CSI-RS :

CSI-RS → Channel State Information Reference Signal.

Why do we need CSI-RS ?

Assume a BS and a UE. Lets say, UE is operating with MCS_10 and 2 layers. Now, how to decide whether to increase / decrease the MCS and No. of Layers ? One way is to do <u>trial and error experiment</u>. (ie) say for example, gNB sends the data with MCS_10, and if UE is continuously able to decode decode, then we may increase the MCS. when the packet fails, then we may decrease the MCS. The same experiment goes for for No. of Layers as well. So, based on how UE is able to decode or failed to decode, we can decide whether should we increase or decrease the MCS and No. of Layers. This is one way.

Other way is, <u>Using the CSI-RS</u>. gNB sends CSI-RS on multiple ports (CSI-RS can support 32 ports). The UE decodes the CSI-RS and signals back the gNB that 'how many layers or how many parallel streams can be decoded'. right now at this channel condition.

UE can also signal back what is the Quality of the channel (ie) Channel Quality Indicator (CQI).

UE can also signal back what kind of Precoding can be used that gives the best energy in a particular direction (ie) Precoding Matrix Indicator (PMI) and

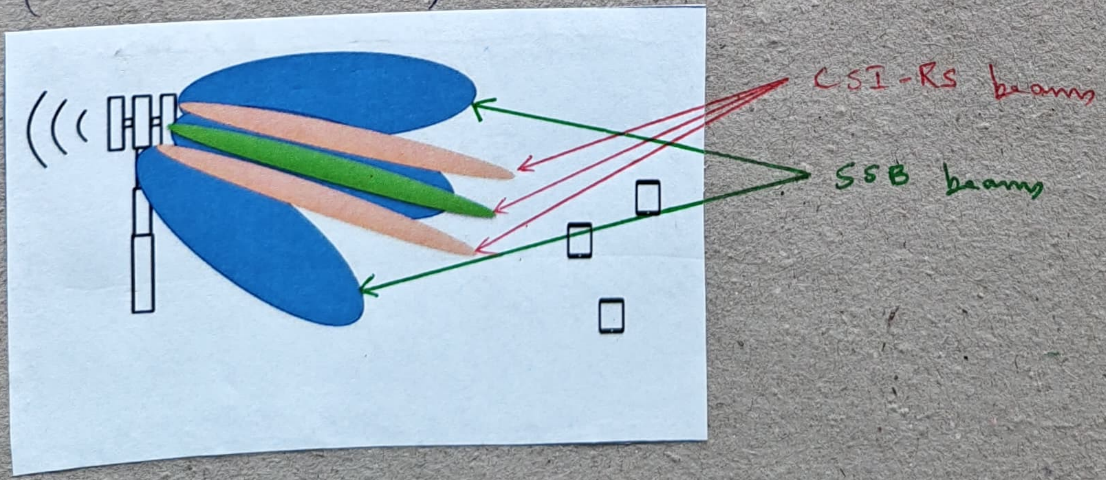
Rank Indicator (RI).

So, gNB uses the CQI, RI and PMI to serve the respective UE with better signal and better throughput.

CSI-RS can also be used for time and frequency synchronization. So far we have seen that SSB is used for time frequency synchronization. But once the UE is synchronized and camped-on to a cell, the gNB can signal the UE to do the time and frequency synchronization using CSI-RS. So, CSI-RS can also be used for time frequency synchronization.

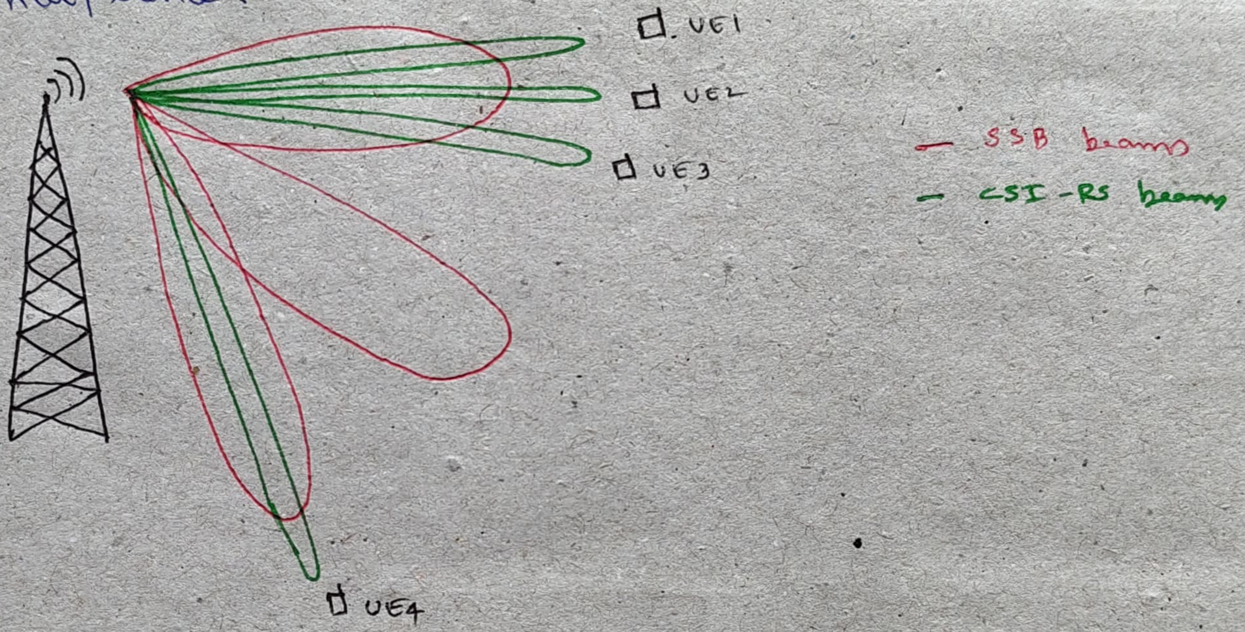
<u>Note</u>: In fact, RSRP and RSRQ are also defined for CSI-RS.

CSI-RS can also be used for SSB beam refining. <u>SSB beams</u> are normally wider (less in number), whereas <u>CSI-RS beams</u> are narrower (more in numbers).



In this example, we actually divide each SSB beam into 3 CSI-RS beams. So that, the UE can signal back which SSB beam suits best so that gNB can precode the signal in a way that it direct the energy in that particular direction for that UE.

CSI-RS can also be used for Interference Measurement. (i) It can be used to detect MU-MIMO interference.

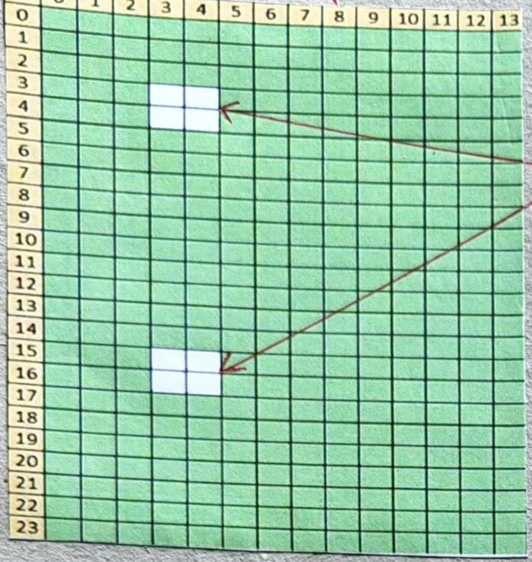


(ii) We want to multiplex UE1 and UE4 in this case. So, we do MU-MIMO between these two UEs. So using CSI-RS, we can find out the interference between UE1 and UE4.

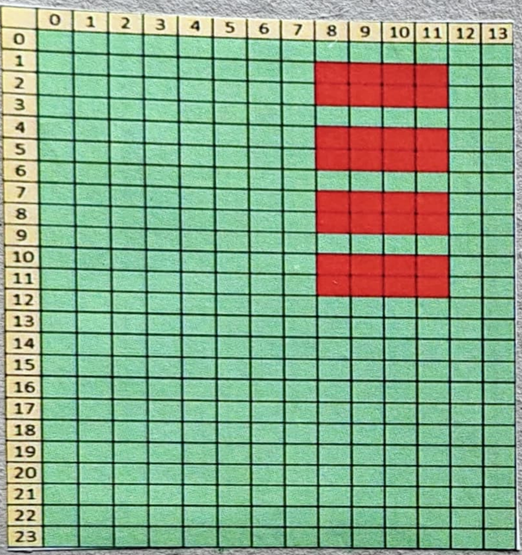
CSI-RS can also be used for Inter-cell-Interference. In fact, there is a signal (CSI-IM) defined for that CSI-RS for Interference measurement. In that case, we send REs without any data, on the cell where we want to calculate Interference coming from other cell.

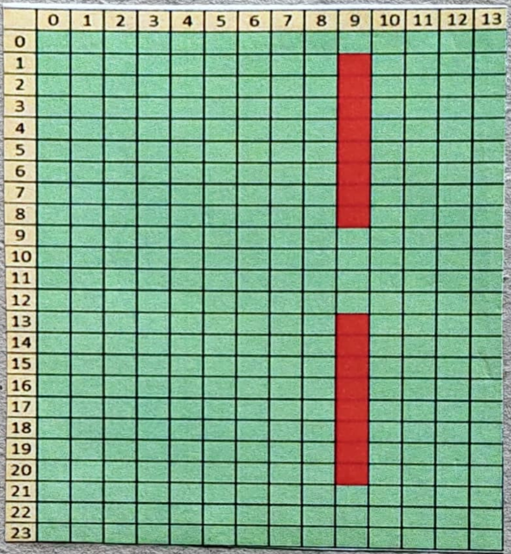
→

CSI-IM



On these REs, where there is no data, UE can calculate signal coming from other gNBs and signal back the Interference.





As we know, CSI-RS supports 32 ports, and the RE arrangement is done using FDM, TDM and CDM. It looks something like as shown in above figures.

Also, there are two types of CSI-RS.

- Zero Power CSI-RS (ZP CSI-RS)
- Non-Zero Power CSI-RS (NZP CSI-RS).

CSI-RS : CDM Concept.

