.1.8 IFFT and CP Insertion

After mapping to the physical antenna the data is taken into the time domain by passing through IFFT block which simply takes the fast Fourier transform of the data. The FFT size used for the simulation purpose is 4096. The need for using 4096 points FFT instead of 2048 or lower is that the PDSCH data, when configured for the full bandwidth part of 275 resource blocks, has a total of 3300 subcarriers. So the FFT size should be greater than 3300 and also be in the power of 2, hence we go for 4096 points IFFT.

NR defines two different CP lengths of 320 for the first and 8th symbol in a slot and for the rest of the symbol, its length is 288. After IFFT processing we attach the CP at the end of each symbol and concatenate it symbol-wise. The length of the output of this block is a vector of length 61440.

4.2 Channel Models

The channel model used for simulation purpose is AWGN and TDLC (Tapped delay Line Channel Model) with delay spread of 30ns. After the IFFT CP insertion block, the data passes through the radio channel[8].

4.3 PDSCH Receiver

This is the crux of this thesis. The wireless channel can be characterized by multipath through which when the data passes the gets attenuated and phase rotated randomly. This phase rotation needs to be countered by the receiver which is done in the equalizer block.

The received data at each of the receiver is the sum of various multipath components with noise added and phase rotated. The main purpose of the receiver is to get back the original bits transmitted by the transmitter.

The flow diagram of the receiver is as shown in the figure:

4.3.1 FFT and CP Removal

In this block, after receiving the data first the CP is removed from each OFDM symbol. This part is just the opposite of the CP insertion at the receiver. We remove the CP part in exactly the same way the CP was inserted after each OFDM symbol.

After the CP removal, the fast Fourier transform of the data vector per OFDM symbol is carried out. The FFT length is 4096 here. After doing this again the data comes in the frequency domain. The need to take the data in the frequency domain is because of the simplicity to implement simpler receiver structures.

4.3.2 Resource Demapping

After the FFT and CP removal block, the data passes through this block. This block is the counterpart of the resource and antenna mapper block. The data coming to this block is of size 4096×14.Here the bandwidth de-mapping is done and the actual data is extracted based on the resource allocation type signaled in the DCI. If the resource allocation type is 0 then the data is stored in non-contiguous resource blocks but if the resource allocation type is 1 then the data is kept in contiguous resource blocks.USing this first the data from the actual position is extracted and then we go for layer de-mapping. The layer de-mapping is just the opposite of the layer mapping done at the transmitter.IN

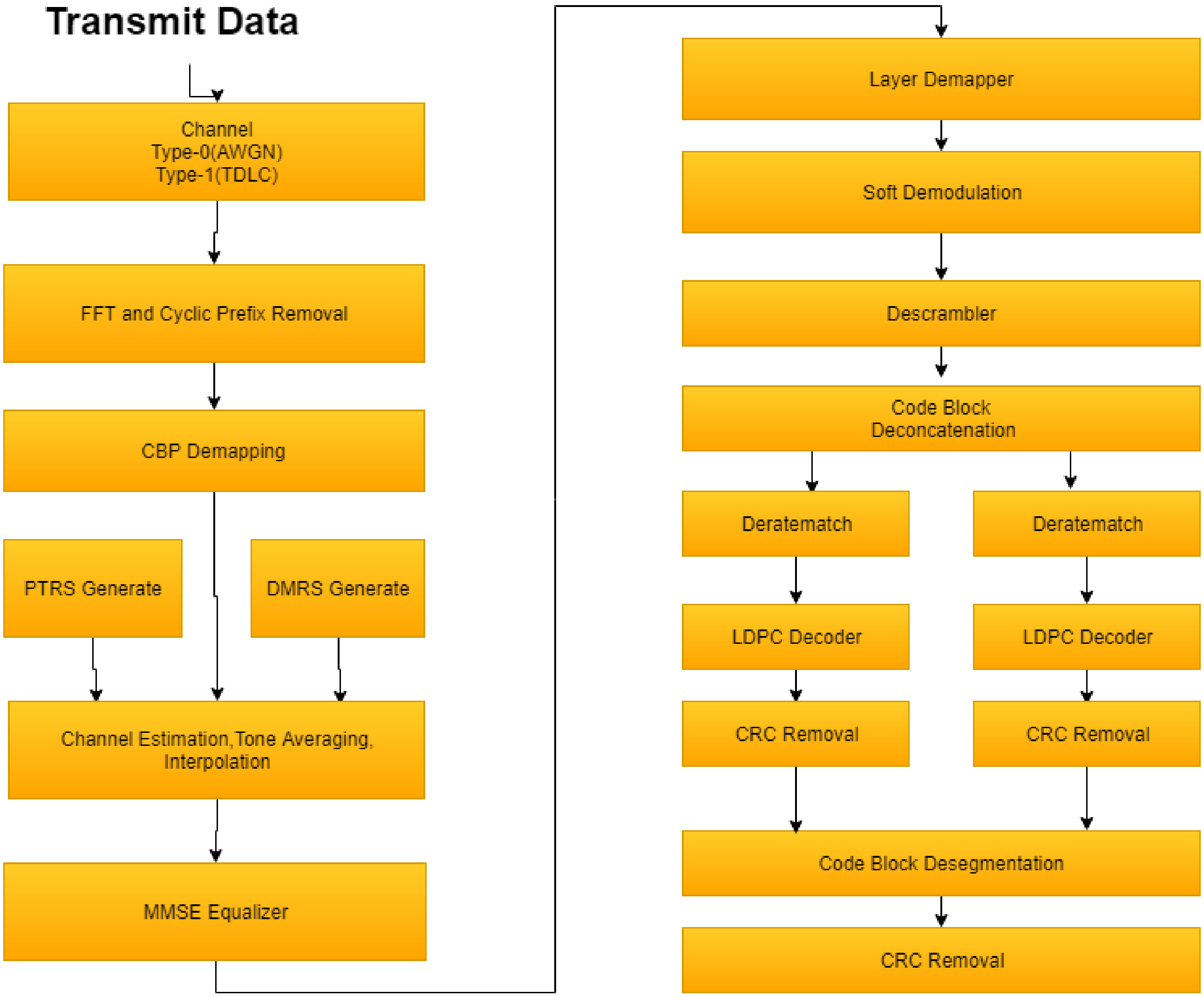


Figure 4.2: Block Diagram of PDSCH Receiver

Nr as mentioned earlier there is one to one mapping between the layer mapping and the antenna mapping block so the output of the layer de-mapping block and the antenna de-mapping block is the same[2].

4.3.3 DMRS and PTRS Generation

According to the configurations signaled DMRS and PTRS is generated at the receiver side. This will be used for estimating the downlink channel. The generation is done in the same way specified in 3GPP Specifications. The receiver knows well in hand that what is the configuration type, mapping type, single or double symbol DMRS, etc. Similarly, for PTRS it is also generated at the receiver. For my simulation purpose, we have not used the PTRS at the transmitter and hence the PTRS generation is not needed at the receiver.

