Hardware Emulations

using 5G Toolkit and SDRs: Hands-on

GIGAYASA

For academia only

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1 | Data Communication using PDSCH in 5G Networks

The primary objective of communication in 5G networks is to transmit data from the transmitter to the receiver. This information is conveyed in the downlink and uplink using the physical downlink shared channel (PDSCH) and physical uplink shared channel (PUSCH) respectively. The scope of this chapter is limited to downlink data communication using PDSCH. We will discuss the design of the air interface for PDSCH and all the MAC and RRC parameters that influence the throughput and reliability performance of the PDSCH.

1.1 | What is PDSCH?

The Physical Downlink Shared Channel (PDSCH) is a downlink physical channel responsible for carrying user equipment (UE) data, system information blocks (SIB), and random access responses (RARs). As the term 'downlink' suggests, it is transmitted from the Base Station (BS) to the User Equipment (UE). PDSCH is scheduled for a specific UE by the BS either using the DCI carried by the Physical Downlink Control Channel (PDCCH) or through RRC signaling. PDSCH performs a sequence of signal processing steps, as shown in Fig-1.1, to ensure

- high reliability,
- maximum throughput,
- secure communication, and
- adaptability to channel conditions.

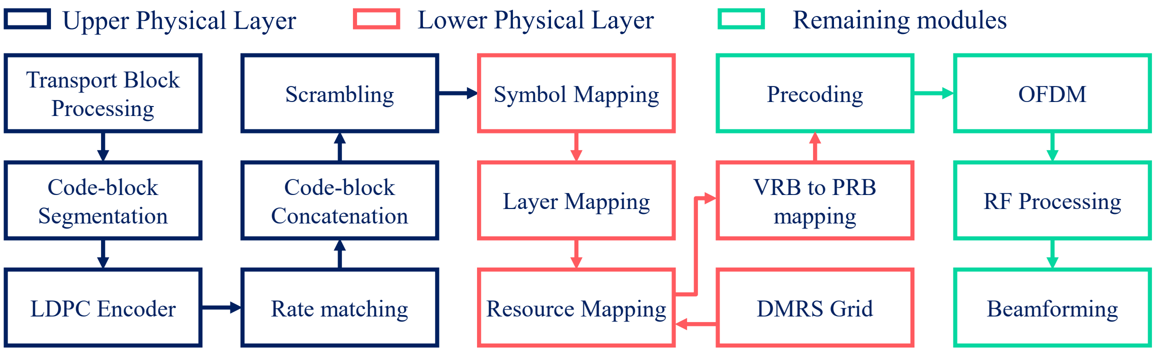


Figure 1.1: PDSCH Transmitter Chain: At BS

The PDSCH receiver at the UE performs complementary operations to accurately decode the data, as illustrated in Fig-1.2. Additionally, the receiver undertakes steps to mitigate the effects of hardware impairments such as carrier frequency offset [??], time offset correction [??], and frequency offset correction [??]. While these modules are generally not specified in the 3GPP standards, they are crucial for normal system operations.

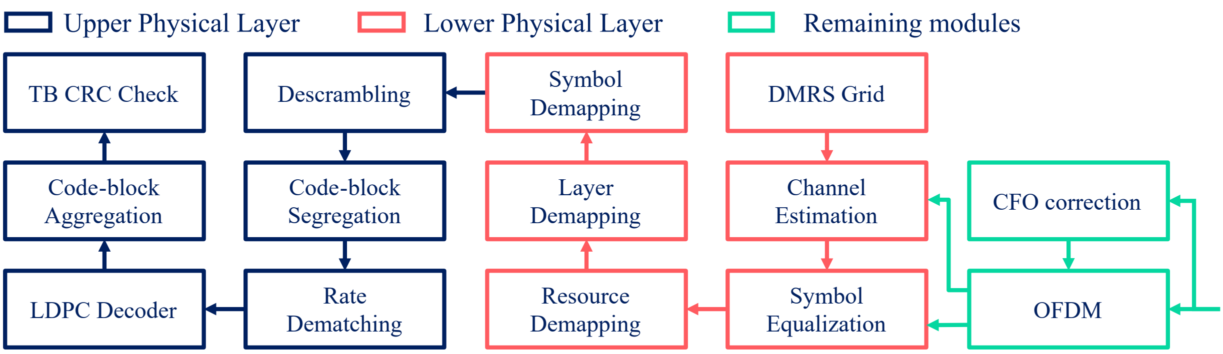


Figure 1.2: PDSCH Receiver Chain: At UE

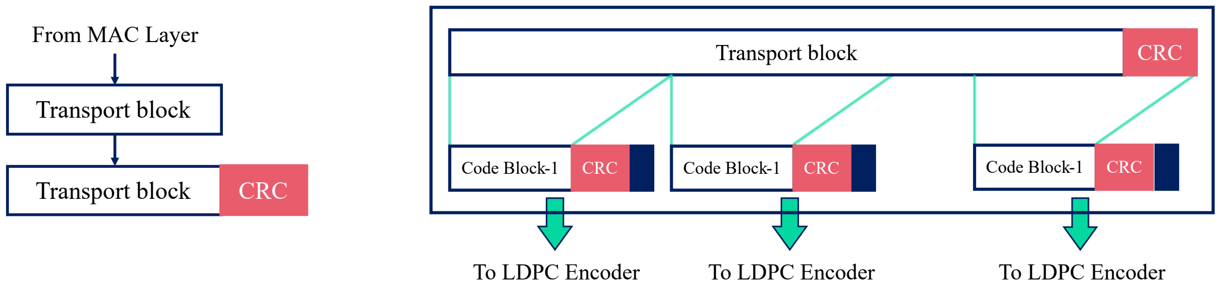
1.2 | Design of the PDSCH Chain: Transmitter

The PDSCH chain is divided into upper physical layer PDSCH chain and lower physical layer PDSCH chain. Upper physical layer PDSCH chain consists of Transport Block(TB) Processing, code block segmentation, LDPC encoder, rate matching and code block concatenation. On the other hand, the lower PHY blocks consists of scrambling, symbol mapping, layer mapping, resource mapping and virtual resource block (VRB) to physical resource block (PRB) mapping. Each of these modules serves a specific role in the PDSCH chain. In the upcoming subsections, we will discuss the importance and function of each of these modules.