CDM stands for Code Division Multiplexing, and it is used to generate Orthogonal sequences for multiple port transmission. The same concept is also being used in DMRS generation as well.

How do we prove whether two sequences are Orthogonal?

Consider the following two sequences

$A = [a_1, a_2]$

$B = [b1, b2]$

If $(a_1 * b1) + (a_2 * b2) == 0$, then the sequence A is Orthogonal with sequence B.

Example 1:

$A = [+1, +1]$

$B = [-1, -1]$

Then, $(+1)(-1) + (+1)(-1) = -2$.

Here the sequences A and B are NOT orthogonal.

Example 2:

$A = [+1, +1]$

$B = [+1, -1]$

Then, $(+1)(+1) + (+1)(-1) = 0$

Here, these two sequences are Orthogonal.

Consider $A = [+1, +1]$ where the sequences A
$B = [+1, -1]$
and B are orthogonal to each other.

Now, consider $C = [-1, +1]$.

We see that, C and A are orthogonal, but C and B are NOT orthogonal.

$|||^{ly}$ consider $D = [-1, -1]$.

We see that, D and A are NOT orthogonal, but D and B are orthogonal.

This implies, we cannot find a third sequence that is orthogonal to both A and B.

With sequence length of 2, we can generate maximum 2 sequences that are orthogonal with each other. (or) We can say, To have two orthogonal sequences, we need sequence length of minimum 2.

Consider $A = [+1, +1, +1, +1]$
$B = [+1, -1, +1, -1]$

Here, $(+1)(+1) + (+1)(-1) + (+1)(+1) + (+1)(-1) = 0$.

So, the sequences A and B are orthogonal to each other.

Now, consider $C = [+1, +1, -1, -1]$.

We see that, C and A are orthogonal, and C and B are also orthogonal.

Now, consider $D = [-1, +1, +1, -1]$

We see that, D and A are orthogonal,
D and B are orthogonal, and
D and C are also orthogonal.

And here, we cannot find a fifth sequence that is orthogonal to A, B, C and D.

With sequence length of 4, we can have maximum 4 orthogonal sequences. (or) We can also say, To have 4 orthogonal sequences, we need sequence length of minimum 4.

Similarly, this exercise can be done for 8, 16, 24, 32, and so on.

So, these sequences which are orthogonal to each other (A, B, C and D) are called Orthogonal Code Cover (OCC).

Now, let us take a base sequence with same amplitude. say $[a, b, c, d]$ and multiply with the Orthogonal Cover Code (OCC).

$$\Rightarrow A = [a, b, c, d]$$

$$B = [a, -b, c, -d]$$

$$C = [a, b, -c, -d]$$

$$D = [-a, b, c, -d]$$

where, all the 4 elements (ie) a, b, c, d have the same amplitude.

Typically, a, b, c, d are complex numbers. To prove the orthogonality, we'll have to multiply with conjugates. say for example, $X = [a, b]$

$$Y = [p, q]$$

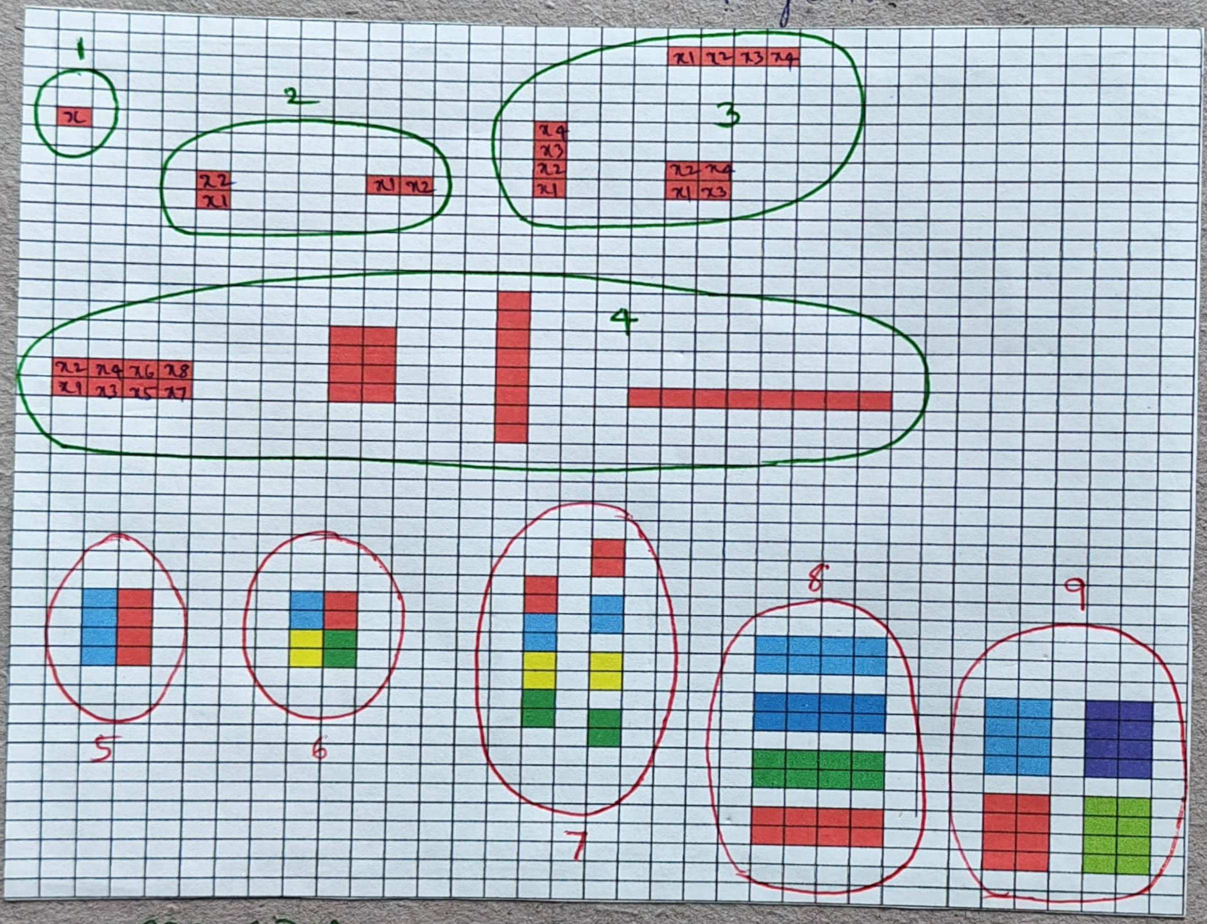
The sequences X and Y are orthogonal, if

$$a^* \cdot p + b^* \cdot q == 0.$$

In summary, we take the base sequence [a, b, c, d], multiply it with the OCCs, to generate 4 different sequences ($\because$ the sequence length (Base) = 4).

Now, this 4 different Orthogonal sequences can go on 4 different ports, at different time and frequency locations.

Now, lets look at this diagram.



no CDM

① ⇒ ⊙ Here, Sequence length = 1

⊙ $\because$ Sequence length = 1, we can have just one CDM Group.

⊙ This is for Single Port

⊙ Only one Orthogonal sequence can be generated. That is, this itself. (ie) x (complex number)

② ⇒ CDM 2

- Here, Sequence length = 2.
- Lets say, we're transmitting $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$ at same time.

so, for one port, we can have $\begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$, and for second port, we can have $\begin{bmatrix} x_1 \\ -x_2 \end{bmatrix}$.

- If we transmit $[x_1 \; x_2]$ at same frequency (different time), in this case,

For Antenna Port 1, we can have $[x_1 \; x_2]$,

For Antenna Port 2, we can have $[x_1 \; -x_2]$.

- Two variants — CDM2-FD2, CDM2-TD2

③ ⇒ CDM 4

- Here, Sequence length = 4.

So, Four orthogonal sequences can be generated.

So, we can have max. 4 ports with this sequence.

- Three variants shown in figure:
  - CDM4 - FD4
  - CDM4 - FD2 - TD2
  - CDM4 - TD4

The concept remains the same, only the mapping changes (mapping to different time and frequency).

- Lets say, we transmit $\begin{bmatrix} x_2 & x_4 \\ x_1 & x_3 \end{bmatrix}$, then

For Port 1, we can have $\begin{bmatrix} x_2 & x_4 \\ x_1 & x_3 \end{bmatrix}$, For Port 2, we can have $\begin{bmatrix} x_2 & x_4 \\ -x_1 & -x_3 \end{bmatrix}$, For Port 3, it could be $\begin{bmatrix} x_2 & -x_4 \\ x_1 & -x_3 \end{bmatrix}$ and For Port 4, it could be $\begin{bmatrix} -x_2 & x_4 \\ x_1 & -x_3 \end{bmatrix}$.

- This way, data for 4 orthogonal ports generated.

④ ⇒ CDM 8

- The same concept applies here as well.
- Sequence length = 8
- The way we map the data may be different, but the concept remains the same. (i.e.) we can have 8 orthogonal sequences that can go on 8 different ports.
- Four variants shown in figure
  - CDM 8 - FD2 - TD4
  - CDM 8 - FD4 - TD2
  - CDM 8 - FD 8
  - CDM 8 - TD8

---

⑤ ⇒

- We've seen CDM 8 - FD4 - TD2, which has 8 orthogonal sequences for 8 ports, for one base sequence $[x_1, x_2, \dots x_8]$.
- What if two CDM4 - FD4 groups, both multiplexed in time?
- Both CDM8-FD4-TD2 and two CDM4-FD4 groups will do the same job.
- (i.e.) The goal of CDM8-FD4-TD2 was to generate 8 orthogonal sequences. And here, each CDM4-FD4 group generates different 4 orthogonal sequences, since they are different in time. So, again, in total 8 orthogonal sequences generated using two CDM4-FD4 groups.

⊙ The advantage here is that, lets say the BS signals 8 CSI-RS ports, and the UE have the capability of only 4 ports. So, if BS uses CDM8-FD4-TD2, UE cannot signal using its 4 ports. But, if BS uses two CDM4-FD4 instead, one UE can signal using one CDM4-FD4 (BLUE) and another UE can signal using another CDM4-FD4 (RED).

6 ⇒

⊙ Similar case as above.

⊙ Here, there are four CDM2-FD2 groups.