4.3.4 Channel Estimation,Tone averaging and Interpolation

The input to this block is the de-mapped data and the generated DMRS. The channel estimator used is the least square. The channel estimator procedure is written hereunder.

The channel estimator is as follows

$$\tilde{H} = X^H * Y \tag{4.1}$$

Where Y is the de-mapped data and X is the DMRS symbol.

After the estimation of the channel at the RE's where DMRS is placed we go for tone averaging. Tone averaging is carried out to nullify the effect of noise. We have also assumed that the delay spread is small so it is reasonable to assume that the channel does not change significantly in one OFDM symbol for a few subcarriers. The tone averaging factor used in the simulation is 6 and 12 subcarriers. After the tone averaging is done we put the averaged value on all the subcarriers for which the averaging is done. In the simulation, we have not assumed that the doppler is zero so we won't be averaging across the symbols. Between the OFDM symbols, we go for linear interpolation. The interpolation is carried in the following way: Till the first DMRS symbol, the channel estimates for the first DMSR symbols are repeated. In between the first and the other DMRS symbol we do the linear interpolation. After the last DMRS symbol and till the last symbol we simply repeat the channel estimates for the last DMRS symbol.

4.3.5 MMSE Equalizer

The system Model used is here under, where H is a $N_r \times N_t$ matrix, x is a $N_t \times 1$ vector and y is a $N_r \times 1$ received vector, n is a $N_r \times 1$ with n follows $(0,\sigma^2 \times I_r)$.

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{n} \tag{4.2}$$

Here G is the equalizer matrix. The purpose of the equalizer is to equalize the data and nullify the interference if any is present. Here for the simulation purpose, I have used MMSE equalizer because the performance of MMSE equalizer is better than Zero forcing equalizer.

$$G = \mathbf{H}^H \left(\mathbf{H}\mathbf{H}^H + \frac{\sigma^2}{P} \cdot \mathbf{I} \right)^{-1} \tag{4.3}$$

4.3.6 Layer De-Mapping

After the data gets equalized by the MMSE equalizer then it passes through layer de-mapper which is the counterpart of layer mapper. In this block data from different layers come as input and then they are de-mapped and vectorized. So initially in layer mapper suppose when there was one code word and no. of layers scheduled was 2 then on the first layer the even bitstream was mapped and on the other layer, the odd bitstream was mapped. Here we will do the reverse engineering of this and take the two or more bit streams and map into a single codeword or multiple codewords. The output of this block is codewords.

4.3.7 Soft Demodulation, Descrambling, Codeblock De-Concatenation

As the LDPC decoder operates on soft bits we go for soft demodulation. After the soft bit demodulation, the sequence is descrambled with the same sequence with which it was scrambled. The scrambling sequence is generated by using the PHysical cell layer Id which is transmitted by the transmitter.

After the De-scrambling we go for code block de-concatenation. In this block, the layer demapped and scrambled data is taken and de concatenated as the LDPC decoder will work on lesser block length size.

4.3.8 LDPC Decoding and De-rate matching

After the descrambling, the data goes for LDPC decoding. The LDPC decoder block is followed by the de-rate matching which is the reverse of rate matching.

4.3.9 Code Block Desegmentation and CRC Removal

The final step in the receiver chain is code block desegmentation. It is the reverse of code block segmentation. remember we have segmented the transport block into code blocks to ease the receiver processing and early detection of the error. In this block what we have done at the transmitter end is reversed.

After this follow the CRC checksum block. In this block, the CRC is removed and the block error rate is calculated. If there is block error then the full block is discarded or else is kept as such as the received data. After this, we plot the block error rate performance for the transmitted data with respect to increasing snrdB which is shown in the next section.

4.4 PDSCH Results and Simulation Parameters

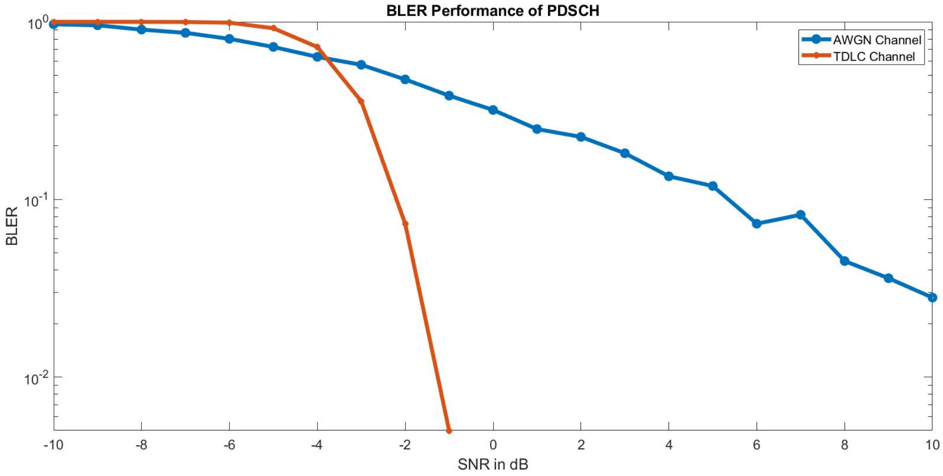
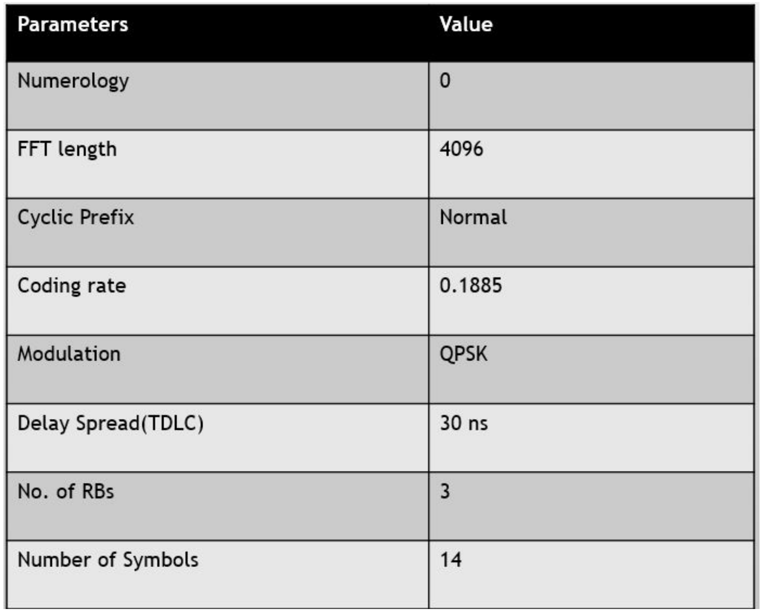


Figure 4.3: Block Error Rate Performance Of PDSCH



Parameters	Value
Numerology	0
FFT length	4096
Cyclic Prefix	Normal
Coding rate	0.1885
Modulation	QPSK
Delay Spread(TDLC)	30 ns
No. of RBs	3
Number of Symbols	14

Figure 4.4: Simulation Parameters

Chapter 5

CSI-RS Transmitter Design

CSI-RS stands for the cell-specific reference signal. A CSI-RS can be configured to be transmitted on a maximum of 32 antenna ports. Whenever a CSI-RS is configured it can be used by various devices for estimating their own channel, provided that the corresponding device is configured accordingly.