1.2.1 | Transport Block Processing

The packet to be transmitted to each UE is passed to the physical layer by the MAC layer. This packet, when in the physical layer, is referred to as a transport block. The size of this transport block is computed by the MAC scheduler using parameters such as the code rate (r), modulation order (Q_m), number of MIMO layers (N_{L}) configured, bandwidth (B), number of OFDM symbols (N_{symb}) allocated to the user, and the reference signal overhead. This module attaches cyclic redundancy check (CRC) bits to the transport block received from the MAC layer, as shown in Fig-1.3a. These bits are attached to the transport block for error detection and enabling hybrid automatic repeat request (HARQ) for re-transmission of the transport block. They cannot be used for error correction in the transport block. The exact length of the CRC attached is selected based on the size of the transport block, as described in equation-1.1, with a higher number of CRC bits required as the size of the transport block increases.

$$L_{\mathrm{TB}} = \begin{cases} 24 & \text{TB length } > 3824 \\ 16 & \text{TB length } \leq 3824 \end{cases} \tag{1.1}$$



(a) Transport block processing

(b) Code block segmentation

Figure 1.3: Transport block processing and code block segmentation for PDSCH in 5G

1.2.2 | Code Block Segmentation

The bits received from the TB processing are expected to be channel encoded using LDPC encoder. This encoder can support a certain maximum size of input block ($N_{\mathrm{CB}}^{\max}$) to keep the complexity of LDPC decoding low at the UE. The value of $N_{\mathrm{CB}}^{\max}$ depends on the base-graph selected for LDPC encoding,

$$N_{\mathrm{CB}}^{\max} = \begin{cases} 8448 & \text{if BG-1 is selected} \\ 3840 & \text{if BG-2 is selected} \end{cases} \tag{1.2}$$

If the TB size exceeds this maximum size limit $N_{\mathrm{TB}}^{\max}$, the TB is segmented into $K_{\mathrm{CB}}, = \left\lceil \frac{N_{\mathrm{TB}}+L_{\mathrm{TB}}}{N_{\mathrm{CB}}^{\max}-24} \right\rceil$, code-block. Furthermore, 24 bit CRC is attached to each code-block for error detection. The block can be summarized as follows,

$$N_{\mathrm{CB}} = \begin{cases} N_{\mathrm{TB}} + L_{\mathrm{TB}} & N_{\mathrm{TB}} + L_{\mathrm{TB}} > N_{\mathrm{CB}}^{\max} \\ \left\lceil \frac{N_{\mathrm{TB}}+L_{\mathrm{TB}}}{K_{\mathrm{CB}}} \right\rceil + 24 & \text{else} \end{cases} \tag{1.3}$$

LDPC encoder accepts inputs of only a certain discrete discrete lengths. To match the supported input length this module adds some filler bits. These bits are removed after channel encoding as shown in Fig-1.3b.

1.2.3 | Channel Coding: Low Density Parity Check Codes

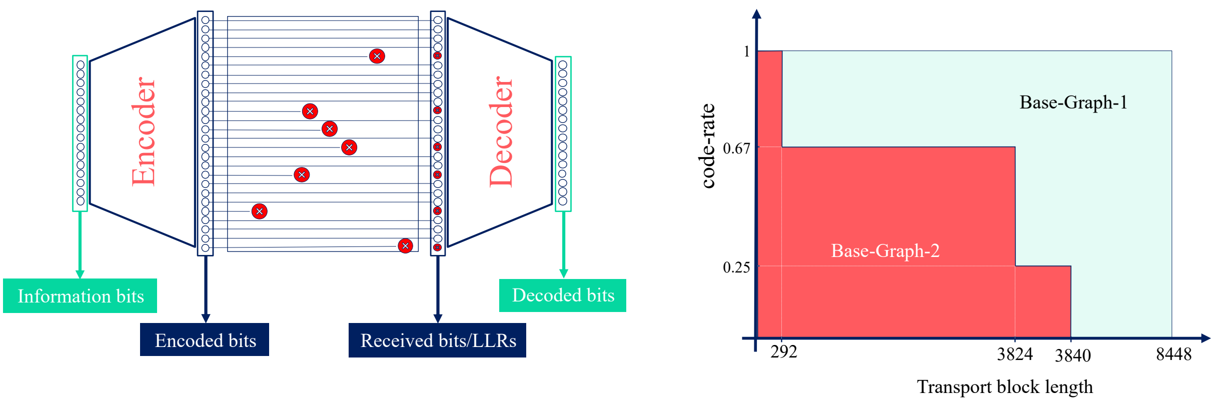
PDSCH uses LDPC as inner channel code for correcting the errors introduced by fading channels and poor link budgets. The decoder for the proposed LDPC channel codes can be implemented efficiently in-terms of silicon foot-print and power consumption by splitting the parity check matrix into smaller units supporting large parallelization in comparison to its predecessor. The LDPC codes standardized in 3GPP is designed have to have following properties [2]:

- **Systematic code**: Computes the parity bits and append them at the end of the information bits. The generator matrix is of the form $[I_k|P_{n-k}]$. This property is desirable for supporting IR-HARQ and low complexity implementation of the code-word.
- **Protograph-based code**: The LDPC codes in 5G uses two different base-graphs, BG-1 and BG-2, supporting the mother code-rates of $\frac{1}{3}$ and $\frac{1}{5}$ respectively. The PCM for both the base-graphs is constructed by lifting the respective base-matrices $H_{\text{BG1}} \in \mathbb{1}^{46\times 68}$ and $H_{\text{BG2}} \in \mathbb{1}^{42\times 52}$ as shown in Fig-1.4b.

Table 1.1: The dimensions of Input-output interface and LDPC hyper-parameters

Parameter	BG-1	BG-2
Mother code-rate	$\frac{1}{3}$	$\frac{1}{5}$
Parity check matrix	$46Z_c \times 68Z_c$	$42Z_c \times 52Z_c$
Generator matrix	$66Z_c \times 22Z_c$	$50Z_c \times 10Z_c$
Number of Information bits	$22Z_c$	$10Z_c$
Number of parity bits	$44Z_c$	$40Z_c$
Number of encoded bits	$66Z_c$	$50Z_c$

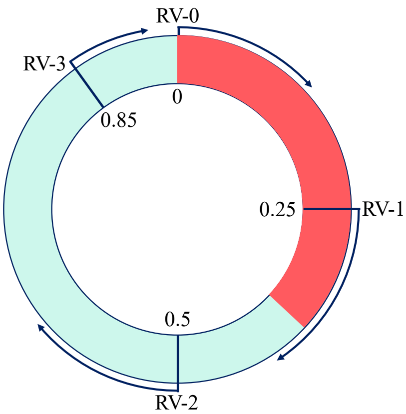
- **Quasi-cyclic code**: The cyclic rotation of the code-word will result in another valid code-word. This property is useful in breaking the complex generation and decoding process into simpler unit decoding.
- **Irregular code**: A code is termed as regular codes if number of 1s in rows of the parity check matrix, $w_r = w_c.\frac{n-k}{n}$ where w_c is the number of ones in the columns of the parity check matrix. Irregular LDPC codes prioritize more important data by mapping them into higher degree protection classes, thereby providing increased protection. The use of different degree protection classes in an LDPC code enhances the overall performance of data transmission against channel errors.



(a) Channel coding and decoding (b) Base-graph selection for LDPC encoding

Figure 1.4: LDPC Channel coding and Base-graph selection for PDSCH

The 5G LDPC encoder lifts the base protograph matrix of 46×68 or 42×52 to $46Z_c \times 68Z_c$ or $42Z_c \times 52Z_c$ for BG-1 or BG-2 respectively where Z_c is smallest integer that satisfy $20Z_c \geq N_{\text{CB}}$. The first $2Z_c$ columns of the generator matrix are punctured to maintain the mother code-rate of $\frac{1}{3}$ and $\frac{1}{5}$ for BG-1 and BG-2 respectively.

