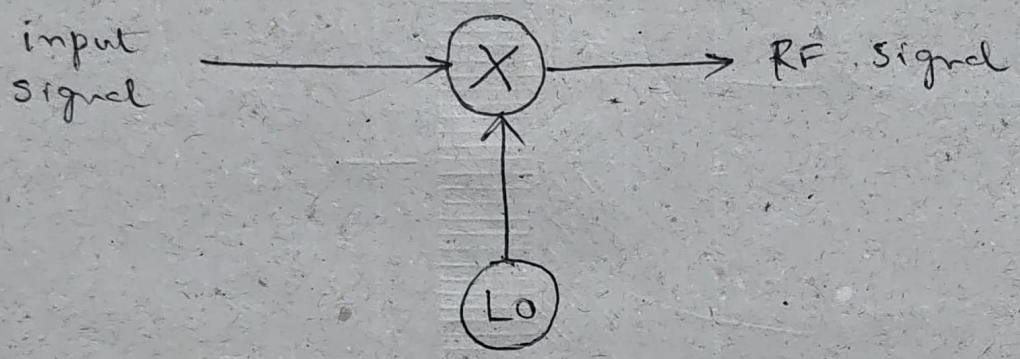
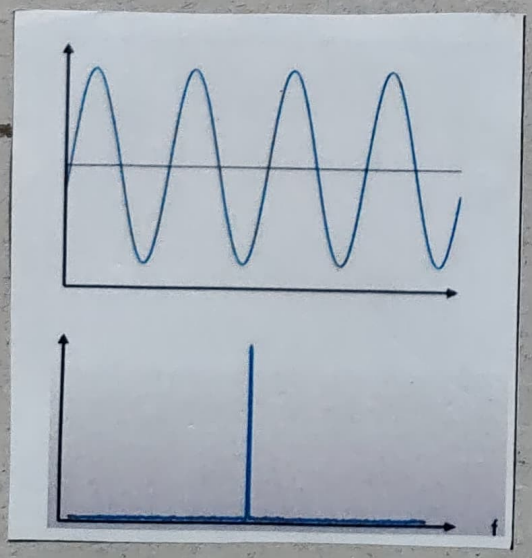
Phase Noise : What and Why ?

Lets understand what is Phase noise, and how it is generated, before we understand PTRS.

As we know, at the transmitter and receiver, we have a MIXER which takes the input signal and LO oscillator signal, and generates RF signal.

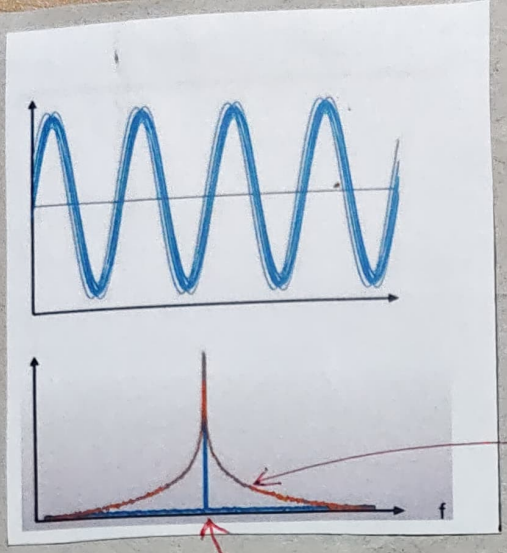


The Local Oscillators are the ones that generate the carrier frequency running either at 2.4 GHz / 3.5 GHz / 35 GHz / 50 GHz / and so on. These Local Oscillators are not Ideal all the time. And, generating very high frequencies is very difficult.



→ When the Local Oscillator is Ideal, then it will generate perfect sine wave like this.

→ The Fourier Transform or the Spectrum will look like this, " a single peak at the frequency at which the sine pulse is generated



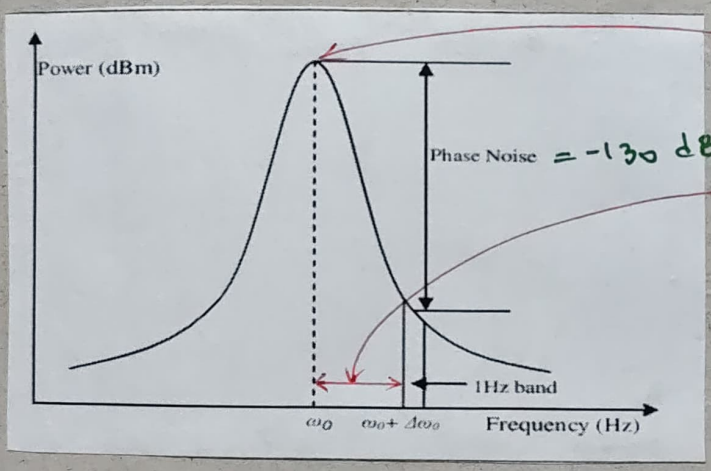
→ When the LO is not ideal, this is how the sine pulse will be generated; having variations in the Amplitude and Phase.