For single port CSI-RS, there is no restriction on where it can occur in a slot, but in order to evade clashes there are some constraints[9]:

Specifically, it is positioned such that it will not conflict with any of the following:

- CORESET configured.
- DMRS for PDSCH transmission.
- Sent SS blocks.

In a multi-port, CSI configured there are three different types of multiplexing. The multiplexing is performed on the following basis:

- Code-Domain Multiplexing: The separation is achieved by modulating with different OCC.
- Frequency-Domain Multiplexing: The separation is achieved by multiplexing in frequency.
- Time-Domain Multiplexing: The separation is achieved by multiplexing in time.

The following is illustrated in the figure below:

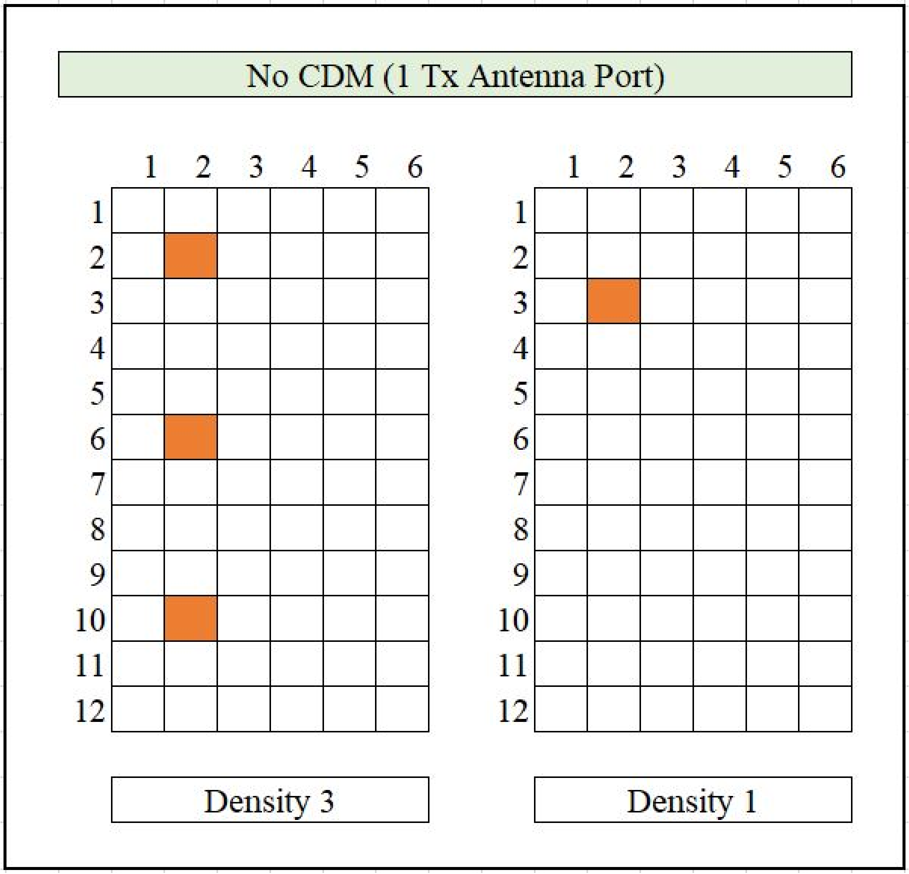


Figure 5.1: CSI Mapping for 1 Antenna Port Configured

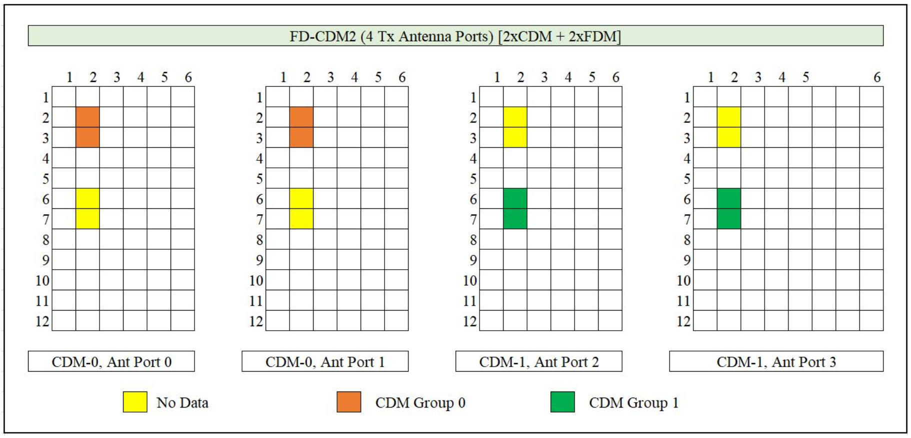


Figure 5.2: CSI Mapping for 4 Antenna Port$2CDM \times 2FDM$ Configured

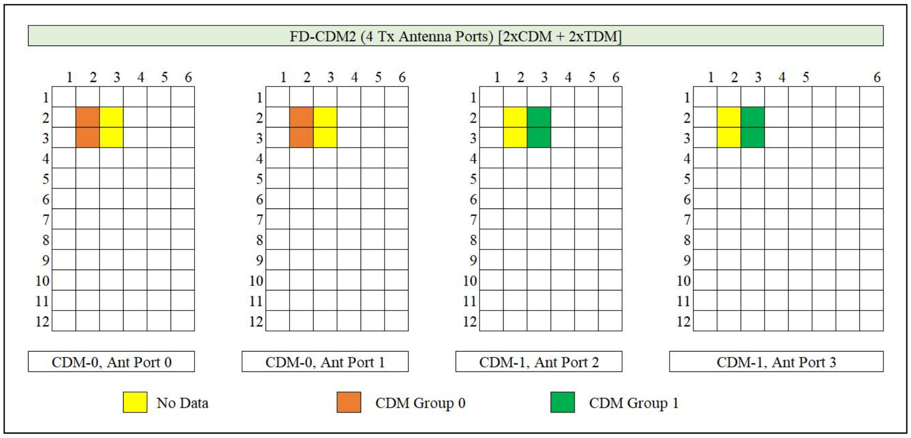


Figure 5.3: CSI Mapping for 4 Antenna Port $2CDM \times 2TDM$ Configured

The point to be noted is that the CSI-RS multiplexed in time/frequency domain need not inevitably fill the nearby sub-carrier/OFDM symbol respectively.