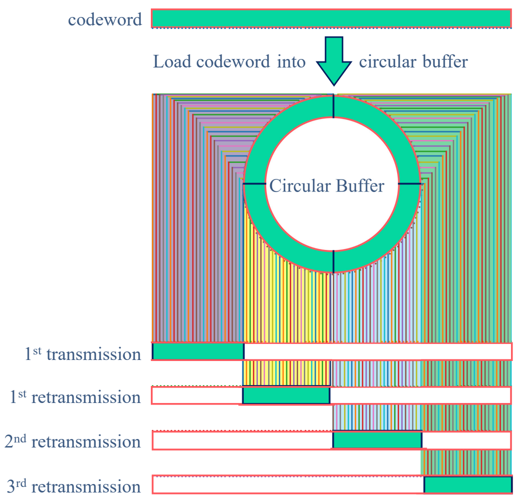


Redundancy version (RV)	Starting Positioning for reading circular buffer	
	BG-1	BG-2
0	0	0
1	$\left\lfloor \frac{17N_{cb}}{66} \right\rfloor \times Z_c$	$\left\lfloor \frac{13N_{cb}}{50} \right\rfloor \times Z_c$
2	$\left\lfloor \frac{33N_{cb}}{66} \right\rfloor \times Z_c$	$\left\lfloor \frac{25N_{cb}}{50} \right\rfloor \times Z_c$
3	$\left\lfloor \frac{56N_{cb}}{66} \right\rfloor \times Z_c$	$\left\lfloor \frac{43N_{cb}}{50} \right\rfloor \times Z_c$

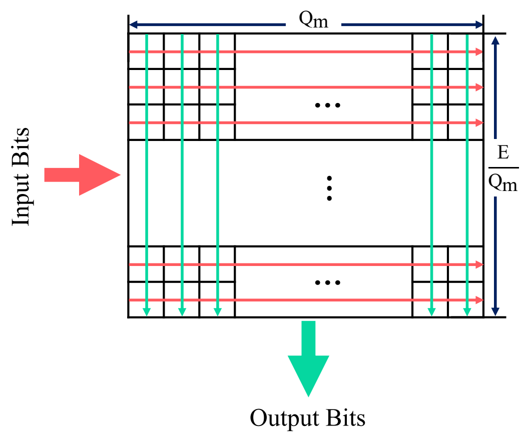
Figure 1.5: Redundancy version for HARQ in 5G-NR

1.2.4 | Rate Matching

The rate-matching is process of shortlisting and processing the encoded bits to match a target number of bits (E) that can fit into the time, frequency, and space resources allocated to a specific UE. The rate matcher comprises two sub-modules: **bit selection** and **bit interleaver**.
In bit selection, the encoded bits are mapped into a circular buffer, as shown in Fig-1.6, where systematic bits are loaded first followed by parity bits. The size of the circular buffer, N_{buff}, can be as large as $66Z_c/50Z_c$ for BG-1/BG-2, respectively. However, in the uplink for PUSCH, the buffer size can be reduced using limited buffer rate matching (LBRM) features to control the buffering of data for HARQ to reduce the cost. This reduction in cost comes at the expense of channel decoding performance when the size of the code-block is large. The bits to be transmitted from the circular buffer are selected based on the redundancy version configured using *RV-ID*, enabling HARQ. 5G-NR supports four versions of redundancy for HARQ, as shown in Fig-1.5, which defines the starting bit location for fetching the next E bits from the circular buffer. Among these versions, only RV-0 is completely self-decodable. Hence, the UE might not decode data transmitted using RV-1, RV-2, and RV-3 alone, especially when E is very small. The RV-ID is configured to the BS by the scheduler based and to the UE by DCI.



(a) Rate matching for PDSCH



(b) Bit-Interleaver in Rate matching

Figure 1.6: Bit Selection and Bit Interleaving in rate matching for PDSCH

The bit interleaver utilizes a rectangular interleaver with Q_m columns and E/Q_m rows. It writes the information row-wise and reads it column-wise. This interleaver is introduced in the LDPC rate matcher to protect against burst errors introduced by frequency-selective deep-fading. This fading occurs due to very low SNR across multiple consecutive REs, resulting in poor channel estimation performance and, eventually, poor equalization results. This phenomenon leads to errors in decoding consecutive constellation symbols. The bit interleaver spreads these burst errors across the entire codeword before passing it to the LDPC decoder, which performs poorly against burst errors.

1.2.5 | Code Block Concatenation

The rate-matched bits outputted by each parallel LDPC codec (LDPC encoder + rate-matcher) are concatenated to create a single code-word (stream of bits) in a round-robin fashion, as shown in Fig-1.7. It's worth noting that the number of target bits generated by each LDPC codec can be different.

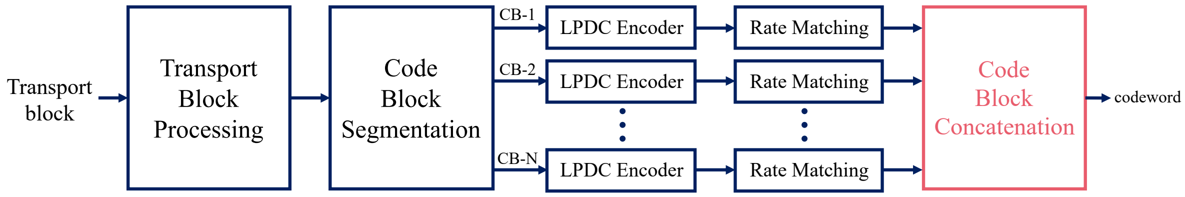


Figure 1.7: Code Block Concatenation for PDSCH

1.2.6 | Scrambling

The concatenated sequence is passed to the scrambler which xor the input bit sequence with random binary sequence as shown in Fig-1.8. This helps in breaking the long sequences of ones and zeros, and randomize the interference of PDSCH.