→ The corresponding spectrum will look like this.

Phase Noise

Carrier Center

Lets understand this in detail.



Max. Carrier Power

10 KHz offset

- Phase Noise is measured in dBc / Hz.

dBc → Decibels relative to the carrier.

So, basically this parameter tells, how much the power of noise exceeds the power of carrier signal, at certain frequency offset.

- Assume,

Carrier Center = 2.4 GHz

Max. carrier Power = 10 dBm = 10^{-2} Watts

At 10 KHz offset from the carrier center, we take a 1 Hz band, where the Noise power is -120 dBm = 10^{-15} Watts.

So, phase Noise is, how much power does the noise exceeds the power of carrier signal, at certain frequency offset.

$$\Rightarrow 10 \log_{10} \left(\frac{\text{Noise Power in Watts}}{\text{Carrier Power in Watts}} \right)$$

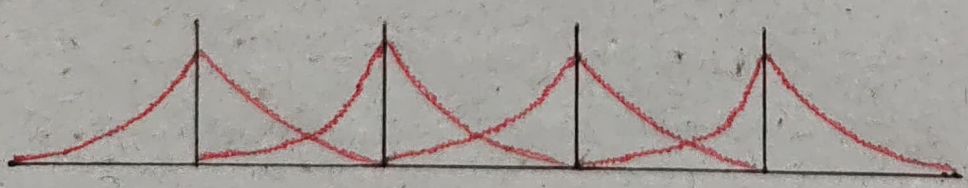
$$\Rightarrow \begin{pmatrix} \text{Phase Noise} \\ \text{over 1 Hz} \\ \text{dBm/Hz} \end{pmatrix} - \begin{pmatrix} \text{Carrier Power} \\ \text{(dBm)} \end{pmatrix}$$

$$\Rightarrow (-120) - (10)$$

$$\Rightarrow \underline{\underline{-130 \text{ dBc/Hz}}}$$

So, what happens because of this phase noise ?

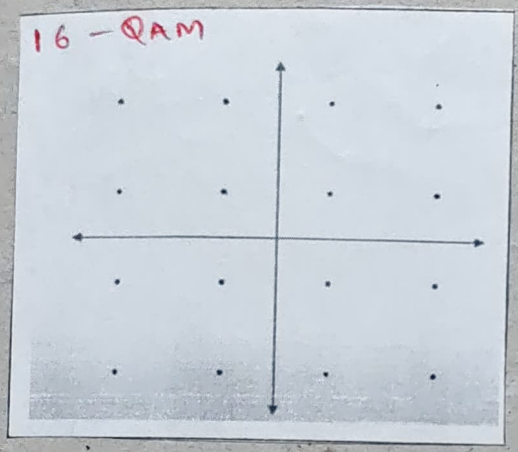
(a)



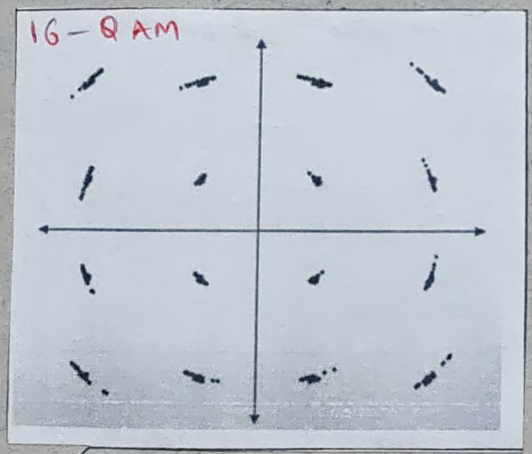
(b)

As we know, in OFDM, if it is a perfect oscillator, then perfect sine pulses are generated, and the spectrum (Frequency Domain) will look like as shown in (a).

If it is not Ideal oscillator, then imperfect sine pulses are generated with phase noise as shown in (b). And because of this, there will be Inter-Carrier Interference (ICI)



→ This is how 16-QAM look like (with Ideal Oscillator)



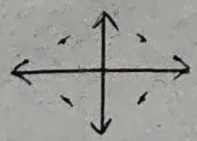
→ When there is phase noise, this is how the 16-QAM constellation looks like.

→ Because of the phase noise, there is rotation, which will cause BLER at the receiver end.

→ Note that, Higher the Modulation order, more the phase noise will impact the system.

→ So, in 64-QAM, the impact is worse than 16-QAM.