5.1 Frequency and Time Domain Configurations of CSI-RS

Moreover, if we see in the frequency the CSI-RS then we can notice that CSI-RS can have a density equal to 1 in which case it will be transmitted in every resource block for the full bandwidth. But the CSI-RS can also be transmitted with a density of 1/2 in which case it will be transmitted in the alternate resource block. The CSI-RS configuration in such a case will indicate that we are transmitting in even or odd-numbered resource block. If the single port CSI-RS is configured with density more than 1, then the number of CSI resources per resource block will be equal to the density. Needless to mention that it occupies any three resource element provided it does not collide with scheduled DMRS for pDSCH transmission, CORESET scheduled, etc.

CSI-RS in the time domain is configured in the following three configurations:

- Periodic: In this case, the CSI-RS transmission is assumed to be configured to such that it occurs every Say Mth time slot where M ranges from 4 to 640. Moreover, there is also an optional slot offset for CSI-RS transmission.
- Semi-persistent: In this case, everything is equivalent to periodic configuration the only difference being that the activation and deactivation of CSI-RS transmission are controlled by MAC.
- Aperiodic: In this case, there is no periodicity in CSI-RS transmission but a device can be configured by signaling in the DCI.

5.2 Zero power or Muted CSI RS

The main difference between NZP & NZP CSI-RS is that in the former one corresponds to a congregation of RE's in which a UE assumes that PDSCH is not mapped i.e it is not used for actual