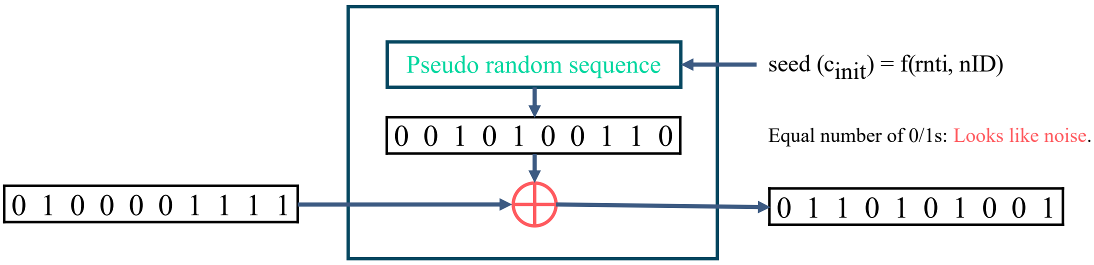


Figure 1.8: Scrambling for PDSCH

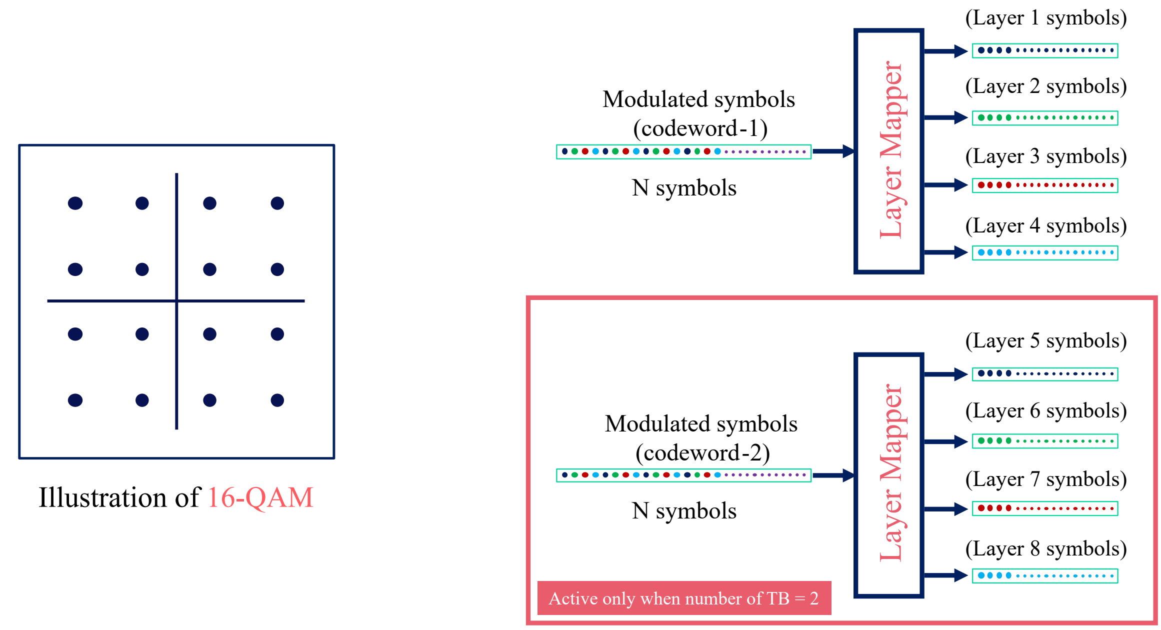
The random sequence at the BS is generated using a seed, which is computed using a *scramblingID* and *RNTI*. This ID is configured to a UE via RRC messages in RRC connected mode for data decoding. During the initial access phase, this ID is configured using Master Information Block (MIB) or System Information Block (SIB) messages.

1.2.7 | Symbol Mapping

The symbol mapper converts the bits into complex modulation symbols. The PDSCH supports PSK and QAM, as detailed in table-1.2. The modulation order (Q_m) defines the number of bits mapped onto a single symbol. It is configured to the BS and UE using *mcs-Index* and the *mcs-table* by the scheduler and DCI, respectively. This parameter is selected based on the quality of the channel between the BS and UE and the transmit power. The constellation diagram of 16-QAM is shown in Fig-1.9a.

Table 1.2: Modulation orders supported in 5G

Constellation	$\frac{\pi}{2}$-BPSK	QPSK	16-QAM	64-QAM	256-QAM	1024-QAM
Modulation order (Q_m)	1	2	4	6	8	10



(a) Symbol mapping (PSK/QAM) **(b)** Layer mapping for MIMO

Figure 1.9: Symbol mapping and layer mapping in PDSCH

1.2.8 | Layer Mapping

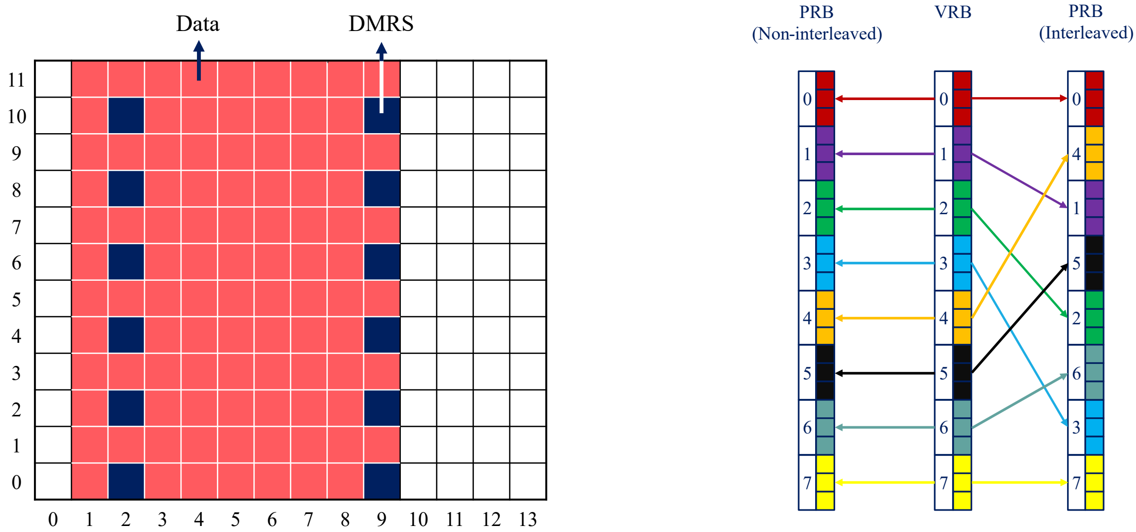
The layer mapper is utilized in MIMO systems where multiple layers (N_{L}) are transmitted for PDSCH. It converts the serial information symbol streams of length (N_{symb}) into parallel (N_{L}) streams, with each stream carrying an equal number of information symbols ($\frac{(N_{\mathrm{symb}})}{N_{\mathrm{L}}}$), as illustrated in Fig-1.9b. The details of the codeword to layer mapping are provided in table-7.3.1.3-1 and section 7.3.1.3 of [1]
In 5G-NR, up to 8 layers can be transmitted for PDSCH based on the rank indicator configured to the BS by the scheduler and to the UE by DCI. For more than 4 layers, the UE expects the transmission of 2 transport blocks, with each transport block processed independently by the upper physical layer. The segregation od transport blocks helps in reducing the re-transmission overhead via HARQ. The number of layers for PDSCH transmission is selected based on the channel condition between the transmitter and receiver antennas. These channel conditions are determined either by the UE using CSI-RS or by the BS using SRS, assuming TDD reciprocity.

1.2.9 | Resource Mapping

5G-NR uses OFDM waveform as the part of air interface. In OFDM, the time frequency and space (MIMO) resources are organized in the form of othrogonal 3D grids, ($N_{\mathrm{port}} \times N_{\mathrm{symbols}} \times N_{\mathrm{sc}}$) called resource grids as discussed in detail in chapter-??. This resource grid defines all the resources that are available with the BS for data transmission. The PDSCH symbols received from the layer mapper are mapped to the resource grid where the number of ports must equal the number of layers. The information symbols corresponding to each layer will be mapped to a specific antenna port. The resource mapping for PDSCH is defined in section 7.3.1.5 of [1]. The PDSCH symbols are expected to not overlap with any reference signal scheduled either by RRC or MAC. The details about the resource mapping are captured in next section.