QPSK



So, in PDSCH or PUSCH, when we do the data transfer,

- At high MCS, the impact of phase noise is very high (ie) basically when UE is in good radio condition
- At Low MCS, the impact of phase noise is very low (ie) basically when UE is in poor radio condition

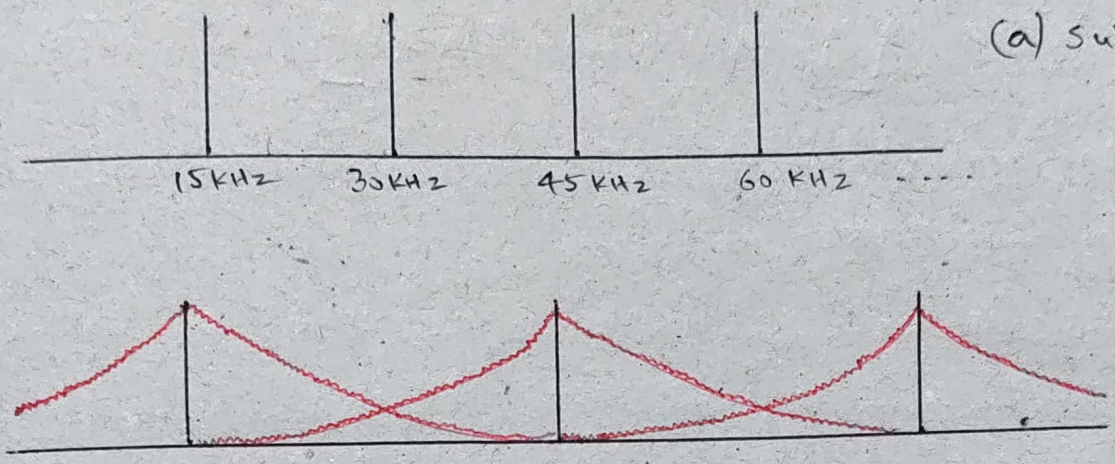
---

Another aspect is, "Phase Noise is high in mmWave". So, basically, when the Oscillator has to generate a very high frequency, then the phase noise is higher compared to when it has to generate the lower frequency.

So, in <u>sub-6</u>, when it has to generate say 2GHz, 3GHz or 700 MHz, for these kind of carriers, the phase noise is <u>negligible</u> (almost phase noise is not there). In <u>mmWave</u>, it has to generate 30, 40, 60 GHz kind of carriers, the phase noise is <u>high</u>.

In sub-6, we have 15 KHz or 30 KHz SCS as shown in (a). Eventhough, in mmWave, we have higher SCS, but that is not enough, to mitigate the impact of phase noise.

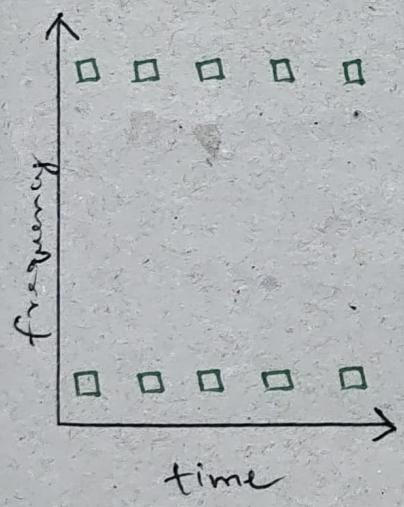
So, there has to be a signal (Reference Signal) to mitigate the impact of phase noise, using which we estimate the phase noise and remove the same from the received data.



(a) Sub-6 SCS

(b) mmWave SCS

We also see that, the phase noise has smaller variations in frequency, and the variation in time is high.



So, the Reference Signal that we design (PTRS) should have higher density in time, and lower density in frequency.

In frequency, we have lower number of REs allocated to PTRS, whereas in time we need to have higher density, since the variation of phase noise in time is high.

So, this is about the purpose to have PTRS and how the imperfect oscillator can impact the overall system.

———— x ————

PTRS : Signal Generation and Mapping

[PDSCH and PUSCH]

Lets understand the Signal Generation and Resource mapping for PTRS.

Since, PTRS for Downlink and PTRS for Uplink, when Transform Precoding is disabled, is same, we'll look into both in this section. And, we'll look into the Transform Precoding part in next section.

So, when it comes to signal generation for PTRS, we don't actually generate a separate reference signal for PTRS. we actually utilize the signal generated for DMRS signals for PDSCH or for PUSCH.