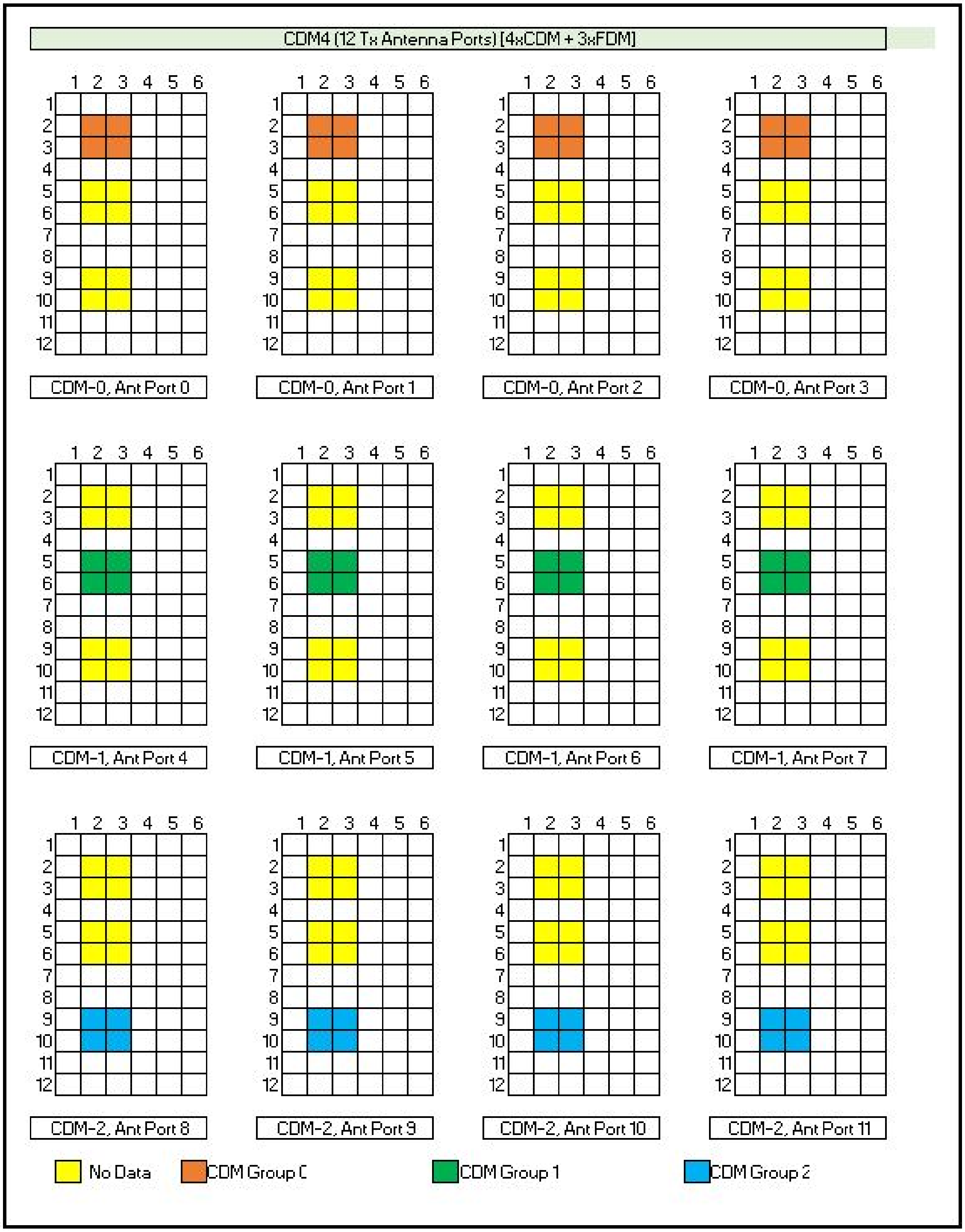


Figure 5.4: CSI Mapping for 12 Antenna Port Configured

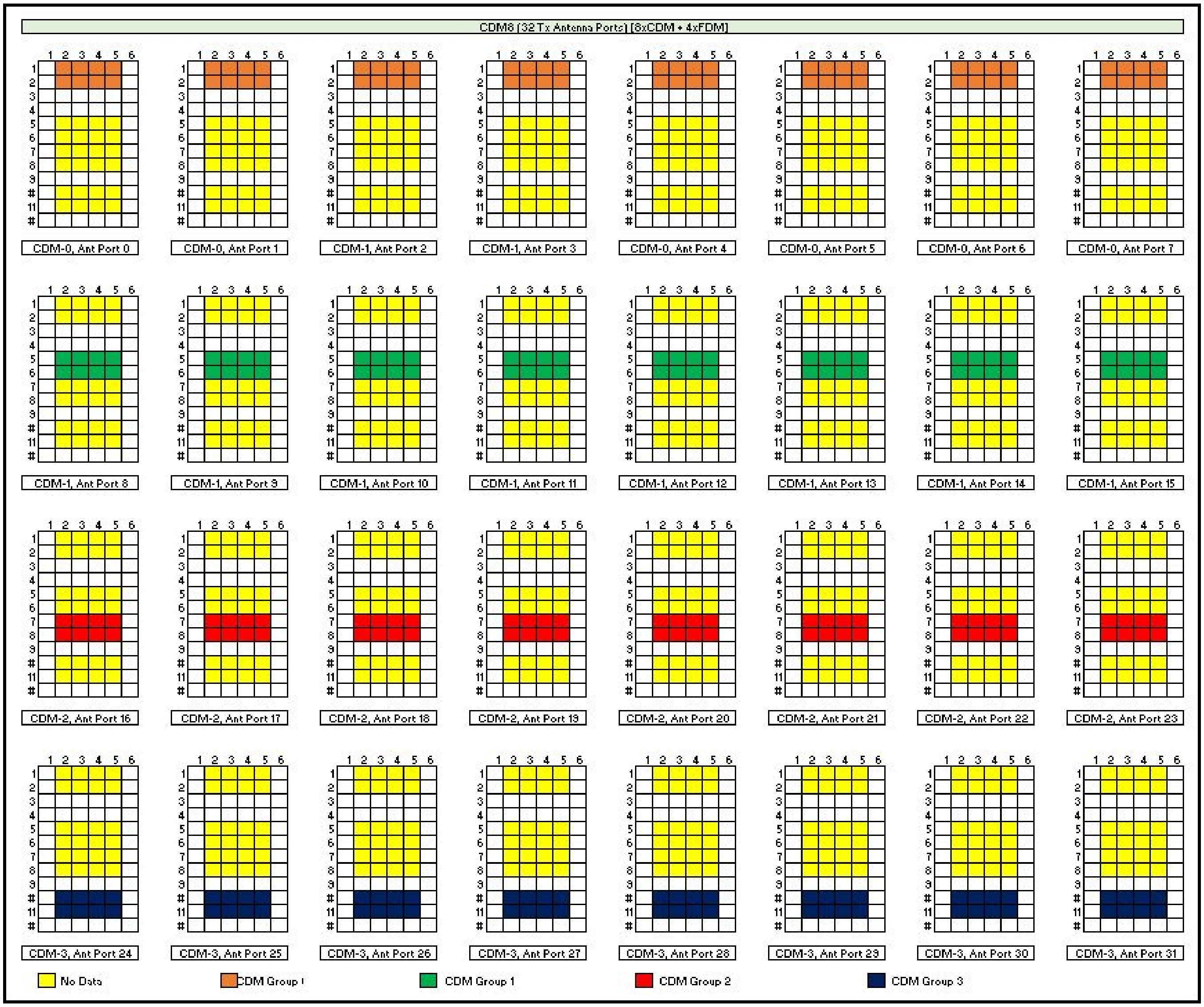


Figure 5.5: CSI Mapping for 32 Antenna Port Configured

data transmission. Specifically, Zero-power does not mean that there is no transmission within the resource element but it means that the RE's pertaining to ZP CSI-RS is used for NZP-CSI RS transmission for the other device.

5.3 CSI-Interference Measurement

The CSI can also be used to estimate the interference by taking the difference between the actual CSI transmitted over the resource and the received signal. The general way to carry is that there is no transmission in a cell and the reception of the CSI-IM resource in an adjacent cell is measured to have an idea of the expected interference due to transmission in the former cells.

5.4 CSI Generation

The PN sequence is generated by a 31 length gold sequence. The output sequence of length M_{pn} is defined by following

$$c(n) = \left(x_1\left(n+N_C\right) + x_2\left(n+N_C\right)\right) \bmod 2 \tag{5.1}$$

$$x_1(n+31) = \left(x_1(n+3) + x_1(n)\right) \bmod 2 \tag{5.2}$$

$$x_2(n+31) = \left(x_2(n+3) + x_2(n+2) + x_2(n+1) + x_2(n)\right) \bmod 2 \tag{5.3}$$

where Nc=1600 and the first m-sequence $x_1(n)$ will be initialized with $x_1(0)$=1 and $x_1(n)$=0 for n=0,1,2,..30.
The initialization of the second m-sequence,$x_2(n)$ is denoted by
$C_{init} = \sum_{i=0}^{30} x_2(i) \times 2^i$.

The reference signal r(m) is defined by

$$r_l(m) = \frac{1}{\sqrt{2}}(1 - 2\cdot c(2m)) + j\frac{1}{\sqrt{2}}(1 - 2\cdot c(2m+1)) \tag{5.4}$$

using the pseudo-random sequence c(i). The pseudo-random sequence generator needs to be initialized with

$$c_{init} = \left(2^{10}\left(N_{symb}^{slot} n_{\mathrm{s,f}}^{\mu} + l + 1\right)\left(2n_{\mathrm{ID}} + 1\right) + n_{\mathrm{ID}}\right) \bmod 2^{31} \tag{5.5}$$

at the start of each OFDM symbol where n_{sf}^{μ} is the slot number within a radio frame, l is the OFDM symbol number within a slot and n_{ID} is the higher layer parameter scrambling.

5.5 CSI Mapping to Physical Resource

For the CSI configured the sequence r(m) is mapped to the resource element $(k, l)_{p,\mu}$ governed by the following equations:

$$a_{k,l}^{(p,\mu)} = \beta_{\mathrm{CSIRS}} w_{\mathrm{f}}\left(k'\right) \cdot w_{\mathrm{t}}\left(l'\right) \cdot r_{l,n_{sf}}\left(m'\right) \tag{5.6}$$

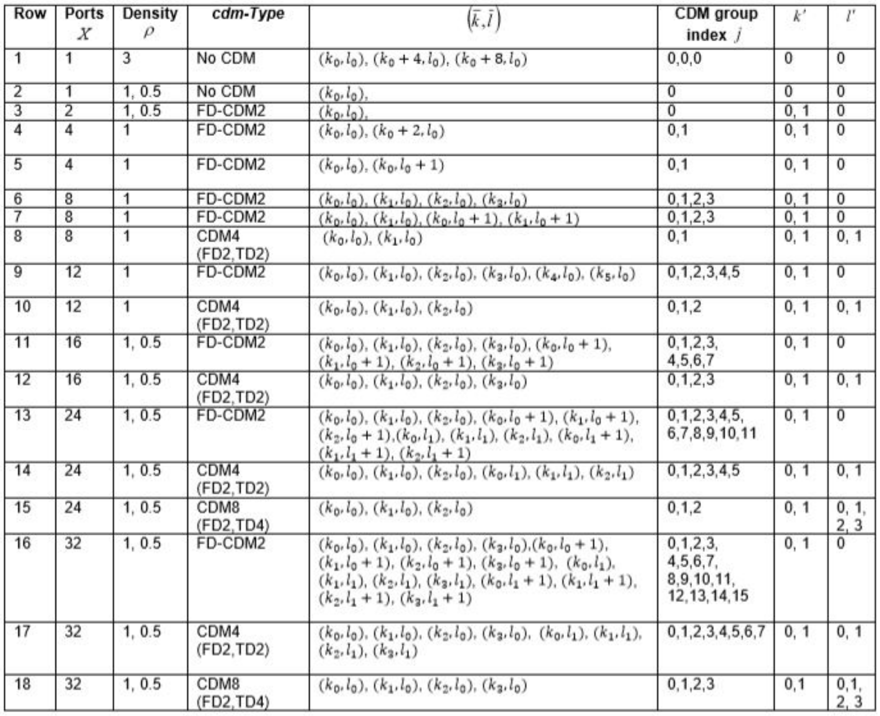
$$m' = \lfloor n\alpha \rfloor + k' + \left\lfloor \frac{\bar{k}\rho}{N_{\mathrm{sc}}^{\mathrm{RB}}} \right\rfloor \tag{5.7}$$