1.2.10 | VRB to PRB Mapping

5G-NR supports virtual resource block (VRB) to physical resource block (PRB) mapping, which allows networks to divide the UE bandwidth part (BWP) into multiple RB bundles, as shown in Fig-1.10b. These RB bundles can be either directly mapped to PRBs or mapped in an interleaved fashion to exploit frequency diversity for robustness against multi-path fading. However, it's important to note that interleaved VRB-to-PRB mapping is supported only for downlink resource allocation type 1, where frequency domain resources are allocated using resource indication value (RIV). Downlink resource allocation type 0 is not supported, as it may allocate non-contiguous VRBs for data transmission, which



(a) Resource mapping

(b) VRB to PRB mapping

Figure 1.10: VRB to PRB mapping and resource mapping in PDSCH chain

could create issues with precoding within a PRB bundle. In interleaved mapping, the UE assumes that the same precoder is applied to all the resource elements (REs) within a PRB bundle, while the precoder across different bundles can vary.

1.3 | PDSCH Resource Allocation and Resource Mapping

1.3.1 | DMRS Generation

In 5G, the DMRS is generated by exploiting the frequency domain parameters/DMRS configuration type and time domain parameters/PDSCH mapping type. The configuration type controls the DMRS allocations in the frequency domain. 5G supports the following configuration types:

- Configuration Type-I: Supports upto 8 ports(maximum of 8 layers can be transmitted). Every alternate RE are allocated to pilot, as shown in figure 1.11. Each RB has 6 pilots thus having pilot density of 50%.

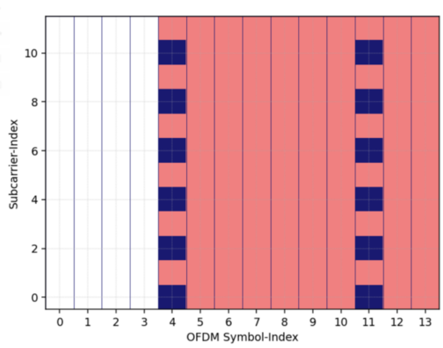


Figure 1.11: An Example of Configuration Type-I from 5G toolkit

- Configuration Type-II: Supports upto 12 ports. Each RB has 4 pilots resulting in pilot density of 33.3%, as shown in figure 1.12

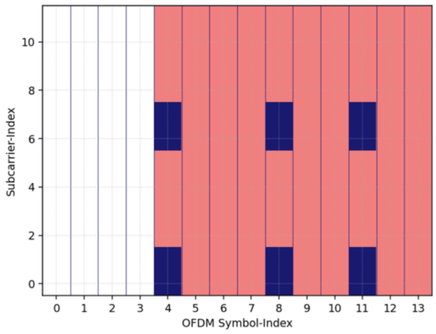


Figure 1.12: An Example of Configuration Type-II from 5G toolkit

The 5G supports two 2 mapping types:

- Mapping Type A: It is an slot based scheduling, the first symbol is determined by parameter *dmrs-TypeA-Position*, which can take value of pos2 ans pos3, indicating the first DMRS symbol can be at OFDM symbol number 2 or 3, as shown in figure 1.13 and figure 1.14.

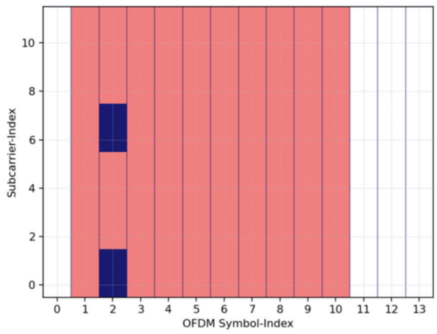


Figure 1.13: An Example of mapping type A with *dmrs-TypeA-Position* = pos2 from 5G toolkit

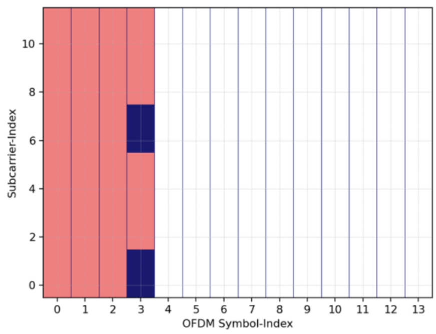


Figure 1.14: An Example of mapping type A with *dmrs-TypeA-Position* = pos3 from 5G toolkit

- Mapping Type B: It is mini slot based scheduling, where the first symbol allocated to PDSCH is allocated to DMRS as shown in figure 1.15.

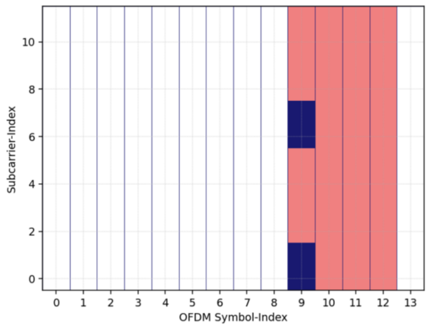


Figure 1.15: An Example of mapping type B from 5G toolkit

Additionally, 5G allows the allocation of additional symbol using the parameter *dmrs-AdditionalPosition*, which can take value of pos1, pos2 and pos3 indicating DMRS at 2, 3 and 4 symbols respectively. Moreover, 5G supports double symbols using the parameter *maxlength*, which takes value len1 and len2 indicating DMRS at single symbol and two symbols respectively.

1.4 | Design of the PDSCH Chain: Receiver

The PDSCH decoder performs mostly the complementary operation to that of PDSCH at the transmitter to decode the data. There are a few additional blocks in PDSCH receiver which are note standardized by 3GPP. These blocks are used to nullify the effect of hardware impairments. Some of these are discussed are discussed as follows.

1.4.1 | CFO Estimation and Correction

The carrier frequency offset arise in all the practical wireless system due to imperfections in the mixers and local oscillators. The mismatch in the local oscillator frequency at the transmitter and receiver results in CFO which translates into time varying phase in frequency/OFDM domain. In this tutorial, we will estimate the CFO using the PSS present in the SSB and use it to offset the phase rotation for PDSCH. The details of CFO estimation using PSS can be find in section-?? of chapter-??.