7 ⇒

⊙ This is another example where to understand that the CDM groups need not to be consecutive in frequency domain in the resource map.

8 ⇒

⊙ In this example, there are four CDM8-FD2-TD4 groups, each generating 8 orthogonal sequences.

⊙ So, in total, 8 × 4 = 32 orthogonal sequences generated. This is how <u>32 ports</u> achieved.

9 ⇒

⊙ This is another example where we have four CDM8-FD4-TD2 groups of size 8, which generates 32 orthogonal sequences for 32 antenna ports.

This is the concept of CDM orthogonality being used in CSI-RS and similar concept is also being used in DMRS generation for PDSCH and PUSCH as well for multi port transmissions (for MIMO).

CSI - RS : Sequence Generation & Mapping

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

UE specific scrambling ID

$$r(m) = \frac{1}{\sqrt{2}}\left(1 - 2 \cdot c(2m)\right) + j\frac{1}{\sqrt{2}}\left(1 - 2 \cdot c(2m+1)\right)$$

$$a_{k,l}^{(p,\mu)} = \beta_{CSIRS} w_f(k') \cdot w_t(l') \cdot r_{l,n_{s,f}}(m')$$

Orthogonal sequences for CDM

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

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

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

Density

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

$$n = 0, 1, \ldots$$

CSI-RS is a QPSK modulated signal (similar to DMRS signals). This QPSK modulated signals are generated from PN sequence.

The input to the PN sequence is Cinit value. The Cinit is a function of Slot number ($n^{\mu}_{s,f}$), Symbol number (l) and Scrambling ID (n_{ID}).

The Scrambling ID (n_{ID}) can be a UE specific ID. So, we can generate UE specific CSI-RS as well.

$(N^{slot}_{symb} \cdot n^{\mu}_{s,f} + l + 1) \rightarrow$ This part in Cinit ensures that, in a Frame, for every symbol, the generated CSI-RS sequence is different.

Now, the generated QPSK symbols $r(m)$ are mapped to resources as follows.

$$\alpha^{(p,\mu)}_{k,l} = \beta_{CSIRS} \, w_f(k') \cdot w_t(l') \cdot r_{l,n_{s,f}}(m').$$

where, $p \rightarrow$ Port

$\mu \rightarrow$ Numerology

$k \rightarrow$ Frequency index

$l \rightarrow$ OFDM symbol index.

$\beta_{CSIRS} \rightarrow$ Power for CSI-RS

$\omega_f(k')$ and $\omega_t(l') \rightarrow$ are to provide orthogonality

$\rightarrow$ are the cover code in time and frequency.

$r_{l, n_{s,f}}(m') \rightarrow$ QPSK symbols that are supposed to be transmitted.

Now, lets understand the mapping. As we see, m' is to navigate through the PN sequence or the QPSK modulated generated sequence (in the $r(m)$).

$k', l' \rightarrow$ Frequency and Time index inside the CDM group.

$\bar{k}, \bar{l} \rightarrow$ is to navigate through different CDM groups.

$\rho \rightarrow$ It tells, what is the density of CSI-RS in a PRB.

$n \rightarrow$ Free index $(0, 1, 2, \ldots)$.

As we see, n is used to calculate k, where k is the location where the DATA will be mapped in the subcarriers.

Also, n is used in the calculation of m' as well.

As we see in k computation, 'n' is multiplied with No. of subcarriers in a PRB (N_{sc}^{RB}). So, 'n' is here to move from one PRB to next PRB. Also we see that, k is a function of $\overline{k}$ and $\overline{k}$, and

l is a function of $\overline{l}$ and $\overline{l}$

This is also just to move to the next PRB.

Table below gives CSI-RS locations within a slot.

Table 7.4.1.5.3-1: CSI-RS locations within a slot.

Row	Ports X	Density ρ	*cdm-Type*	$(\bar{k}, \bar{l})$	CDM group index j	k'	l'
1	1	3	noCDM	$(k_0, l_0), (k_0+4, l_0), (k_0+8, l_0)$	0,0,0	0	0
2	1	1, 0.5	noCDM	(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

First column is the Row index that goes from 1 to 18. Second column is the No. of Antenna ports. Possible Number of Ports → 1, 2, 4, 8, 12, 16, 24, 32. Third column is the Density, which tells the No. of CSI-RS going into a single PRB. As we see, Row 1 is highly dense ($\rho = 3$) and the rest all have density of 1 or 0.5. Fourth column is CDM-Type. We've seen the CDM-Types (no CDM, CDM2, CDM4 and CDM8). Fifth column is the index $(\bar{k}, \bar{l})$. As we've already

seen, $\bar{k}$ and $\bar{l}$ is to move to the next CDM group.
For example, we take Row index 4 (ii) fd-CDM2. The is single CDM group of size 2. But there are 2 CDM groups. One at location k_0, and one at location $(k_0 + 2)$ at symbol location l_0 (both)

$k' = 1$

$k' = 0$

$\bar{k} = k_0 + 2$

$k' = 1$

$k' = 0$

$\bar{k} = k_0$

- We use k' to navigate inside the CDM group
- We use $\bar{k}$ to navigate to the different CDM group.
- Since there is single symbol, $l' = \bar{l}$

The location in time and frequency $(\bar{k}, \bar{l})$ are given in terms of $\begin{Bmatrix} k_0, k_1, k_2, \dots \\ l_0, l_1, l_2, \dots \end{Bmatrix}$

The locations $l_0, l_1, l_2, \dots$ directly represents the Time domain location. But the locations $k_0, k_1, k_2, \dots$ are calculated based on different bitmaps as shown below.

- $[b_3 \cdots b_0], k_{i-1} = f(i)$ for row 1 of Table 7.4.1.5.3-1
- $[b_{11} \cdots b_0], k_{i-1} = f(i)$ for row 2 of Table 7.4.1.5.3-1
- $[b_2 \cdots b_0], k_{i-1} = 4f(i)$ for row 4 of Table 7.4.1.5.3-1
- $[b_5 \cdots b_0], k_{i-1} = 2f(i)$ for all other cases

For Rows 1, 2, and 4, it is defined separately. And for the rest of the rows, it is defined separately.
Example: $\longrightarrow$

Lets take the Row 4, it is of size 3 (ie)
$[b_2 \ b_1 \ b_0]$; defined as $k_{i-1} = 4 f(i)$

$\Rightarrow$

$i=1$; $k_0 = 4 f(1)$,
$i=2$; $k_1 = 4 f(2)$ and
$i=3$; $k_2 = 4 f(3)$.

Here, $f(i)$ is the i^{th} bit index, where the bit is set to 1.

Eg.1 If $[b_2 \ b_1 \ b_0] = [0 \ 1 \ 0]$,
here, the first set bit (ie) 1 is at location 1.

$\Rightarrow f(1) = 1$

$\Rightarrow \boxed{k_0 = 4}$

Eg.2 If $[b_2 \ b_1 \ b_0] = [1 \ 1 \ 0]$,
here, the first set bit (ie) 1 is at location 0.
the second set bit (ie) 1 is at location 1

$\Rightarrow f(1) = 0$
$f(2) = 1$

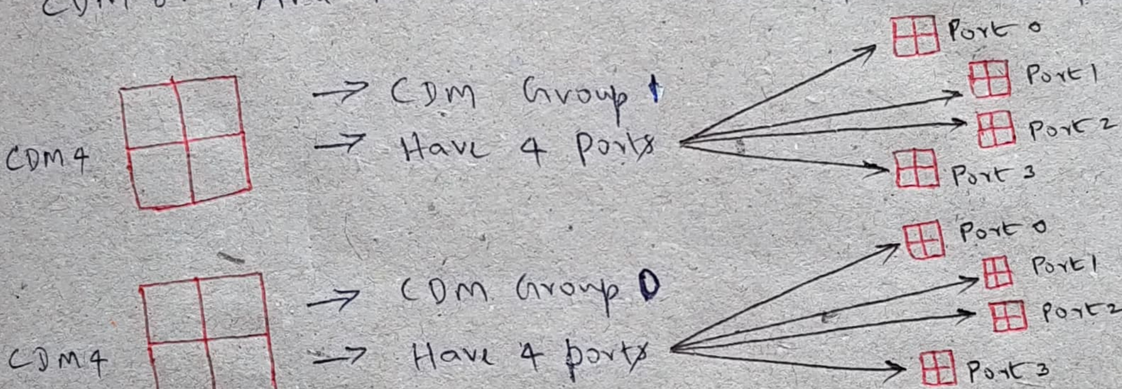
$\Rightarrow \boxed{k_0 = 0, \ k_1 = 4}$

This is how we decode this bitmap. And this gives us the frequency location where the CSI-RS CDM groups will be going (ie) (k_0, k_1, k_2).

CSI-RS is transmitted using antenna ports p numbered according to

$$p = 3000 + s + jL;$$
$$j = 0,1,\ldots, N/L - 1$$
$$s = 0,1,\ldots, L-1;$$

Above snippet shows how the antenna ports for CSI-RS is defined. 'p' is the port index, and it depends on two indices 's' and 'j' and the CDM group size L (ie) {1, 2, 4, 8} (ie) no CDM, CDM2, CDM4, CDM 8. And N is the total No. of CSI-RS ports.



When we map the CSI-RS data to different ports, first we map to a single CDM Group (increment 's') (ie) CDM Group 0, and then map the remaining data to next CDM Group (ie) CDM Group 1.

UE shall assume that the CSI-RS is transmitted in slots satisfying

$$\left(N_{\text{slot}}^{\text{frame},\mu} n_f + n_{s,f}^{\mu} - T_{\text{offset}}\right) \bmod T_{\text{CSI-RS}} = 0$$

CSI-RS is transmitted in the slots where the above equation satisfies.

n_f → Frame number

$n_{s,f}^{\mu}$ → slot number

T_{offset} → Slot offset

T_{CSI-RS} → Periodicity.

Table 7.4.1.5.3-2: The sequences $w_f(k')$ and $w_t(l')$ for *cdm-Type* equal to 'noCDM'.

Index	$w_f(0)$	$w_t(0)$
0	1	1

Table 7.4.1.5.3-3: The sequences $w_f(k')$ and $w_t(l')$ for *cdm-Type* equal to 'fd-CDM2'.