$$k = nN_{\mathrm{sc}}^{\mathrm{RB}} + \bar{k} + k' \tag{5.8}$$

$$l = \bar{l} + l' \tag{5.9}$$

$$\alpha = \begin{cases} \rho & for X = 1 \\ 2\rho & for X > 1 \end{cases} \tag{5.10}$$

$$n = 0, 1, \ldots \tag{5.11}$$



Row	Ports X	Density ρ	*cdm-Type*	$(\bar{k}, \bar{l})$	CDM group index j	k'	l'
1	1	3	No CDM	(k_0, l_0), (k_0+4, l_0), (k_0+8, l_0)	0,0,0	0	0
2	1	1, 0.5	No CDM	(k_0, l_0),	0	0	0
3	2	1, 0.5	FD-CDM2	(k_0, l_0),	0	0, 1	0
4	4	1	FD-CDM2	(k_0, l_0), (k_0+2, l_0)	0,1	0, 1	0
5	4	1	FD-CDM2	(k_0, l_0), (k_0, l_0+1)	0,1	0, 1	0
6	8	1	FD-CDM2	(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0)	0,1,2,3	0, 1	0
7	8	1	FD-CDM2	(k_0, l_0), (k_1, l_0), (k_0, l_0+1), (k_1, l_0+1)	0,1,2,3	0, 1	0
8	8	1	CDM4 (FD2,TD2)	(k_0, l_0), (k_1, l_0)	0,1	0, 1	0, 1
9	12	1	FD-CDM2	(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0), (k_4, l_0), (k_5, l_0)	0,1,2,3,4,5	0, 1	0
10	12	1	CDM4 (FD2,TD2)	(k_0, l_0), (k_1, l_0), (k_2, l_0)	0,1,2	0, 1	0, 1
11	16	1, 0.5	FD-CDM2	(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0), (k_0, l_0+1), (k_1, l_0+1), (k_2, l_0+1), (k_3, l_0+1)	0,1,2,3, 4,5,6,7	0, 1	0
12	16	1, 0.5	CDM4 (FD2,TD2)	(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0)	0,1,2,3	0, 1	0, 1
13	24	1, 0.5	FD-CDM2	(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_0, l_0+1), (k_1, l_0+1), (k_2, l_0+1),(k_0, l_1), (k_1, l_1), (k_2, l_1), (k_0, l_1+1), (k_1, l_1+1), (k_2, l_1+1)	0,1,2,3,4,5, 6,7,8,9,10,11	0, 1	0
14	24	1, 0.5	CDM4 (FD2,TD2)	(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_0, l_1), (k_1, l_1), (k_2, l_1)	0,1,2,3,4,5	0, 1	0, 1
15	24	1, 0.5	CDM8 (FD2,TD4)	(k_0, l_0), (k_1, l_0), (k_2, l_0)	0,1,2	0, 1	0, 1, 2, 3
16	32	1, 0.5	FD-CDM2	(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0),(k_0, l_0+1), (k_1, l_0+1), (k_2, l_0+1), (k_3, l_0+1), (k_0, l_1), (k_1, l_1), (k_2, l_1), (k_3, l_1), (k_0, l_1+1), (k_1, l_1+1), (k_2, l_1+1), (k_3, l_1+1)	0,1,2,3, 4,5,6,7, 8,9,10,11, 12,13,14,15	0, 1	0
17	32	1, 0.5	CDM4 (FD2,TD2)	(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0), (k_0, l_1), (k_1, l_1), (k_2, l_1), (k_3, l_1)	0,1,2,3,4,5,6,7	0, 1	0, 1
18	32	1, 0.5	CDM8 (FD2,TD4)	(k_0, l_0), (k_1, l_0), (k_2, l_0), (k_3, l_0)	0,1,2,3	0,1	0,1, 2, 3

Figure 5.6: CSI RS location within a slot

Chapter 6

CSI-RS Receiver

6.1 CSI Reports

The CSI reports consist of three parameters RI(Rank Indicator), PMI(Precoding Matrix Index) and CQI(Channel Quality Information) which is fed back to the transmitter. This report is, however, the recommendation to the transmitter about the channel but the transmitter is free to decide whether it will follow that recommendation or not. In the case, the transmitter doesn't follow the recommendation made by the UE the same has to be signaled to the UE by some means.

Rank Indicator

It is a recommendation sent by the UE to the base station on how many independent layers can be transmitted by the base station.

Precoding Matrix Indicator

It says that what precoding matrix should be used by the transmitter for beam-forming when operating in the spatial multiplexing mode. The precoding matrix index belongs to the set of indices corresponding to a particular matrix from the codebook. The PMI is calculated based on the RI reported by the UE.

Channel Quality Indicator

This comprises of the highest modulation and coding scheme to be used by the transmitter. This is calculated based on the RI and PMI values. Usually, for the MCS the notion is, that index to be fed back for which the coded block error rate is less than 10 percent. The point to be noted here is that the rate should not increase the maximum channel capacity limit as specified by Shannon.

6.2 Types of Channel State Reports

There are basically two types of channel state reports: Aperiodic and periodic, the difference between them is how they are signaled i.e, periodic reports are sent after every regular interval with a defined periodicity. The periodic reports are less detailed and are sent on the PUCCH which is capable of carrying a lesser payload in terms of bits. This report contains CQI and PMI. The rank indicator is not sent very often assuming that the appropriate rank varies relatively slower than the channel conditions for PMI and RI.

Aperiodic reports, on the other hand, are more detailed and sent only when it is triggered by the base station exclusively It is sent on PUSCH which is able to carry more amount of data. The overhead in terms of bits is not a big issue over here as it is reasonable to assume that the base station will be sending more number of bits and hence exclusively requested for the aperiodic report.

Irrespective of the report whether it is periodic or aperiodic the CSI reports can be divided into three further subclasses:

- Wideband Reports: This means that the recommendation sent by the UE is valid across the full bandwidth.
- UE configured Reports: This report means that the report has been generated by the UE for a few specific subbands and the report is valid for that bandwidth only.
- M-band Reports: This is also in some sense similar to the UE configured reports but the only difference is that the UE selects the best M- subbands and then sends two different recommendations one for full bandwidth and other for the specific sub-bands only.

After the data is The channel model used for the simulation was both AWGN and TDLC as defined in the specifications of 5G-NR.