So, if we look at the PTRS signal generation and Mapping,

$$r_k = r(2m + k')$$

$$a_{k,l}^{(p,\mu)} = \beta_{\text{PT-RS},l} r_k$$

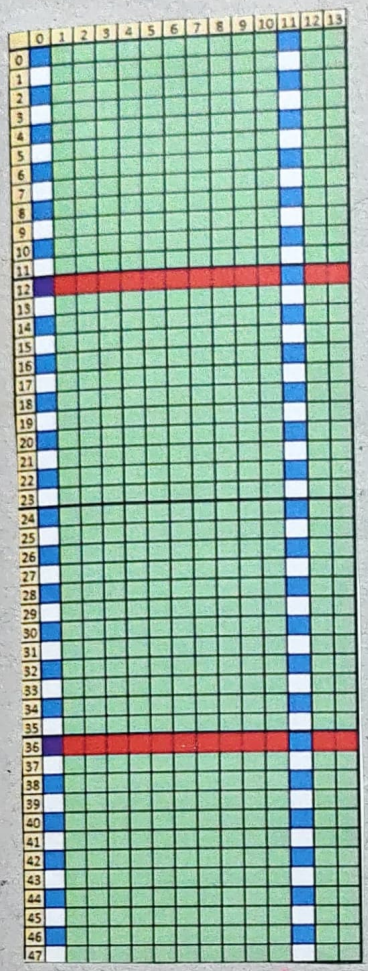
- Same as PDSCH DMRS
- This is Downlink PTRS
- Uses 1 port

$$r^{(\bar{p}_j)}(m) = \begin{cases} r(m) & \text{if } j = j' \text{ or } j = j'' \\ 0 & \text{otherwise} \end{cases}$$

$$\begin{bmatrix} a_{k,l}^{(p_0,\mu)} \\ \vdots \\ a_{k,l}^{(p_{\rho-1},\mu)} \end{bmatrix} = \beta_{\text{PT-RS}} W \begin{bmatrix} r^{(\bar{p}_0)}(2n + k') \\ \vdots \\ r^{(\bar{p}_{v-1})}(2n + k') \end{bmatrix}$$

$$k = \begin{cases} 4n + 2k' + \Delta & \text{configuration type 1} \\ 6n + k' + \Delta & \text{configuration type 2} \end{cases}$$

- Same as PUSCH DMRS
- This is Uplink PTRS
- Uses 2 ports



Example 1

→ In short, what we do is, we pick the first DMRS symbol (in this case, first DMRS symbol (Sym. 0), second DMRS symbol (Sym. 11)) and then we pick a particular subcarrier from a particular PRB. (0th subcarrier on 2nd PRB)

→ We use that particular DMRS RE, and we repeat it across time.

→ And, based on the density of PTRS in frequency, we pick second DMRS RE (0th subcarrier on 4th PRB) and we repeat it across time.

→ The repetition in time is also depends on the Time density.

In Downlink, normally a single oscillator is used to generate data (Sine pulse) for a single antenna panel. Since the phase noise is coming from the impurities of the oscillator, we assume that single antenna port at the transmitter is enough to convey the phase noise.

In Uplink, two ports are there, given that we can have more than one oscillator and then we need to find out phase noise for both.

This is one major difference between Downlink PTRS and Uplink PTRS. Apart from that, the mapping part is same.

So, as we see,

$$r^{(\bar{p}_j)}(m) = \begin{cases} r(m) & , \text{if } j = j' \text{ or } j = j'' \\ 0 & , \text{otherwise} \end{cases}$$

this is for two different ports. And 'W' conveys that, the PTRS signal is precoded. So, when we do the resource mapping, the PTRS generated data (ie) nothing but the DMRS, they're precoded and then assigned to the resource blocks.

Now, lets understand the Time and Frequency density of PTRS.

$$k = k_{\text{ref}}^{\text{RE}} + \left(iK_{\text{PT-RS}} + k_{\text{ref}}^{\text{RB}}\right) N_{\text{sc}}^{\text{RB}}$$

$$k_{\text{ref}}^{\text{RB}} = \begin{cases} n_{\text{RNTI}} \bmod K_{\text{PT-RS}} & \text{if } N_{\text{RB}} \bmod K_{\text{PT-RS}} = 0 \\ n_{\text{RNTI}} \bmod \left(N_{\text{RB}} \bmod K_{\text{PT-RS}}\right) & \text{otherwise} \end{cases}$$

This is the definition of Frequency allocation (ie) which DMRS REs to pick for PTRS. Here k is the subcarrier index, which depends on $k_{ref}^{RE} + (i K_{PT-RS} + K_{ref}^{RB}) N_{sc}^{RB}$.

Here, $N_{sc}^{RB} = 12$

K_{PT-RS} comes from the below Table.