Index	$[w_f(0) \;\; w_f(1)]$	$w_t(0)$
0	$[+1 \;\; +1]$	1
1	$[+1 \;\; -1]$	1

Table 7.4.1.5.3-4: The sequences $w_f(k')$ and $w_t(l')$ for *cdm-Type* equal to 'cdm4-FD2-TD2'.

Index	$[w_f(0) \;\; w_f(1)]$	$[w_t(0) \;\; w_t(1)]$
0	$[+1 \;\; +1]$	$[+1 \;\; +1]$
1	$[+1 \;\; -1]$	$[+1 \;\; +1]$
2	$[+1 \;\; +1]$	$[+1 \;\; -1]$
3	$[+1 \;\; -1]$	$[+1 \;\; -1]$

Table 7.4.1.5.3-5: The sequences $w_f(k')$ and $w_t(l')$ for *cdm-Type* equal to 'cdm8-FD2-TD4'.

Index	$[w_f(0) \;\; w_f(1)]$	$[w_t(0) \;\; w_t(1) \;\; w_t(2) \;\; w_t(3)]$
0	$[+1 \;\; +1]$	$[+1 \;\; +1 \;\; +1 \;\; +1]$
1	$[+1 \;\; -1]$	$[+1 \;\; +1 \;\; +1 \;\; +1]$
2	$[+1 \;\; +1]$	$[+1 \;\; -1 \;\; +1 \;\; -1]$
3	$[+1 \;\; -1]$	$[+1 \;\; -1 \;\; +1 \;\; -1]$
4	$[+1 \;\; +1]$	$[+1 \;\; +1 \;\; -1 \;\; -1]$
5	$[+1 \;\; -1]$	$[+1 \;\; +1 \;\; -1 \;\; -1]$
6	$[+1 \;\; +1]$	$[+1 \;\; -1 \;\; -1 \;\; +1]$
7	$[+1 \;\; -1]$	$[+1 \;\; -1 \;\; -1 \;\; +1]$

Above tables shows the sequences $w_f(k')$ and $w_t(l')$ for various cdm-Types. There are Orthogonal cover codes. For example, we take $w_f(k')$ and $w_t(l')$ for CDM4-FD2-TD2.

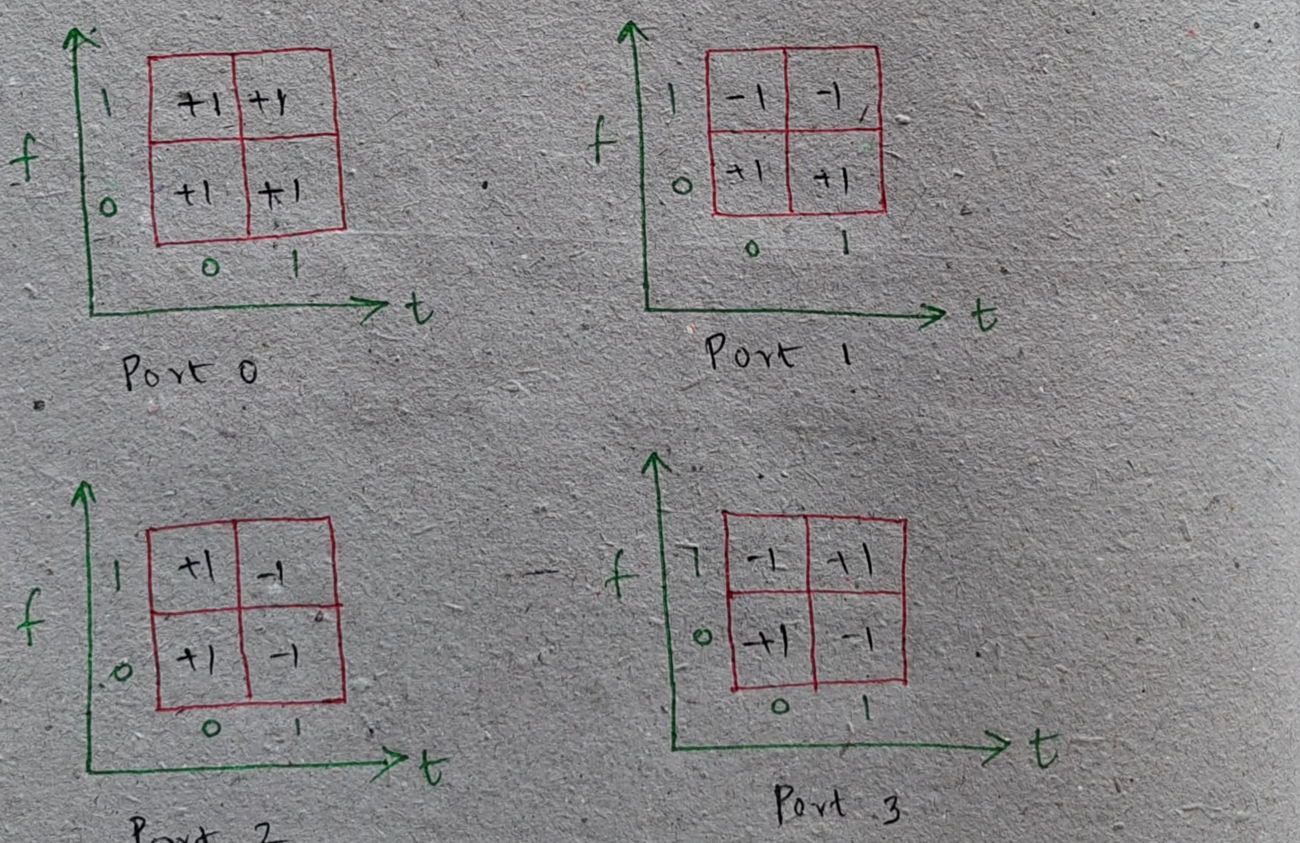


Fig: One CDM Group with 4 Antenna Ports.

This is how the orthogonal code covers are defined in specification. Similarly we can work around for no CDM, CDM2 and CDM8 as well.

The sixth column of Table 7.4.1.5.3-1 (i.e.) CDM group index (j) is used in the CSI-RS Antenna Port mapping formula (i.e.) $p = 3000 + s + jL$.

For example, Row 8, here CDM4 has 8 orthogonal ports, hence there are two CDM groups indexed $j = 0$ and 1. Another example, Row 9, here CDM2 has 12 orthogonal ports, hence there are six CDM groups indexed $j = 0, 1, 2, 3, 4$ and 5. Another example, Row 17, here CDM4 has 32 orthogonal ports, hence there are eight CDM groups indexed $j = 0, 1, \ldots, 7$.

This is how the CSI-RS mapping is done to different ports inside a slot, in different CDM groups.

CSI-RS : Sequence Generation & Mapping

(Example)

We know, CSI-RS Resource Mapping is quite complicated, One of the reason is there are 32 ports unlike any other channels.

Table 7.4.1.5.3-1: CSI-RS locations within a slot.

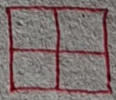
Row	Ports X	Density ρ	*cdm-Type*	$(\bar{k}, \bar{l})$	CDM group index j	k'	l'
1	1	3	noCDM	$(k_0, l_0), (k_0+4, l_0), (k_0+8, l_0)$	0,0,0	0	0
2	1	1, 0.5	noCDM	$(k_0, l_0),$	0	0	0
3	2	1, 0.5	fd-CDM2	$(k_0, l_0),$	0	0, 1	0
4	4	1	fd-CDM2	$(k_0, l_0), (k_0+2, l_0)$	0,1	0, 1	0
5	4	1	fd-CDM2	$(k_0, l_0), (k_0, l_0+1)$	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

Lets take Row 10. With this example, we'll see how the mapping goes.

Ports, $X = 12$

Density, $\rho = 1$

cdm-Type = CDM4-FD2-TD2



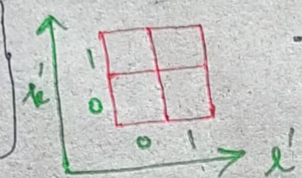
$\bar{k} = \{k_0, k_1, k_2\}$

$\because$ there are 12 ports, and its CDM4, so we need to have 3 CDM groups. One at location k_0, one at k_1 and one at k_2.

$\bar{l} = \{l_0\} = 3$ (assumption)

CDM group index, $j = 0, 1, 2$

$k' = 0, 1$
$l' = 0, 1$



→ Inside the CDM group, we navigate using k' and l'.

- $[b_3 \cdots b_0]$, $k_{i-1} = f(i)$ for row 1 of Table 7.4.1.5.3-1
- $[b_{11} \cdots b_0]$, $k_{i-1} = f(i)$ for row 2 of Table 7.4.1.5.3-1
- $[b_2 \cdots b_0]$, $k_{i-1} = 4f(i)$ for row 4 of Table 7.4.1.5.3-1
- $[b_5 \cdots b_0]$, $k_{i-1} = 2f(i)$ for all other cases ✓

∴ Row = 10, this formula is applicable.

Here, the bitmap size is 6.

Lets assume $[b_5\ b_4\ b_3\ b_2\ b_1\ b_0] = [1\ 0\ 1\ 0\ 1\ 0]$

$$\boxed{k_{i-1} = 2f(i)}$$

$\Rightarrow i=1,\ k_0 = 2f(1)$
$i=2,\ k_1 = 2f(2)$
$i=3,\ k_2 = 2f(3)$
$i=4,\ k_3 = 2f(4)$
$i=5,\ k_4 = 2f(5)$
$i=6,\ k_5 = 2f(6)$

First set bit (i.e.) 1 is at location 0

$\Rightarrow f(1) = 0 \quad \Rightarrow \boxed{k_0 = 0}$

Second set bit (i.e.) 1 is at location 2

$\Rightarrow f(2) = 2 \quad \Rightarrow \boxed{k_1 = 4}$

Third set bit (i.e.) 1 is at location 4

$\Rightarrow f(3) = 4 \quad \Rightarrow \boxed{k_2 = 8}$

k_0, k_1 and k_2 gives the frequency location where the CSI-RS CDM groups will be going. So, we've 3 CDM groups.

Lets also find the ports as well.