6.3 Basics of precoding

Due to fast varying mobile radio channels with time used for wireless communication there comes frequency selectivity of the which means different frequency components will see varying gain and phase response when acted upon by the channel. One of the ways to achieve the diversity gain or to curb the frequency selectivity of this channel is to go for multi-antenna transmission.At the receiver side, we go for more number of receive antenna knows as receive diversity to increase the directivity towards the target signal or we have more number of transmit antennas to beamform in a particular direction known as transmit diversity. If we have multiple numbers of antennas at the receiver and transmitter then it is called spatial multiplexing in which we can transmit in parallel and receive multiple numbers of independent data streams. In terms of digital processing, it is termed as precoding. The antenna weights which can be flexibly controlled is called the precoder matrix W and such processing is termed as multi-antenna precoding.

One of the key aspects of multi-antenna precoding is that whether the DMRS's are precoded or not. If DMRS is not precoded then the transmitter has to inform the UE by some means that what precoder matrix needs to be used for coherent demodulation. On the other hand, if it is precoded then the receiver will see an updated channel matrix of dimension Nr-by-Nl instead of Nr-by-Nt.

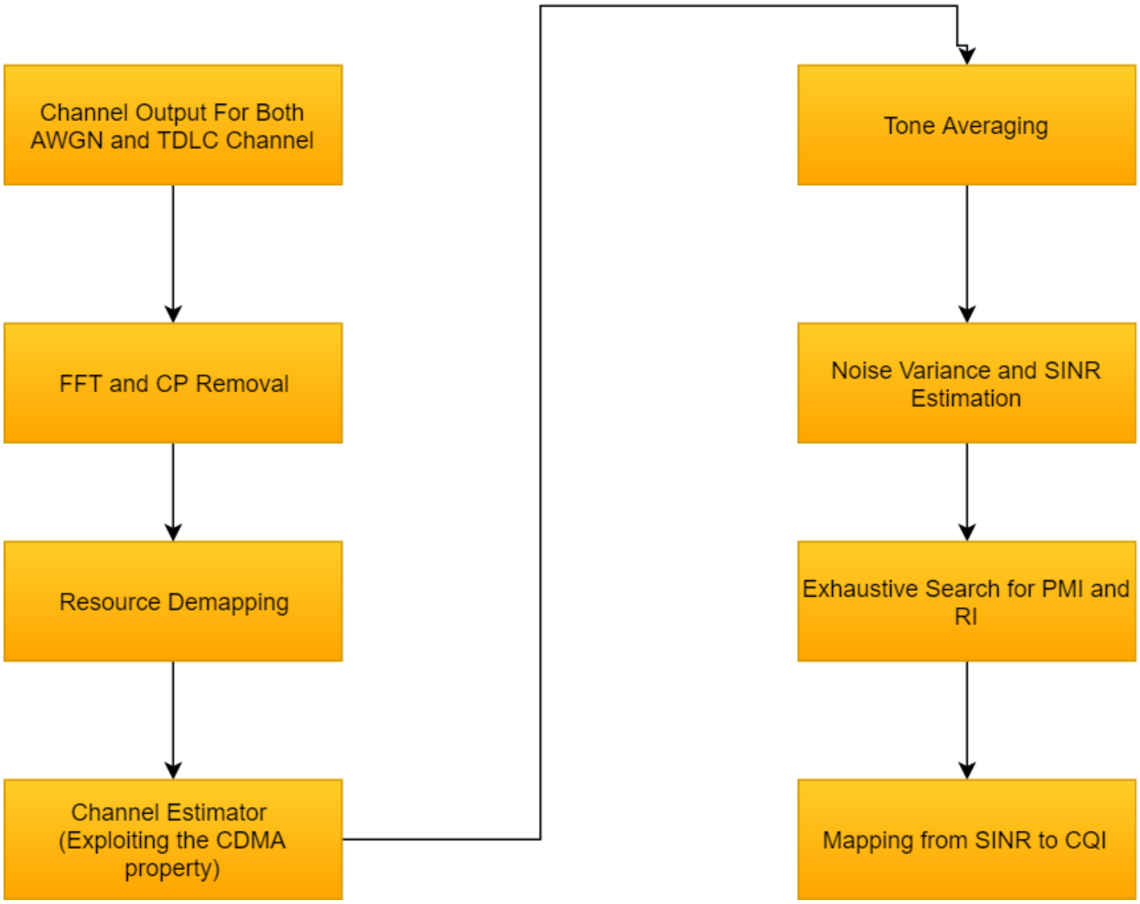


Figure 6.1: tBlock Diagram of CSI-Receiver

6.4 System Model

The system model assumed is as follows: y_s is $r \times 1$ received vector on the s^{th} subcarrier, H_s is the $N_r \times N_t$ matrix seen by the s^{th} subacrrier, , $W_{r,i_1,i_2,i_3,i_4,s}$ is the $N_t \times r$ precoding matrix corresponding to different indices in the codebook x_s is the $r \times 1$ transmitted vectorwhere r is the rank of transmission and n_s is the $r \times 1$ vector following $(0,\sigma^2 \times I_r)$.

$$\mathbf{y}_s = \mathbf{H}_s \mathbf{W}_{r,i_1,i_2,i_3,i_4,s} \mathbf{x}_s + \mathbf{n}_s \tag{6.1}$$

The receiver flow goes like the shown in the figure: The transmitted data after passing through the channel is received at the receiver. First, the received data is passed through the FFT and CP removal block in which the cyclic prefix attached to each symbol is removed and then fast Fourier transform is taken to convert the received data back in the Fourier domain in which it easy to analyze and process the data.

6.5 Generation of CSI-RS

At the receiver end, the CSI-RS is generated using the cell layer ID and then it is used to estimate the effective channel between link-to-link. The CSI-RS generation is the same as that at the transmitter end as it is the reference signal and the receiver knows what data is transmitted from the configured CSI port.

6.6 Channel Estimator

The channel estimator proposed to estimate the channel between the links exploits the CDM property i.e, uses different OCC(orthogonal cover codes) for different per antenna port CSI-RS. The assumption made over here is that the channel is constant on 1 RB, which is a valid assumption to make as the delay spread assumed in case of TDLC channel model for the simulation purpose was 10ns which means the coherent bandwidth of the channel is large and in turn, means that each of the subcarriers will be undergoing flat fading.

After the channel estimation, the channel estimates were averaged and interpolated for all those RE's where the CSI-RS were placed. The benefit of averaging is that it helps in canceling the effect of noise.