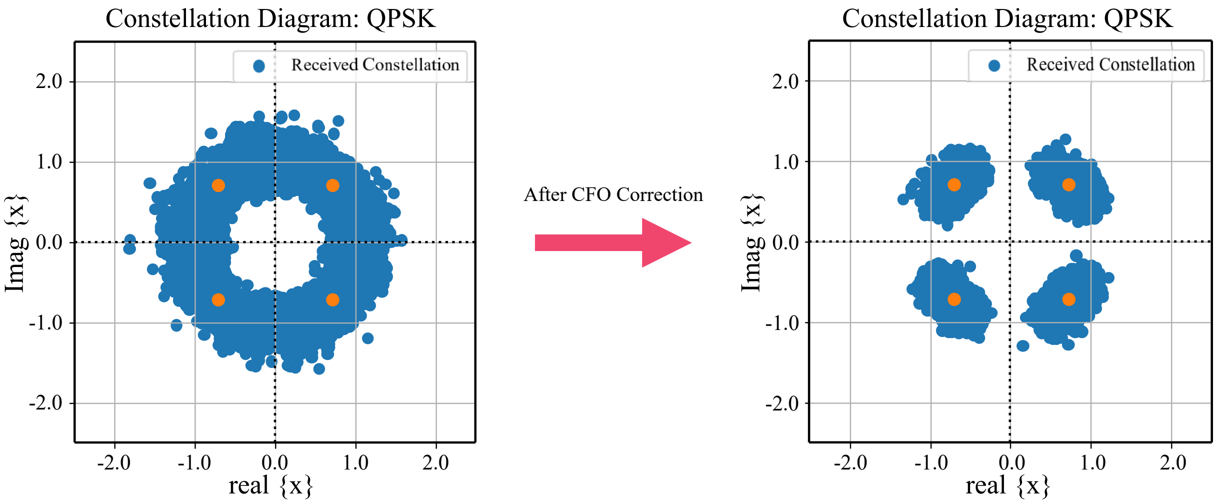


Figure 1.16: Carrier Frequency Offset (CFO) estimation and correction for PDSCH.

1.4.2 | Channel Estimation and Equalization

In 5G-NR, the channel is estimated using the DMRS transmitted alongside PDSCH as detailed in section-1.3.1. The estimated channel is used for equalization of the channel to recover the constellation symbols.

1.5 | Results

The simulation parameters and evaluation methodology considered for this experiment is given in table-1.3.

Table 1.3: Simulation parameters and evaluation methodology

Parameters	Value
center frequency (f_c)	1000 MHz
Bandwidth (B)	30 MHz
FFT size (N_{FFT})	1024
subcarrier spacing (Δf)	30 KHz
Numbers of Resource Blocks (RBs) (N_{RB})	85
Numbers of slots for PDSCH (N_{slot})	7
Numbers of BS (N_{BS})	1
PDSCH mapping type	"mapping type B"
maxLength (single or double DMRS)	'len1'
startSymbol (OFDM start symbol)	0
configurationType	"Configuration-type-1"
dmrsTypeAPosition	"pos2"
dmrsAdditionalPosition	"pos2"
rank (N_{L})	1
mcsIndex	0
mcsTable	"pdschTable1"
Transmitter-receiver separation (d)	10cm/1m

The simulation follows the procedure shown in fig-1.17

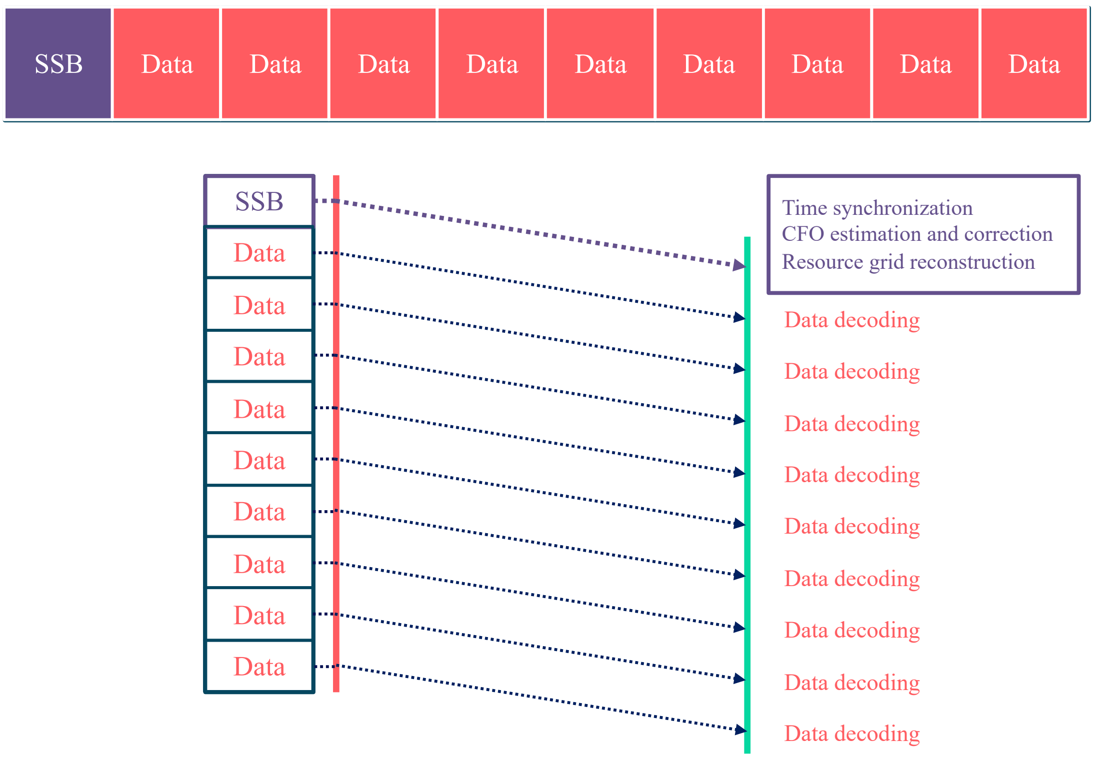


Figure 1.17: Organization of the simulations

Observation 1: *The quality of the constellation of the received signal depends on the reception of the resource grid, precision in mitigating hardware impairments, accuracy of channel estimates and symbol equalization.*
Since the downlink data is contained in PDSCH, it becomes necessary to detect PDSCH. The heat map of the received PDSCH grid is shown in figure 1.18.