CSI-RS is transmitted using antenna ports p numbered according to

$$p = 3000 + s + jL;$$
$$j = 0,1,\ldots, N/L - 1$$
$$s = 0,1,\ldots, L-1;$$

We have, CDM group size, $L = 4$ ($\because$ CDM 4-FD2-TD2)

No. of Ports, $N = 12$

So, $s = 0,1,2,3$

$j = 0,1,2$

$\Rightarrow \boxed{p = 3000 \text{ to } 3011}$

Now, lets look into Orthogonal cover code as well.

Table 7.4.1.5.3-2: The sequences $w_f(k')$ and $w_t(l')$ for *cdm-Type* equal to 'noCDM'.

Index	$w_f(0)$	$w_t(0)$
0	1	1

Table 7.4.1.5.3-3: The sequences $w_f(k')$ and $w_t(l')$ for *cdm-Type* equal to 'fd-CDM2'.

Index	$[w_f(0)\ w_f(1)]$	$w_t(0)$
0	$[+1\ +1]$	1
1	$[+1\ -1]$	1

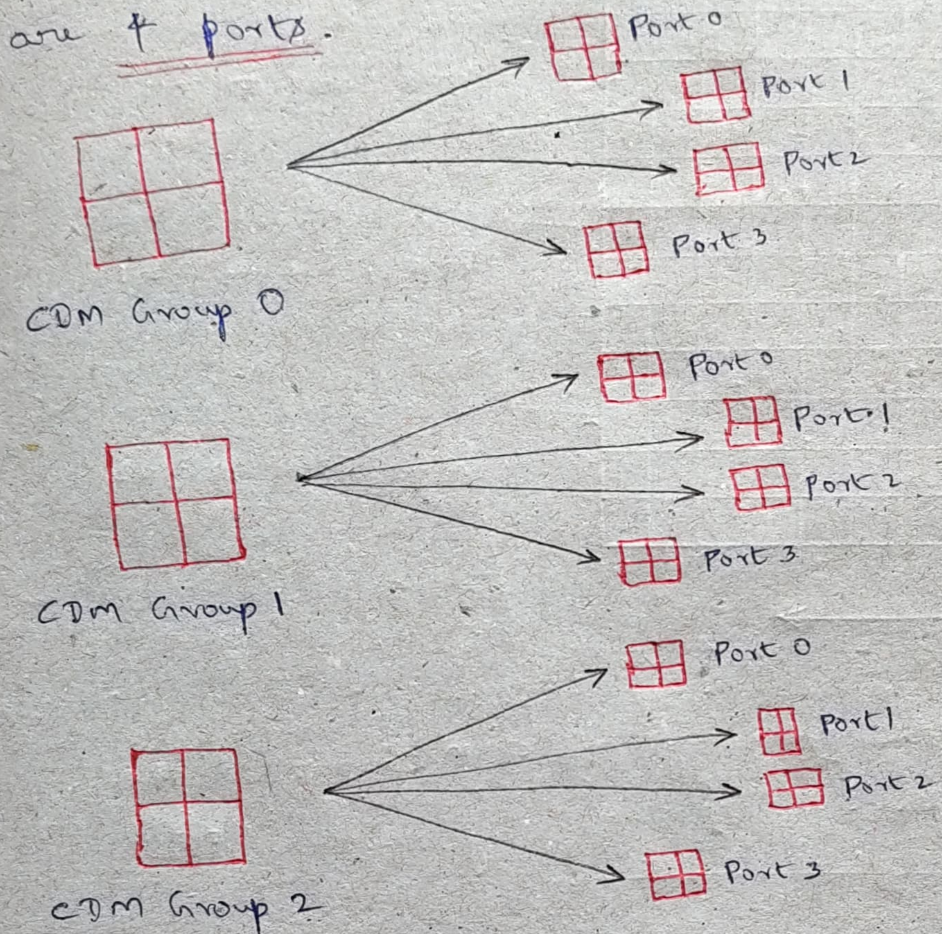
Table 7.4.1.5.3-4: The sequences $w_f(k')$ and $w_t(l')$ for *cdm-Type* equal to 'cdm4-FD2-TD2'.

Index	$[w_f(0)\ w_f(1)]$	$[w_t(0)\ w_t(1)]$
0	$[+1\ +1]$	$[+1\ +1]$
1	$[+1\ -1]$	$[+1\ +1]$
2	$[+1\ +1]$	$[+1\ -1]$
3	$[+1\ -1]$	$[+1\ -1]$

Table 7.4.1.5.3-5: The sequences $w_f(k')$ and $w_t(l')$ for *cdm-Type* equal to 'cdm8-FD2-TD4'.

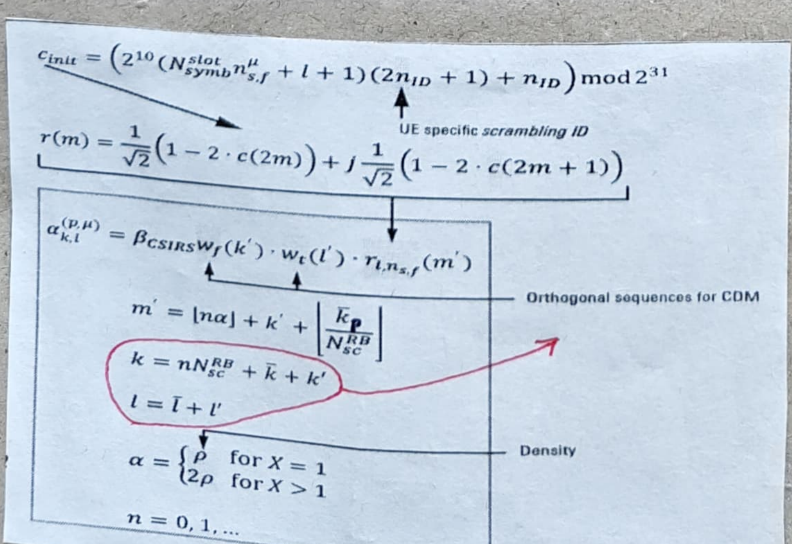
Index	$[w_f(0)\ w_f(1)]$	$[w_t(0)\ w_t(1)\ w_t(2)\ w_t(3)]$
0	$[+1\ +1]$	$[+1\ +1\ +1\ +1]$
1	$[+1\ -1]$	$[+1\ +1\ +1\ +1]$
2	$[+1\ +1]$	$[+1\ -1\ +1\ -1]$
3	$[+1\ -1]$	$[+1\ -1\ +1\ -1]$
4	$[+1\ +1]$	$[+1\ +1\ -1\ -1]$
5	$[+1\ -1]$	$[+1\ +1\ -1\ -1]$
6	$[+1\ +1]$	$[+1\ -1\ -1\ +1]$
7	$[+1\ -1]$	$[+1\ -1\ -1\ +1]$

Since, our example is CDM4-FD2-TD4, Table 4 above is applicable for $w_f(k')$ and $w_t(l')$ data. This table is for single CDM group with 4 ports. And we have 3 CDM groups. For all 3 CDM groups, the same table will be used, where for each CDM group, there are 4 ports.



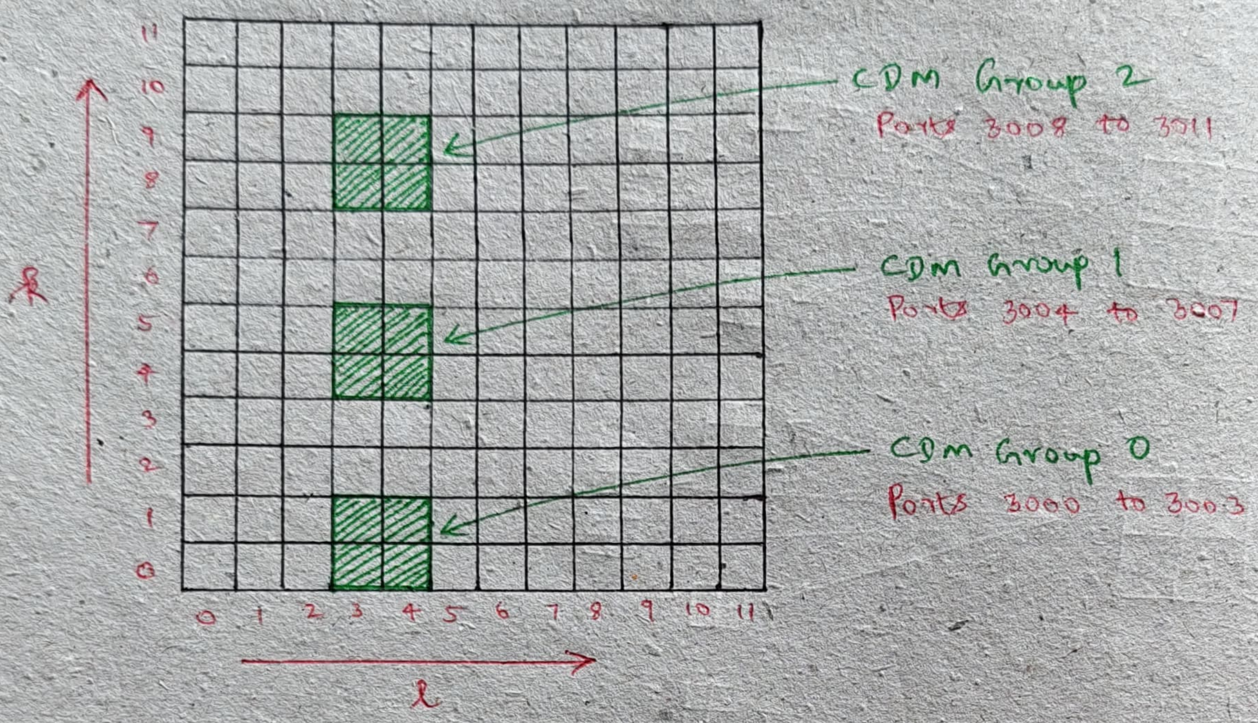
The Orthogonality of these Ports are given by Table 7.4.1.5.3-4. These 3 CDM groups are at 3 different locations k_0, k_1 and k_2.

$$\boxed{k_0 = 0 \;;\; k_1 = 4 \;;\; k_2 = 8 \;;\; l_0 = 3}$$



⊙ $l = \bar{l} + l'$
$= l_0 + l'$
$= 3 + l'$
$\Rightarrow \boxed{l = 3, 4}$

⊙ $k = nN_{sc}^{RB} + \bar{k} + k' \quad (n = 0)$
$= \bar{k} + k'$
$= \{k_0, k_1, k_2\} + \{0, 1\}$
$= \{0, 4, 8\} + \{0, 1\}$
$\Rightarrow \boxed{k = \{0, 1\}, \{4, 5\}, \{8, 9\}}$



This is how the mapping of CDM Group is done.
(ie) this is how DATA will be going inside PRB.