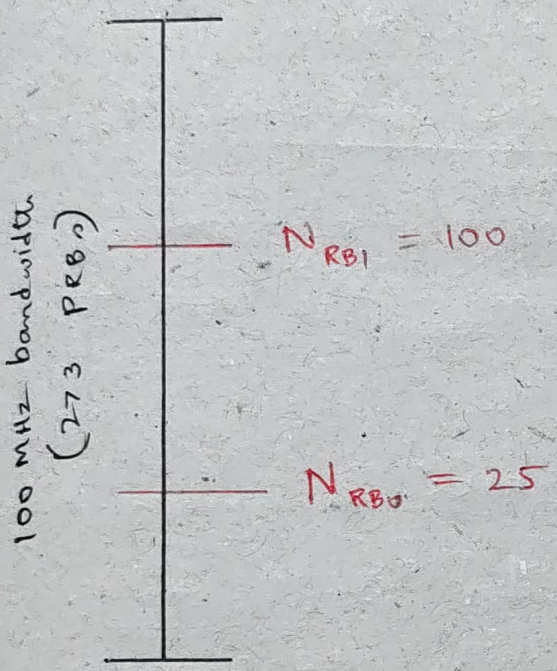
Table 5.1.6.3-2: Frequency density of PT-RS as a function of scheduled bandwidth

Scheduled bandwidth	Frequency density (K_{PT-RS})
$N_{RB} < N_{RB0}$	PT-RS is not present
$N_{RB0} \leq N_{RB} < N_{RB1}$	2
$N_{RB1} \leq N_{RB}$	4

K_{PT-RS} is the one that defines the density of PTRS in frequency. So, it is a Frequency density.

K_{PT-RS} can take values 0 → PT-RS not present
2 → Every Second PRB
4 → Every Fourth PRB

depending on the conditions. For example.



As we know, Phase noise doesn't have variations across the frequency. So, thats why we use less dense PTRS in frequency where higher dense in time. This also saves the resources in frequency and gives better throughput.

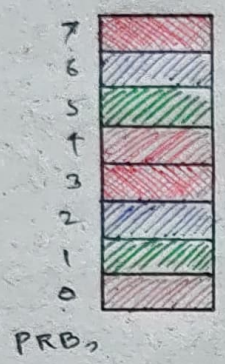
We can say, if the No. of PRBs allocated for PUSCH / PDSCH is less than 25 PRBs, then there is no PTRS.

If the No. of PRBs allocated is between 25 and 100, then the Frequency density $K_{PT-RS} = 2$.

If the No. of PRBs allocated is more than 100, then the Frequency density $K_{PT-RS} = 4$.

So, this way, we are not using many REs.

There is another parameter k_{ref}^{RB}. Lets say, $K_{PT-RS} = 4$.



(i.e) PTRS is going one in every 4 PRBs.

Here, we see there are 4 different choices

(i.e) 0 & 4, 1 & 5, 2 & 6 and 3 & 7.

The decision of which of the above choices depends on the RNTI of the UE. (n_{RNTI}).

So, basically n_{RNTI} is the UE ID that conveys which PRB to pick for PTRS. n_{RNTI} is used to avoid PTRS to PTRS collision. (i.e)

Basically, when one UE's PTRS collides with other UE's PTRS, then the performance of PTRS goes down.

And, when one UE's PTRS collide with other UE's PDSCH or PUSCH, then the performance of PTRS is better.

So, to avoid the PTRS to PTRS collision, the n_{RNTI} is used, to assign different PRB to different UE.

Now, another parameter left is k_{ref}^{RE}. (inside the PRB, which subcarrier to pick). So, k_{ref}^{RE} takes values from 0 to 11. This values comes from the below Tables

Table 7.4.1.2.2-1: The parameter k_{ref}^{RE}. (For PDSCH)

DM-RS antenna port p	k_{ref}^{RE}							
	DM-RS Configuration type 1 *resourceElementOffset*				DM-RS Configuration type 2 *resourceElementOffset*			
	offset00	offset01	offset10	offset11	offset00	offset01	offset10	offset11
1000	0	2	6	8	0	1	6	7
1001	2	4	8	10	1	6	7	0
1002	1	3	7	9	2	3	8	9
1003	3	5	9	11	3	8	9	2
1004	-	-	-	-	4	5	10	11
1005	-	-	-	-	5	10	11	4

Table 6.4.1.2.2.1-1: The parameter k_{ref}^{RE}. (For PUSCH)

DM-RS antenna port $\tilde{p}$	k_{ref}^{RE} DM-RS Configuration type 1 *resourceElementOffset*				DM-RS Configuration type 2 *resourceElementOffset*			
	offset00	offset01	offset10	offset11	offset00	offset01	offset10	offset11
0	0	2	6	8	0	1	6	7
1	2	4	8	10	1	6	7	0
2	1	3	7	9	2	3	8	9
3	3	5	9	11	3	8	9	2
4	-	-	-	-	4	5	10	11
5	-	-	-	-	5	10	11	4

Both the tables looks same, except the Port indices. So, these tables tells us that, based on the DMRS configuration type, and Antenna ports, there are different values defined, to pick the DMRS RE for PTRS. As we know, for DMRS configuration type 1, DMRS goes in alternative REs. And, for DMRS configuration type 2, DMRS goes in pairs, like 0,1 ; 6,7.