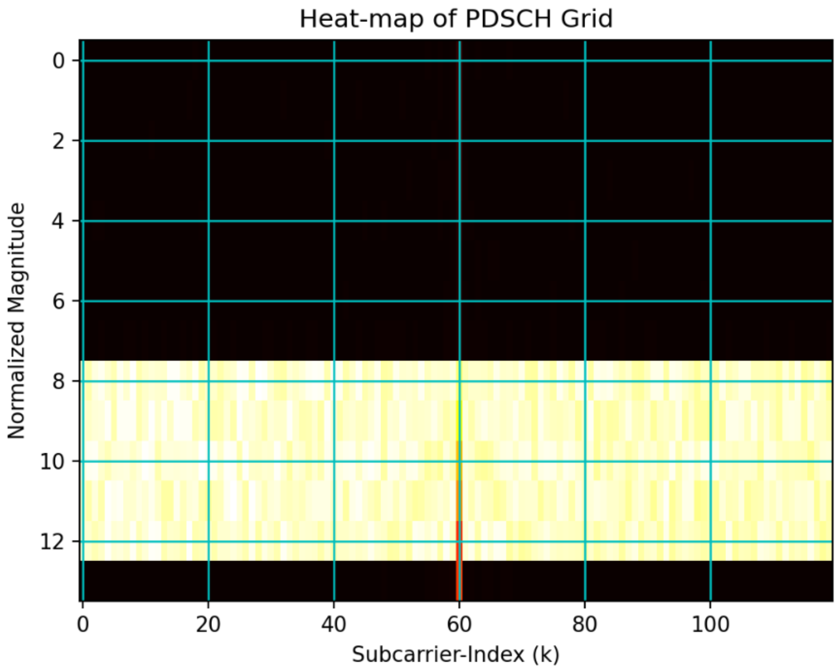


Figure 1.18: Heat map of received PDSCH grid

The figure 1.18 verifies the reception of PDSCH, since PDSCH was transmitted on 5 OFDM symbols(8-12). Recall from figure 1.2, after OFDM demodulation and CFO correction, the channel estimation and symbol equalization is carried out. The channel is estimated using the class **ChannelEstimationAndEqualizationPDSCH**, all relevant parameters are passed on to the class. To compute the equalized symbols, the inputs are passed onto the object of class: pdschGrid(the received PDSCH grid), interpolator(channel interpolator can be spline,linear or cubic, polyOrder (required only for cubic interpolator).
After symbol equalization, the resource demapping is carried out by carring out layer demapping and symbol demapping using the class **LayerDemapper** and **Demapper** respectively. Here the term rank refers to the numbers of transmission layers, numTBs refers to numbers of transport block and are always 1 when numbers of transmission layers is less then 4.

Upon demapper, descarmbling is pefromed at UE as shown in figure 1.2, upon descarmbling the bits are passed onto class **PDSCHDecoderUpperPhy**, which performs code block segregation, rate dematching, LDPC decoder, code block aggregation and transport block CRC removal. The received bits of PDSCH is shown in figure 1.20a. The result of observation 1 is for mcsIndex = 0 (QPSK).

Observation 2: *The mcs index allows the gNB to adapt the PDSCH transmission to channel conditions.*
The modulation order and code rate are configured for transmission using MCS index. When channel conditions are favorable, higher MCS indices are selected to maximize throughput while satisfying reliability requirements. However, if the channel conditions are harsh, the network selects more conservative MCS indices. Table-1.4 clearly shows that throughput increases with MCS index until the channel conditions support it. However, once the MCS index becomes too aggressive for the channel conditions, throughput starts to degrade due to a degradation in reliability (BLER) performance.

Table 1.4: Performance for different mcs index for transmitter gain of 0 dB and receiver gain of 60 dB.

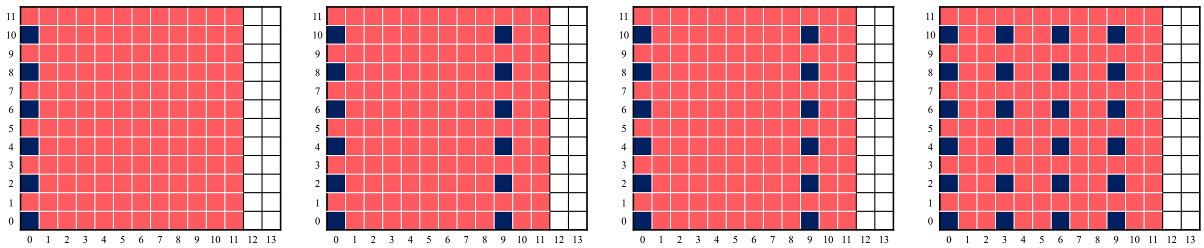
mcs Index	Q_m	r	Throughput	Spectral Efficiency	BLER
0	2	0.117	4.438 Mbps	0.147 bits/sec/Hz	0
4	2	0.3	11.2 Mbps	0.373 bits/sec/Hz	0
10	4	0.332	24.654 Mbps	0.8218 bits/sec/Hz	0
15	4	0.6	44.814 Mbps	1.4938 bits/sec/Hz	0
20	6	0.554	62.748 Mbps	2.091 bits/sec/Hz	0
23	6	0.7	3.758 Mbps	0.1252 bits/sec/Hz	0.952
24	6	0.754	0 Mbps	0 bits/sec/Hz	1

Observation 3: *Higher transmit power and receiver gain are required as the distance between transmitter and receiver increases.*
As the distance between transmitter and receiver increases, the power reaching at the receiver reduces. This results in degradation in the SNR at the receiving SDR. This limitation of link budget can be overcome by either transmitting higher power or higher amplification at the receiver as shown in table-1.5.

Table 1.5: Variation in performance with Tx-Rx separation for MCS Index 15

Distance		10 cm			1 m		
Tx gain	Rx gain	Throughput	BLER	BER	Throughput	BLER	BER
-20 dB	40 dB	44.814 Mbps	0	0	0 Mbps	1	0.406
-10 dB	50 dB	44.814 Mbps	0	0	0 Mbps	1	0.223
-0 dB	60 dB	44.814 Mbps	0	0	4.801 Mbps	0.892	0.010

Observation 4: *The pilot density in time can be configured to manage the temporal variations in the channel arising from residual time and frequency errors or UE mobility.*
The higher the time density of pilots, the better the system performance, especially when the channel is varying across time, as shown in figure 1.19. This temporal variation in the channel can result from factors such as UE mobility or residual time-frequency errors like time synchronization error, phase noise (PN), or carrier frequency offset (CFO). The increased number of demodulation reference signal (DMRS) symbols across time helps reduce the aging of channel estimates, improving symbol equalization performance, and consequently reducing the block error rate (BLER) of communications.



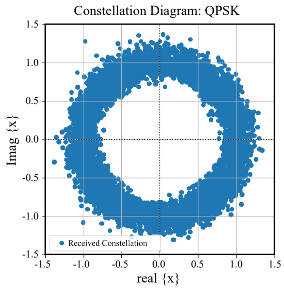
(a) "pos0". (b) "pos1". (c) "pos2". (d) "pos3".

Figure 1.19: PDSCH resource mapping in for different *dmrsAdditionalPosition*.

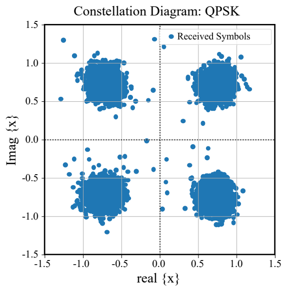
The parameter which determines the density of pilots in time domain is *dmrsAdditionalPosition*, as also shown in figure 1.19. The table 1.6 shows the performance for different *dmrsAdditionalPosition* in PDSCH. It can be observed clearly from table 1.6 that as pilot density across time increases the performance improves. Moreover, owing to increased overhead due to pilot the throughput for "pos2" is higher then "pos3".

Table 1.6: PDSCH performance with different *dmrsAdditionalPosition* and MCS indices (I_{MCS}).