Just to validate the proposed channel estimation algorithm the mean-squared error for channel estimates is plotted against the SNR in decibel scale below: The simulation parameters are as follows :

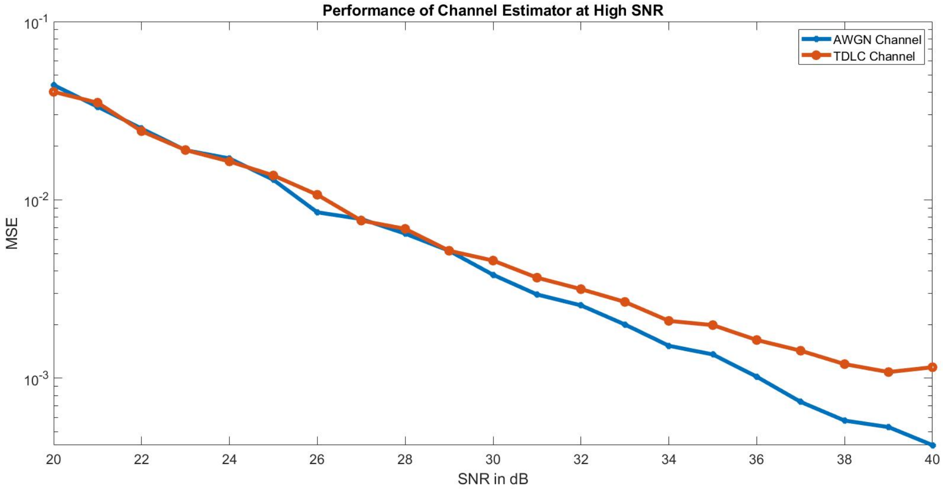


Figure 6.2: Mean Square Error for 8-port Configured

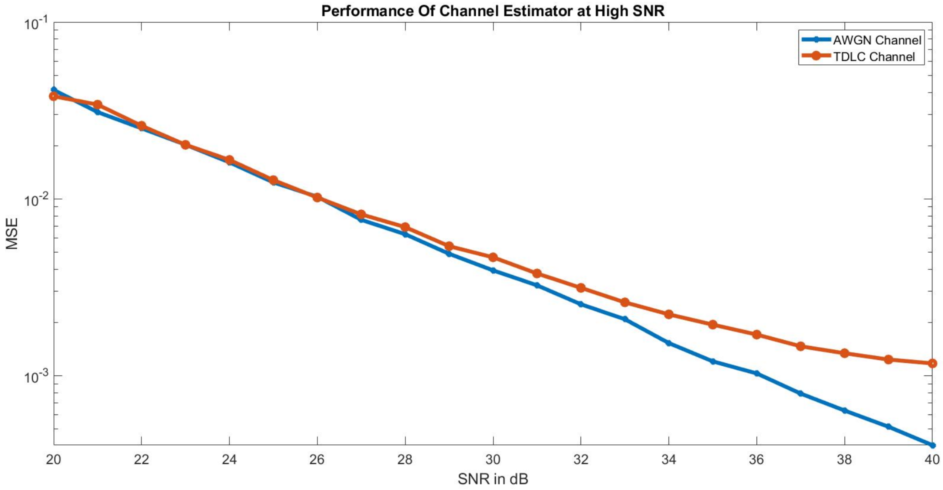


Figure 6.3: Mean Square Error for 32-port Configured

6.7 RI and PMI estimation algorithm

Here the Signal to Noise plus interference ratio corresponding to layer p is given by, where $p <= r$

$$\beta_{p,r,i_1,i_2,i_3,i_4,s} = \frac{1}{\sigma^2 \left[\sigma^2 \mathbf{I}_r + \mathbf{W}^H_{r,i_1,i_2,i_3,i_4,s}\mathbf{H}_k^H\mathbf{H}_k\mathbf{W}_{r,i_1,i_2,i_3,i_4,s}\right]^{-1}_{p,p}} - 1 \tag{6.2}$$

After calculating the SINR we find the sum channel capacity by suming over all the layers scheduled.

$$C_{r,i_1,i_2,i_3,i_4,s} = \sum_{p=1}^{r} \log_2\left(1 + \beta_{p,r,i_1,i_2,i_3,i_4,s}\right) \tag{6.3}$$

The rank, first index and second index is calculated by maximizing over all the possible ranks, first index and second index.

$$\left(\hat{r}, \hat{i}_1, \hat{i}_2\right) = \arg \max_{r\in R, i_1\in A_r^{(1)}, i_2\in A_r^{(2)}} \left(\sum_{s=1}^{N} \max_{i_3\in A_r^{(3)}, i_4\in A_r^{(4)}} C_{r,i_1,i_2,i_3,i_4,s}\right) \tag{6.4}$$

After calculating the rank and the first and second index we calculate the third and fourth index by plugging the calculated values in the base equation.

$$\left(\hat{i}_{3,s}, \hat{i}_{4,s}\right) = \arg \max_{i_3\in A_r^{(3)}, i_4\in A_r^{(4)}} C_{\hat{r},\hat{i}_1,i_2,i_3,i_4,s} \tag{6.5}$$

A lesser Complexity Algorithm

The calculation based on the above formulas need to exhaustively search for all the possible ranks, and I indices in the codebook. It is computationally inefficient. Another method is to find the modified channel matrix by summing it overall subcarrier and then use it for maximizing mutual information [1].

$$\Gamma = \frac{1}{N} \sum_{s=1}^{N} \mathbf{H}_k^H \mathbf{H}_k \tag{6.6}$$

After calculating this we plug into the channel capacityy equation and sum it over all the possible layers. The firts and second indices and the rank is calculateed by equation 6.8.

$$G_{r,i_1,i_2,i_3,i_4} = \sum_{p=1}^{r} \log_2 \left(\frac{1}{\sigma^2 \left[\sigma^2 \mathbf{I}_r + \mathbf{W}_{r,i_1,i_2,i_3,i_4}^H \mathbf{\Gamma} \mathbf{W}_{r,i,i_2,i_3,i_4} \right]_{p,p}^{-1}} \right) \tag{6.7}$$

For calculating the 3rd and 4th indices we resort to the previous method.

$$\left(\hat{r}, \hat{i}_1, \hat{i}_3 \right) = \arg \max_{r \in R, i_1 \in A_r^{(1)}, i_2 \in A_r^{(2)}} G_{r,i_1,i_2,i_3,i_4} \tag{6.8}$$

Chapter 7

Conclusion and Future Work

By having the channel state information the performance increases manifolds and the base station uses the pre-coding weights to beam-form in direction of a particular UE when operating in spatial multiplexing mode. Moreover, the modulation order and coding scheme used and the number of independent layers for transmission also depends upon the downlink channel quality. In the case of reciprocity, we can use the uplink channel quality too.

The channel estimates are used for Post MMSE SINR calculation per subcarrier for a given rank and the precoding matrix indices. The PMMSE SINR is used to find the channel capacity per subcarrier.The rank and the precoding matrix indices which maximize the channel capacity is feedback to the gNB.The MCS calculation is done by mapping the SINR with the MCS specified in such a way that the block error rate is less than 10 percent and also keeping in mind that the rate should not increase the capacity for AWGN i.e Log2(1+SNR).

Due to the scarcity of time, I could not calculate and validate the PMI, RI and CQI algorithms. It is supposed to be my future work.

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