This is all about Frequency density of PTRS

Now, Time density is defined by the Table below.

Table 5.1.6.3-1: Time density of PT-RS as a function of scheduled MCS

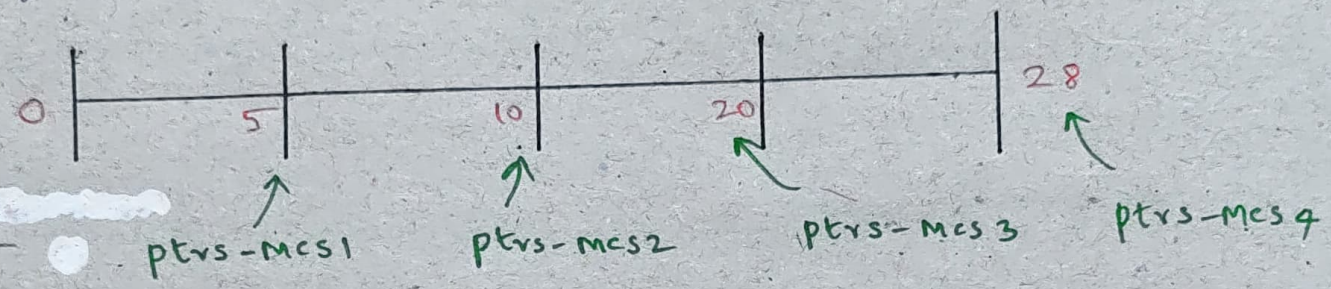
Scheduled MCS	Time density (L_{PT-RS})
I_{MCS} < ptrs-MCS$_1$	PT-RS is not present
ptrs-MCS1 ≤ I_{MCS} < ptrs-MCS2	4
ptrs-MCS2 ≤ I_{MCS} < ptrs-MCS3	2
ptrs-MCS3 ≤ I_{MCS} < ptrs-MCS4	1

PTRS can take either every RE (Time density, $L_{PT-RS} = 1$), or alternate REs ($L_{PT-RS} = 2$), or ($L_{PT-RS} = 4$), or not present at all.

The time density of PTRS depends on MCS. As we know, PTRS has higher impact on Higher modulation schemes. (i.e) 256-QAM or 64-QAM are highly affected by Phase noise, whereas the QPSK

is less likely affected by the phase noise.

So, when we go for higher MCS (higher modulation order), then we use high density of PTRS REs in time. And, when we have lower MCS, then we use low density of PTRS-REs in time. This is how the table is defined.



Lets say, we have MCS ranges between 0 to 28.

- When the MCS of PDSCH/PUSCH is less than ptrs-MCS1 (say 5) (QPSK modulation only) → No PTRS

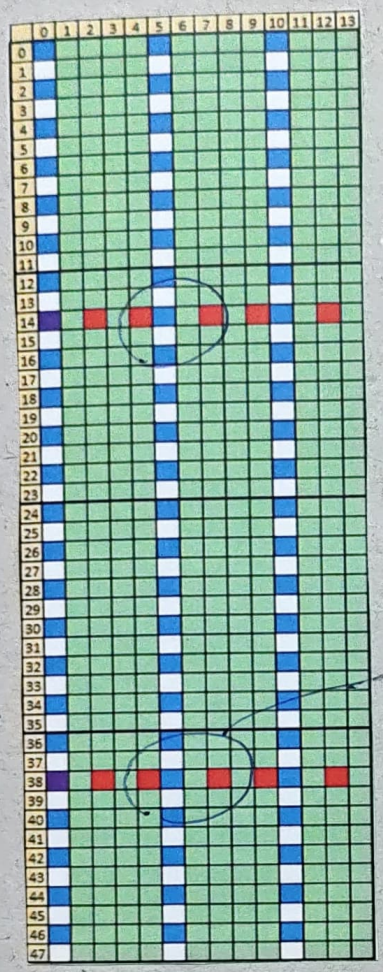
- When MCS is between ptrs-MCS1 and ptrs-MCS2 (say 5 to 10) → PTRS density = 4

- When MCS is between ptrs-MCS2 and ptrs-MCS3 (say 10 to 20) → PTRS density = 2

- When MCS is above ptrs-MCS3 (say above 20) → PTRS density = 1

This is how the Mapping of PTRS looks like.

We have already seen example 1.