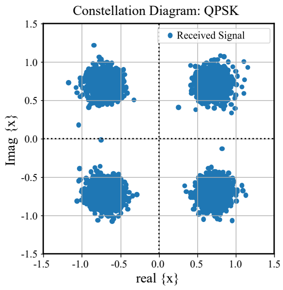
dmrsAdditionalPosition	"*pos0*"		"*pos1*"		"*pos2*"		"*pos3*"	
I_{MCS}	η	BLER	η	BLER	η	BLER	η	BLER
10	0	1	12.5475	0.75	–	0	–	–
16	0	1	50.19	0	48.40	0	45.71	0
20	0	1	31.36	0.51	62.75	0.0	49.03	0.17



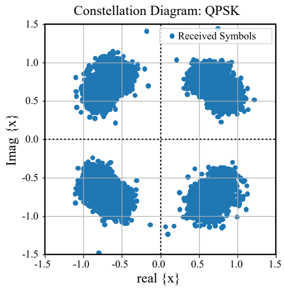
(a) "pos0"



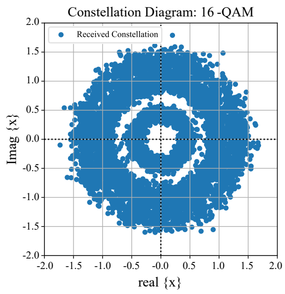
(b) "pos1"



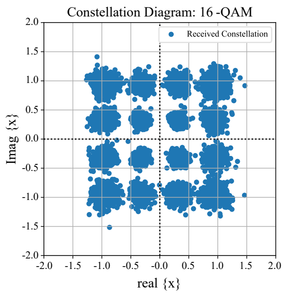
(c) "pos2"



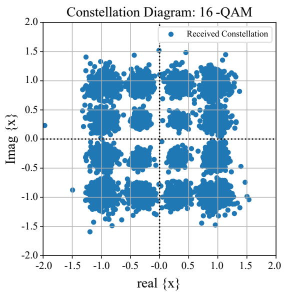
(d) "pos3"



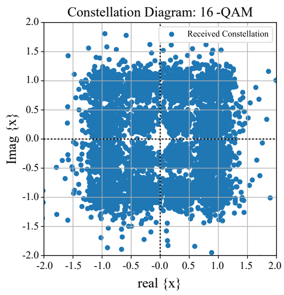
(e) "pos0"



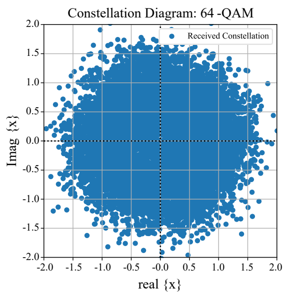
(f) "pos1"



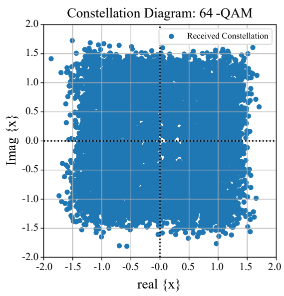
(g) "pos2"



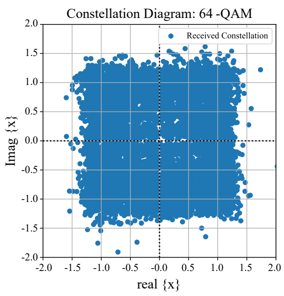
(h) "pos3"



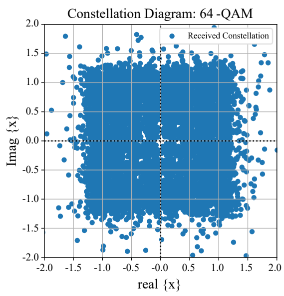
(i) "pos0"



(j) "pos1"



(k) "pos2"



(l) "pos3"

Figure 1.20: Constellation of the received PDSCH symbols for mcs-index (I_{MCS}) $= 4, 16, 20$ (row-wise) for different *dmrsAdditionalPosition* (column-wise).

The figure 1.20 shows the constellation of received PDSCH symbols. It is quite evident from figure as pilot density increases across time the constellation looks much clear.

1.6 | Appendix

1.6.1 | CQI tables

Table 1.7: CQI tables | I_{CQI} is CQI index | Q_m is modulation order | r is code-rate.

CQI Index	CQI table 1		CQI table 2		CQI table 3		CQI table 4	
I_{CQI}	Q_m	$r \times 1024$	Q_m	$r \times 1024$	Q_m	$r \times 1024$	Q_m	$r \times 1024$
0	-	-	-	-	-	-	-	-
1	2	78	2	78	2	30	2	78
2	2	120	2	193	2	50	2	193
3	2	193	2	449	2	78	2	449
4	2	308	4	378	2	120	4	378
5	2	449	4	490	2	193	4	616
6	2	602	4	616	2	308	6	567
7	4	378	6	466	2	449	6	666
8	4	490	6	567	2	602	6	772
9	4	616	6	666	4	378	6	873
10	4	466	6	772	4	490	8	711
11	4	567	6	873	4	616	8	797
12	4	666	8	711	6	466	8	885
13	4	772	8	797	6	567	8	948
14	4	873	8	885	6	666	10	853
15	4	948	8	948	6	772	10	948

1.6.2 | MCS Table

Table 1.8: MCS tables for PDSCH | I_{MCS} is MCS index | Q_m is modulation order | r is code-rate.

MCS index	PDSCH table 1		PDSCH table 2		PDSCH table 3		PDSCH table 4	
I_{MCS}	Q_m	$r \times 1024$	Q_m	$r \times 1024$	Q_m	$r \times 1024$	Q_m	$r \times 1024$
0	2	120	2	120	2	30	2	120
1	2	157	2	193	2	40	2	193
2	2	193	2	308	2	50	2	449
3	2	251	2	449	2	64	4	378
4	2	308	2	602	2	78	4	490
5	2	379	4	378	2	99	4	616
6	2	449	4	434	2	120	6	466
7	2	526	4	490	2	157	6	517
8	2	602	4	553	2	193	6	567
9	2	679	4	616	2	251	6	616
10	4	340	4	658	2	308	6	666
11	4	378	6	466	2	379	6	719
12	4	434	6	517	2	449	6	772
13	4	490	6	567	2	526	6	822
14	4	553	6	616	2	602	6	873
15	4	616	6	666	4	340	8	682.5
16	4	658	6	719	4	378	8	711
17	6	438	6	772	4	434	8	754
18	6	466	6	822	4	490	8	797
19	6	517	6	873	4	553	8	841
20	6	567	8	682.5	4	616	8	885
21	6	616	8	711	6	438	8	916.5
22	6	666	8	754	6	466	8	948
23	6	719	8	797	6	517	10	805.5
24	6	772	8	841	6	567	10	853
25	6	822	8	885	6	616	10	900.5
26	6	873	8	916.5	6	666	10	948
27	6	910	8	948	6	719	2	R
28	6	948	2	R	6	772	4	R
29	2	R	4	R	2	R	6	R
30	4	R	6	R	4	R	8	R
31	6	R	8	R	6	R	10	R

2 | References

[1] TS 38.211 3rd Generation Partnership Project. Physical channels and modulation (Release 17). *Technical Specification Group Radio Access Network*, Version(v17.5.0):35–52, 2023-06.

[2] Paul Bezner. 5G LDPC Codes. Institute of Telecommunications, University of Stuttgart, Germany, Apr 2024. Webdemo.