How the DATA is generated ?

As we know, for different symbol (l), different DATA (using different PN sequence) is generated. Say for example, we pick $l = 3$, and at different k (0,1,4,5,8,9) we generate different DATA and then we map in the REs. (ie)

We have, $\alpha = \begin{cases} \rho, & \text{for } X = 1 \\ 2\rho, & \text{for } X > 2 \end{cases}$

For this particular example (Row 10), $\rho = 1$, $X > 2$

$$\Rightarrow \boxed{\alpha = 2}$$

We have,

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

$$m' = \lfloor 2n \rfloor + \{0,1\} + \left\lfloor \frac{\{0,4,8\}}{12} \right\rfloor$$

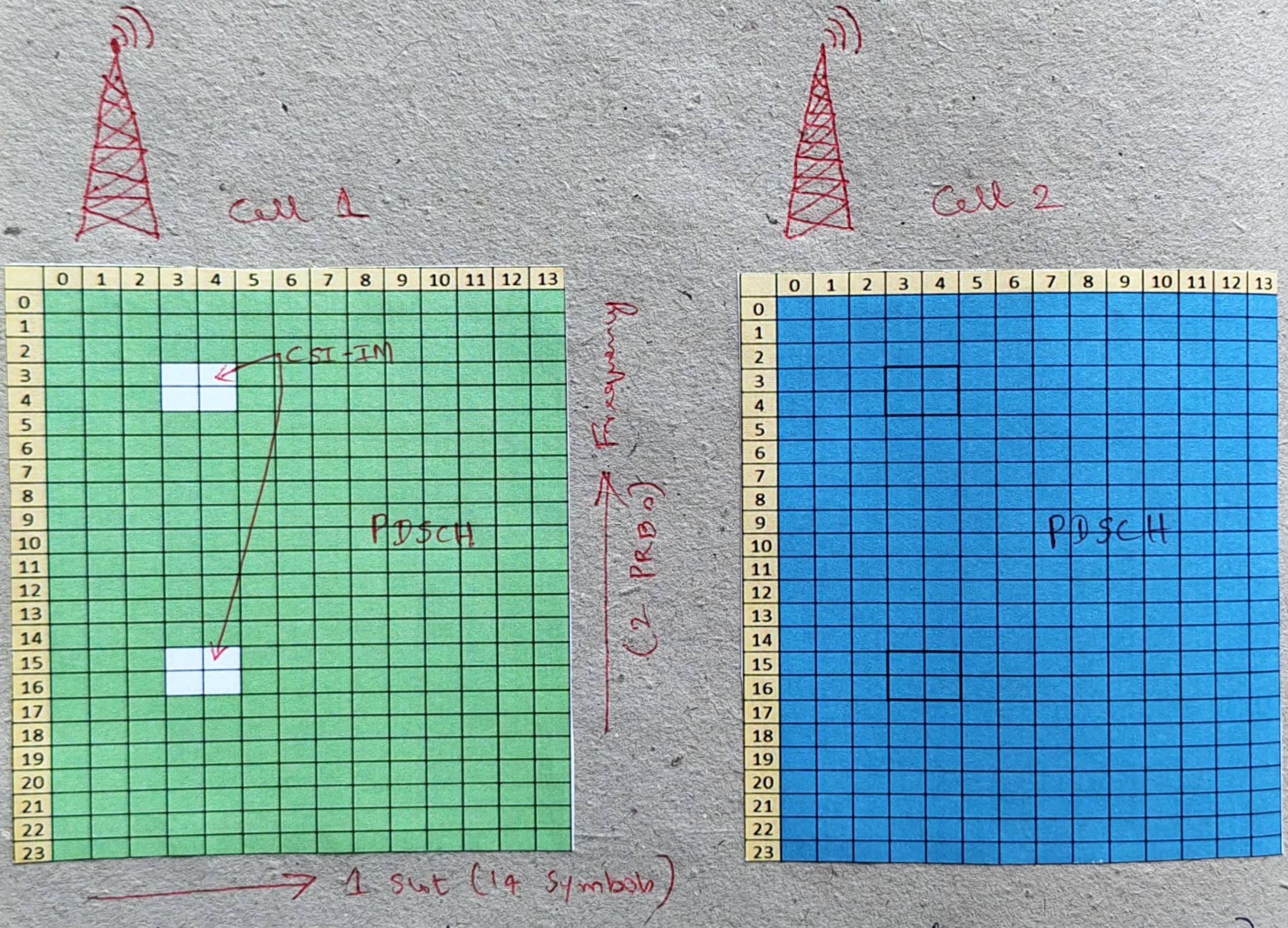
This is how we get m'. In summary,

- First we pick a symbol number (l) based on $\bar{l}$ and l'
- Then we find k, by varying $\bar{k}$ and k', and incrementing n (navigating through PRBs).
- Generate m' values based on different k' and $\bar{k}$ values.
- For different m', different $r_{l,n_{s,f}}(m')$ sequences are generated.
- Pick appropriate OCC codes (ie) $w_f(k')$ and $w_t(l')$, multiply it with $r_{l,n_{s,f}}(m')$ and the Power (β_{CSIRS}), and compute the final DATA to be mapped to the REs. for all the 12 Antenna Ports.

———— x ————

CSI-IM : CSI for Interference Measurement

This concept is very simple and easy to understand. Basically, the concept is, we configure CSI-RS on one cell, to measure the interference coming from other cell.



Let us consider cell 1 and cell 2 (neighboring cell). In cell 1, CSI-IM is configured. CSI-IM REs are Zero Power (ZP) REs, meaning there is no IQ Data transmitted on those REs. And, on the rest of the REs, PDSCH data is mapped.

Figure shows 2 PRBs, but it can be across the frequency band allocated for CSI-IM.

Now, assume, a neighboring cell (cell 2) transmitting PDSCH, at the same time. So, as we see, the CSI-IM resources of cell 1 will collide with the PDSCH data of cell 2. (of course, they'll collide everywhere, but we are concerned with the CSI-IM resources).

So, in cell 1, we configure CSI-IM to measure the power coming from the neighboring cell (cell 2), (ie) nothing but the interference from cell 2 to cell 1.

(ie) Absolute Interference.

Note: There are two patterns defined for CSI-IM in Specification.

5.2.2.4 Channel State Information – Interference Measurement (CSI-IM)

The UE can be configured with one or more CSI-IM resource set configuration(s) as indicated by the higher layer parameter *CSI-IM-ResourceSet*. Each CSI-IM resource set consists of $K \geq 1$ CSI-IM resource(s).

The following parameters are configured via higher layer parameter *CSI-IM-Resource* for each CSI-IM resource configuration:

- *csi-IM-ResourceId* determines CSI-IM resource configuration identity
- *subcarrierLocation-p0* or *subcarrierLocation-p1* defines subcarrier occupancy of the CSI-IM resource within a slot for *csi-IM-ResourceElementPattern* set to 'pattern0' or 'pattern1', respectively.
- *symbolLocation-p0* or *symbolLocation-p1* defines OFDM symbol location of the CSI-IM resource within a slot for *csi-IM-ResourceElementPattern* set to 'pattern0' or 'pattern1', respectively.
- *periodicityAndOffset* defines the CSI-IM periodicity and slot offset for periodic/semi-persistent CSI-IM.
- *freqBand* includes parameters to enable configuration of frequency-occupancy of CSI-IM

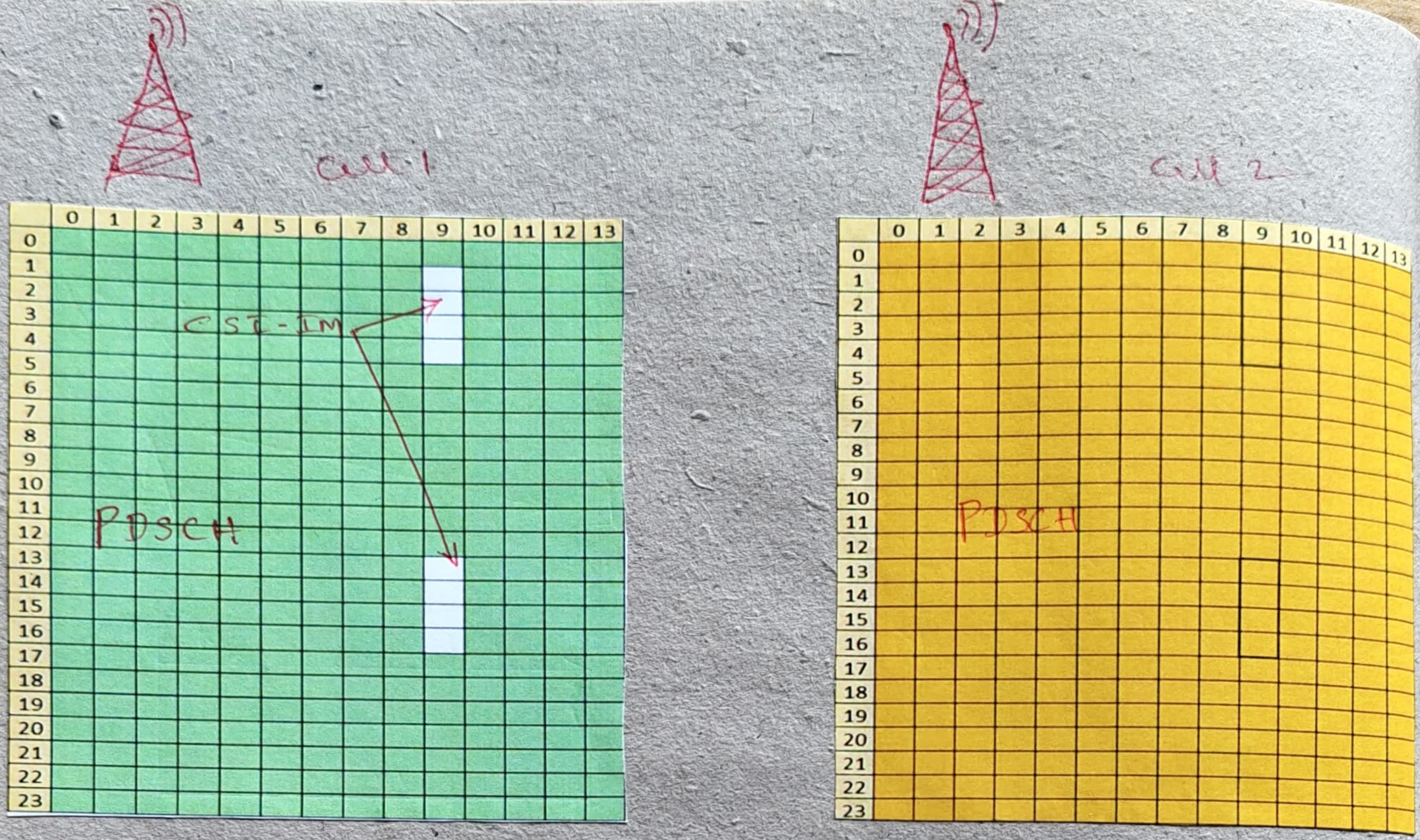
In each of the PRBs configured by *freqBand*, the UE shall assume each CSI-IM resource is located in,