Example 2

→ In this example, we pick the first DMRS symbol (Sym 0), Second P.RB

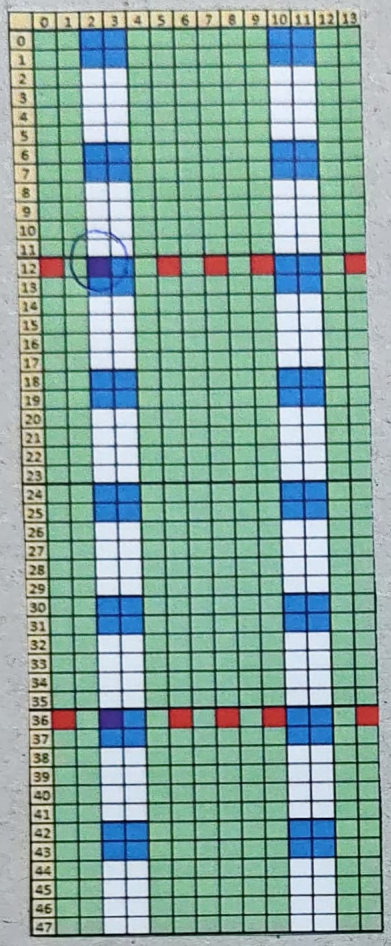
→ Here, the frequency density, $K_{PT-RS} = 2$ and Time density is also 2, $L_{PT-RS} = 2$ as it is going on every alternative RE.

→ RE offset is also 2. (i.e) from PRB 12 to PRB 14, we pick one.

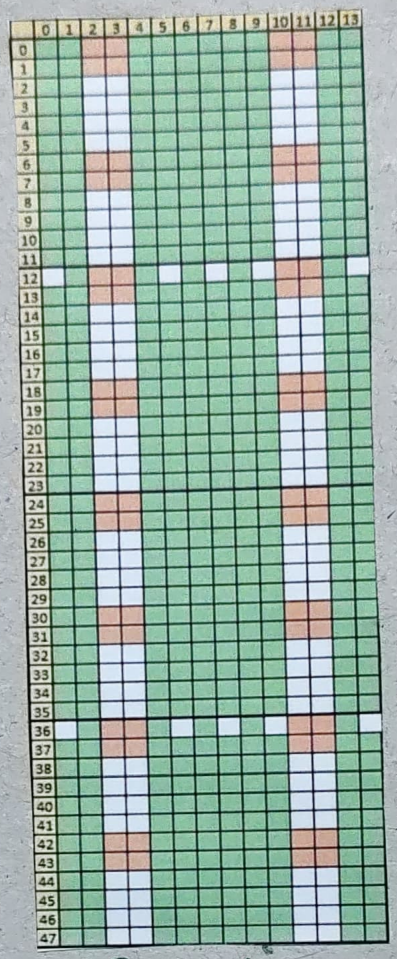
→ Note that, in time domain, whenever DMRS comes, it is skipped and the next RE of DMRS Symbol is also skipped, until unless the time density is 1 (example 1).

Note: If we don't have PTRS, we can also do the Phase noise estimation using DMRS symbols. Since the DMRS is very costly (it takes full symbol), it degrades the throughput. So, instead of DMRS, we use a light allocation (i.e) PTRS.