- resource elements (k_{CSI-IM}, l_{CSI-IM}), $(k_{CSI-IM}, l_{CSI-IM}+1)$, $(k_{CSI-IM}+1, l_{CSI-IM})$ and $(k_{CSI-IM}+1, l_{CSI-IM}+1)$, if *csi-IM-ResourceElementPattern* is set to 'pattern0',
- resource elements (k_{CSI-IM}, l_{CSI-IM}), $(k_{CSI-IM}+1, l_{CSI-IM})$, $(k_{CSI-IM}+2, l_{CSI-IM})$ and $(k_{CSI-IM}+3, l_{CSI-IM})$ if *csi-IM-ResourceElementPattern* is set to 'pattern1',

where k_{CSI-IM} and l_{CSI-IM} are the configured frequency-domain location and time-domain location, respectively, given by the higher layer parameters in the above list.

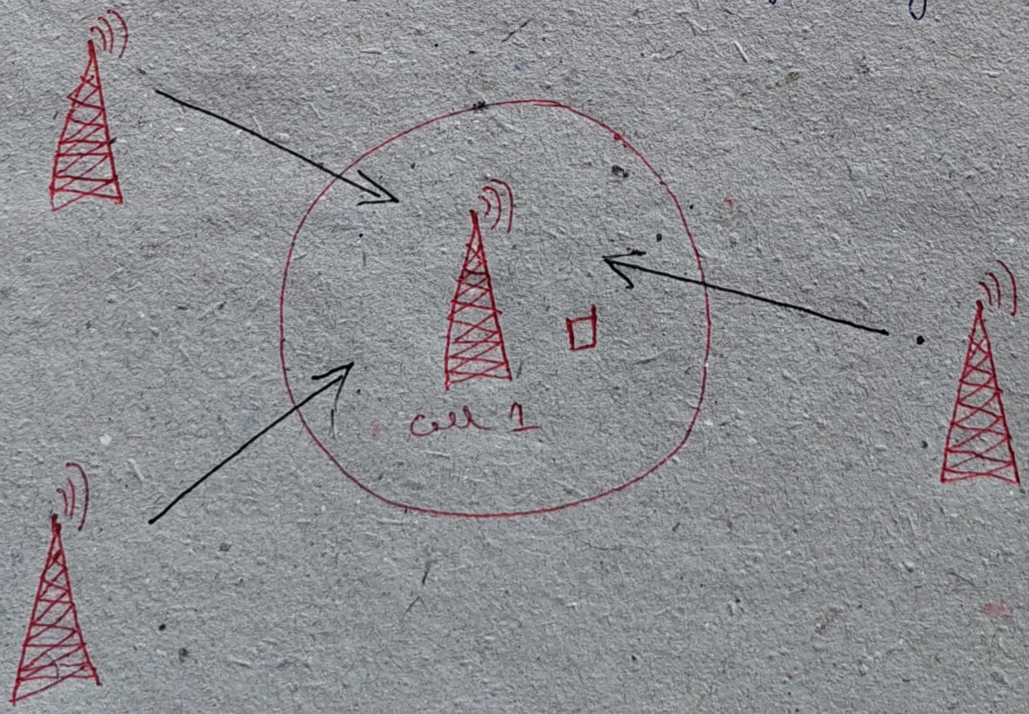
Pattern 0: Here, there are 2 REs in time and 2 REs in Frequency (we just saw above)

Pattern 1: Here, there exists 4 REs in Frequency. (as shown below).



Here, the cell 1 measures the interference coming from cell 2 (neighboring cell) on those CSI-IM REs, where nothing is transmitted.

As shown above, the interference measurement need not to be from one neighboring cell. (ie)



The cell 1 here (where CSI-IM is configured) will measure the interference coming from all the neighboring cells, on those RE, which is configured as CSI-IM in cell 1.

UE after measuring the Interference, it will report the interference back to gNB. Note, the UE here is connected to cell 1, but it receives data from all other neighboring cells as well.

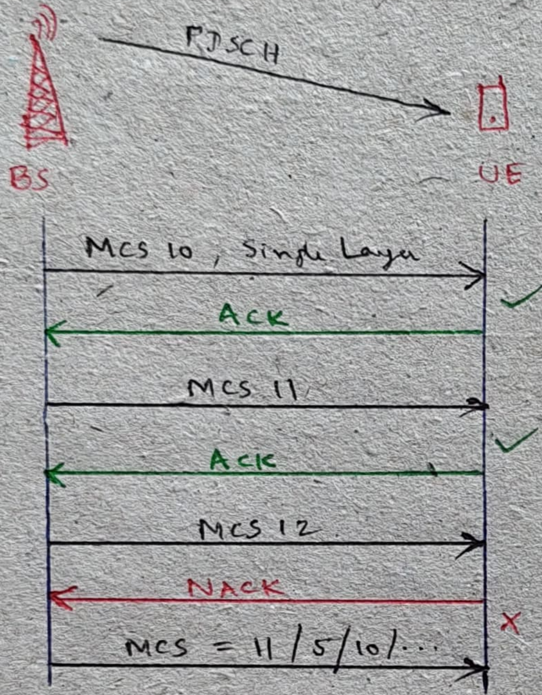
———————— x ————————

CSI-RS : CQI and RI

CQI → Channel Quality Indicator

RI → Rank Indicator

Why do we need CQI and RI in 5G ?

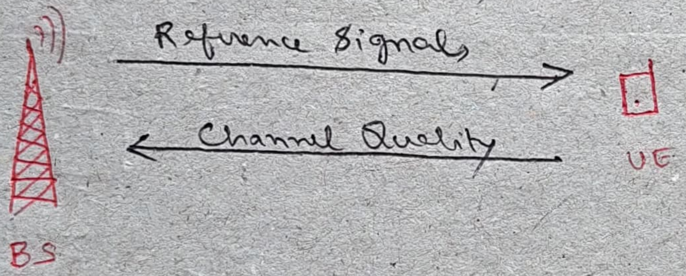


Consider a BS sending data in downlink PDSCH with the given MCS and MIMO Layers. How does the BS decides what is the right MCS to use or the right number of layers to be used at a particular time ?

One simple method is that, BS can take the decision based on the packet failure. Lets say, BS starts transmission with MCS_10 and Singe Layer to the UE. Assume, UE has received successfully and sends ACK to the BS. Then, the BS increases the MCS (MCS_11) and sends the new packet. Lets say, again the UE has successfully received the packet and sends ACK to the BS. Now, the BS further increases the MCS (MCS_12) and sends the new packet to the UE. Now, lets say, this time UE has failed to decode the packet and sends NACK to the BS. So, the BS now have to decrease the MCS and retransmit the same packet once again.

Now, the decision to increment or decrement the MCS may depend on a particular algorithm (implemented by the vendor). Also, the decision to change the number of Layers is also implementation specific. This is one way.

The other way to take the decision of changing the MCS and MIMO layers is based on the channel Quality.



In this case, gNB sends some reference signals. And UE will find out the Quality of the channel using this reference signal, and it will inform the BS that, "This is the current channel quality and now you take the decision of what is the right MCS that can be used".

So, for this channel quality based MCS selection, CQI and RI are being used.

Actually, the BS sends CSI-RS to the UE, and the UE first calculates the SINR.

$$SINR = \frac{\text{Signal Power}}{\text{Interference + Noise}}$$

The signal power is calculated based on the Non-Zero Power CSI-RS (NZP-CSI-RS) that are sent to the UE for Measurements. And the Interference + noise can be calculated from CSI-IM. This is how UE calculates the SINR. This SINR is aligned to a particular number called CQI index.

The BS maps this CQI index to an MCS value.

Note:

The SINR can be calculated for Full Bandwidth part, which is known as Wideband CQI.

Or, The SINR can be calculated for the sub-bands, and report for each sub-band. This is known as Sub-band CQI.

This information (Wideband CQI / Sub-band CQI) is sent to the gNB, based on which the gNB decides which MCS to be used for transmission.

Following 3 tables are defined in the 3GPP Specification. These tables are designed in a way that, the Target BLER = 10 % (for Table 1 and Table 2). And for Table 3 (Lowest Spectral Efficiency Table), the Target BLER = 0.001 %.

Table 5.2.2.1-2: 4-bit CQI Table 1

CQI index	modulation	code rate x 1024	efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

Say for example, when UE signals gNB that CQI index = 12, the gNB uses the appropriate MCS as given in the Table. And, with this MCS, the Probability of Error (error rate) is 10 %.

Table 5.2.2.1-3: 4-bit CQI Table 2

CQI index	modulation	code rate x 1024	efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	193	0.3770
3	QPSK	449	0.8770
4	16QAM	378	1.4766
5	16QAM	490	1.9141
6	16QAM	616	2.4063
7	64QAM	466	2.7305
8	64QAM	567	3.3223
9	64QAM	666	3.9023
10	64QAM	772	4.5234
11	64QAM	873	5.1152
12	256QAM	711	5.5547
13	256QAM	797	6.2266
14	256QAM	885	6.9141
15	256QAM	948	7.4063

Table 5.2.2.1-4: 4-bit CQI Table 3

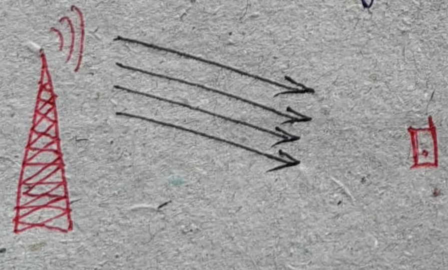
CQI index	modulation	code rate x 1024	efficiency
0	out of range		
1	QPSK	30	0.0586
2	QPSK	50	0.0977
3	QPSK	78	0.1523
4	QPSK	120	0.2344
5	QPSK	193	0.3770
6	QPSK	308	0.6016
7	QPSK	449	0.8770
8	QPSK	602	1.1758
9	16QAM	378	1.4766
10	16QAM	490	1.9141
11	16QAM	616	2.4063
12	64QAM	466	2.7305
13	64QAM	567	3.3223
14	64QAM	666	3.9023
15	64QAM	772	4.5234

These CQI feedbacks from the UE, are tightly associated with the PMI, RI and the resources.

When UE calculates the CQI, it is associated with that particular beam. (ie) At a particular moment, the UE calculates the CQI for that given Precoding Matrix, and Rank (given MIMO Layers) and the given CSI resources. So, if we change the Precoding Matrix, CQI may change and UE may feedback a different CQI even when the channel is constant.

So, for the same channel, UE may feedback a different CQI, if the PMI or Rank changes.

RI stands for "The Number of MIMO Layers that gNB can transmit". (ie) UE conveys to gNB that "these many layers can be configured for PDSCH".



(ii) UE conveys to gNB that, "There are the uncorrelated Propagation paths available. So, these many MIMO Layers can be scheduled"

The gNB takes that input and schedules the number of Layers accordingly.

The gNB might either schedule the same number of layers or it may also schedule less number of layers (if sufficient data is not available).
For example, if the UE signals that, Maximum 4 layers can be scheduled, but the gNB may schedule just 1 or 2 layers if there is no sufficient data for 4 layers.

This is all about CQI and RI (the UE feedbacks given using CSI-RS signal).

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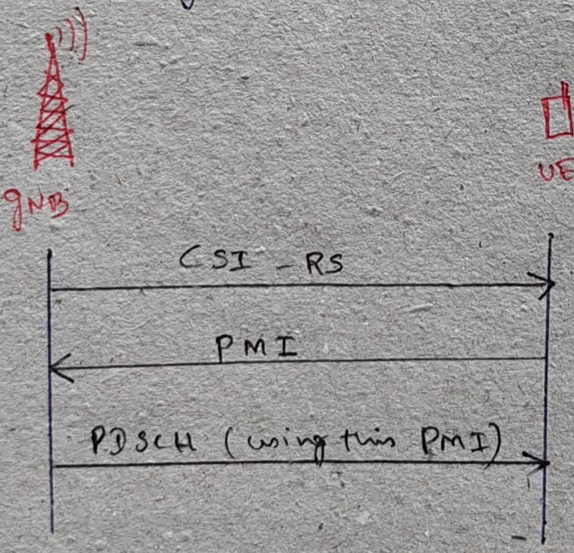
CSI-RS : PMI

Lets understand PMI (Precoding Matrix Indicator) from CSI-RS perspective. As we know, one the we care for CSI-RS is, to help gNB to find out CQI, RI and PMI.

When the gNB transmits CSI-RS to the UE, UE calculates the best Precoding Matrix for that particular transmission instance, and signals back the Precoding Matrix to the gNB, so that for the next transmission for the PDSCH, gNB can apply this precoding Matrix.



The Precoding Matrix looks as shown in below Table.

Codebook index	Number of layers υ	
	1	2
0	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\1\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\1 & -1\end{bmatrix}$
1	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\j\end{bmatrix}$	$\frac{1}{2}\begin{bmatrix}1 & 1\\j & -j\end{bmatrix}$
2	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-1\end{bmatrix}$	-
3	$\frac{1}{\sqrt{2}}\begin{bmatrix}1\\-j\end{bmatrix}$	-

This particular table is for single Panel (Type 1) Codebook, when there are maximum 2 Antenna Ports.

Basically, the UE will signal back the codebook index to the gNB, and the gNB will apply these matrices in the next PDSCH transmission.

Note: It is up to the gNB (may or may not apply the Precoding Matrix in the next PDSCH transmission. Also, the UE does not know whether the gNB has applied the Precoding Matrix or not) (UE does not need to know about it).

UE relies on PDSCH transmission that comes with DMRS associated with it. So, UE will decode the DMRS, using which it will decode the PDSCH. ($\because$ the DMRS is also Precoded).

This is one of the very simple case where UE will signal directly the codebook index. But this is not always the case.

The Precoding Matrices in 5G is very flexible.

codebookMode = 1			
$i_{1,1}$	$i_{1,2}$	i_2	
$0,1,\ldots,N_1O_1-1$	$0,\ldots,N_2O_2-1$	$0,1,2,3$	$W^{(1)}_{i_{1,1},i_{1,2},i_2}$
where $W^{(1)}_{l,m,n} = \frac{1}{\sqrt{P_{\text{CSI-RS}}}}\begin{bmatrix} v_{l,m} \\ \varphi_n v_{l,m} \end{bmatrix}$.			

Like as we see here, this is another Precoding Matrix, $W^{(1)}_{i_{1,1},i_{1,2},i_2}$. The Precoding Matrix here depends on $i_{1,1}$, $i_{1,2}$ and i_2 in this particular example

$W^{(1)}_{i_{1,1}, i_{1,2}, i_2}$ is rewritten as $W^{(1)}_{l,m,n}$ takes the form,

$$W^{(1)}_{l,m,n} = \frac{1}{\sqrt{P_{CSI-RS}}} \begin{bmatrix} V_{l,m} \\ \phi_n V_{l,m} \end{bmatrix}$$

To expand this $W^{(1)}_{l,m,n}$, we have to derive $V_{l,m}$ and ϕ_n as described below.

$$\varphi_n = e^{j\pi n/2}$$

$$\theta_p = e^{j\pi p/4}$$

$$u_m = \begin{cases} \begin{bmatrix} 1 & e^{j\frac{2\pi m}{O_2 N_2}} & \cdots & e^{j\frac{2\pi m(N_2-1)}{O_2 N_2}} \end{bmatrix} & N_2 > 1 \\ 1 & N_2 = 1 \end{cases}$$

$$v_{l,m} = \begin{bmatrix} u_m & e^{j\frac{2\pi l}{O_1 N_1}} u_m & \cdots & e^{j\frac{2\pi l(N_1-1)}{O_1 N_1}} u_m \end{bmatrix}^T$$

$$\tilde{v}_{l,m} = \begin{bmatrix} u_m & e^{j\frac{4\pi l}{O_1 N_1}} u_m & \cdots & e^{j\frac{4\pi l(N_1/2-1)}{O_1 N_1}} u_m \end{bmatrix}^T$$

And, $V_{l,m}$ and ϕ_n depends on $i_{1,1}$, $i_{1,2}$ and i_2.

Based on this, the UE will find out what is the best Precoding Matrix that can be used. And, instead of signaling back the $W^{(1)}_{l,m,n}$ matrix, UE will just signal back $i_{1,1}$, $i_{1,2}$ and i_2 to the gNB. Using these parameters, gNB can reconstruct the $W^{(1)}_{l,m,n}$ matrix. (Precoding Matrix)

So, as a PMI feedback, UE will be signaling $i_{1,1}$, $i_{1,2}$ and i_2 to gNB, instead of signaling the Precoding Matrix. This is because, the Precoding Matrix could be very complicated as shown below.

codebookMode = 2, $N_2 = 1$					
$i_{1,1}$	$i_{1,2}$	i_2			
		0	1	2	3
$0,\ldots,\frac{N_1 O_1}{2}-1$	0	$W^{(2)}_{2i_{1,1},2i_{1,1}+k_1,0,0,0}$	$W^{(2)}_{2i_{1,1},2i_{1,1}+k_1,0,0,1}$	$W^{(2)}_{2i_{1,1}+1,2i_{1,1}+1+k_1,0,0,0}$	$W^{(2)}_{2i_{1,1}+1,2i_{1,1}+1+k_1,0,0,1}$
$i_{1,1}$	$i_{1,2}$	i_2			
		4	5	6	7
$0,\ldots,\frac{N_1 O_1}{2}-1$	0	$W^{(2)}_{2i_{1,1}+2,2i_{1,1}+2+k_1,0,0,0}$	$W^{(2)}_{2i_{1,1}+2,2i_{1,1}+2+k_1,0,0,1}$	$W^{(2)}_{2i_{1,1}+3,2i_{1,1}+3+k_1,0,0,0}$	$W^{(2)}_{2i_{1,1}+3,2i_{1,1}+3+k_1,0,0,1}$
where $W^{(2)}_{l,l',m,m',n} = \frac{1}{\sqrt{2P_{CSI-RS}}}\begin{bmatrix} v_{l,m} & v_{l',m'} \\ \varphi_n v_{l,m} & -\varphi_n v_{l',m'} \end{bmatrix}$, and the mapping from $i_{1,3}$ to k_1 is given in Table 5.2.2.2.1-3.					

In this case, transmitting $W^{(2)}_{l,l',m,m',n}$ matrix (Precoding Matrix) is quite complicated. Hence, the parameter $i_{1,1}$, $i_{1,2}$ and i_2 which are used to reconstruct the Precoding Matrix, are signalled to the gNB, and gNB reconstructs the Precoding Matrix and use the same for the PDSCH transmission.

This is all about the Precoding Matrix Indicator (PMI) in the CSI-RS.

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