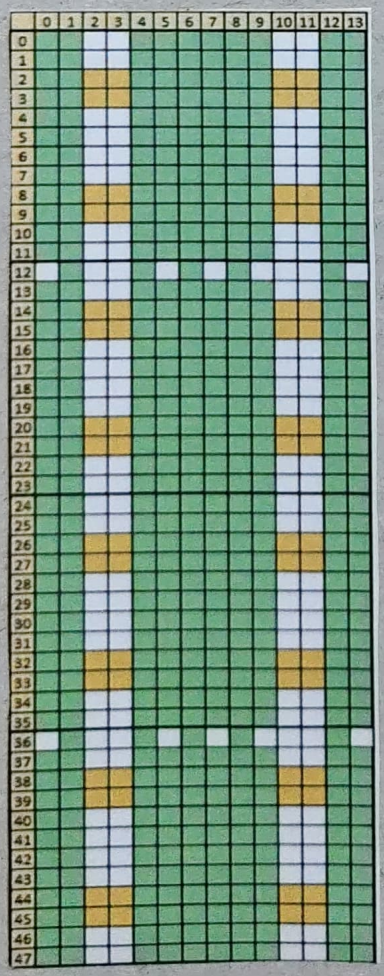
Example 3



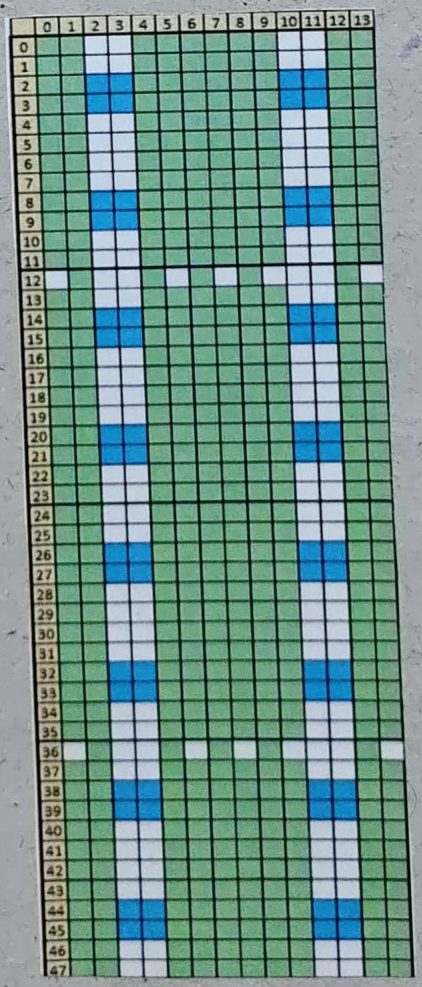
Port 0



Port 1



Port 2



Port 3

In Example 3, as we see this is a different DMRS configuration (Type-2). In this, we pick the first DMRS RE (symbol 2), second PRB, RE offset 0. And then, with Time density $L_{PT-RS} = 2$, we map the PTRS as shown ■, leaving the RE that is just after the DMRS, and repeat it across the full subcarrier.

In downlink, it takes 1 port, and in uplink, it takes 2 ports. So, the REs of other layer for that UE are marked zeros □.

So, if a UE is allocated 4 layers, PTRS is going on Port 0, then the other 3 ports will have zeros □ wherever the PTRS is going.

So, PTRS takes the first antenna port allocated to the UE. When there are two different Transport Blocks, meaning more than 4 layers, then PTRS takes the port with higher MCS order.

Note: In UE side, we have coherent, non-coherent, and fully-coherent antennas. When we have fully coherent antennas, in that case, we use only single port PTRS. When we have non-coherent or partially coherent antennas, in that case, we use more than one PTRS ports can be used in uplink.

PTRS : Signal Generation and Mapping

[PUSCH Transform Precoding]

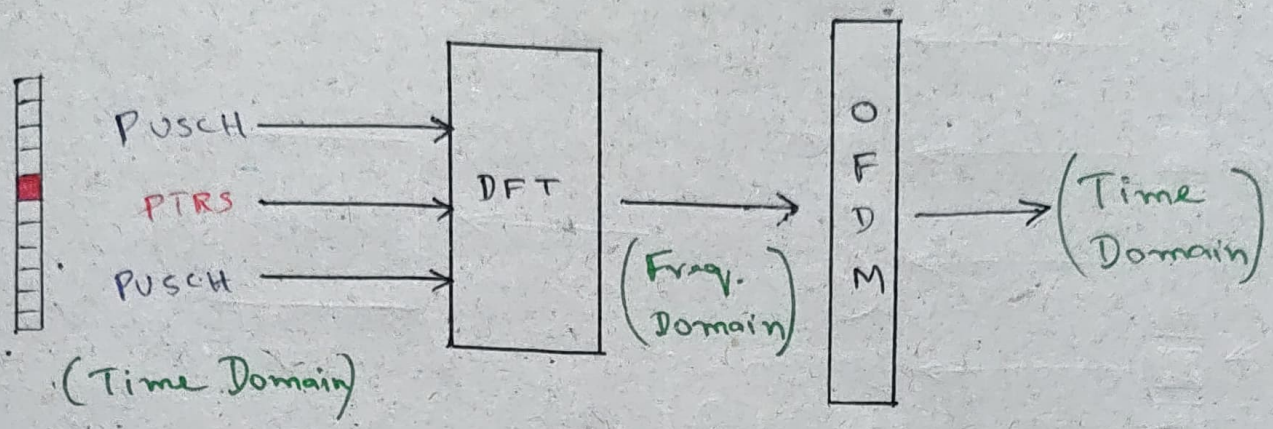
In the last section, we've seen PTRS for PDSCH and PUSCH, when there is no Transform precoding in OFDM. In this section, we'll see PTRS for PUSCH, when the Transform precoding is enabled in PUSCH.

As we've seen in the last section (in the normal OFDM case), there is no signal generation for PTRS. We only pick the first DMRS symbol (i) we pick the REs as per which PRB or which subcarrier to pick, and then we repeat that particular data across the symbols, based on the Time density. Thats not the case in PUSCH when the Transform Precoding is enabled. In this case, we generate the sequence and map it differently. Lets understand this part in this section.

Before we go to the signal generation part, lets understand how the PTRS and PUSCH are transmitted together.

- PUSCH data and PTRS data are multiplexed before they go to the Transform Precoding module. (a) PUSCH and PTRS data (Time Domain) go to the DFT module which gives (Frequency Domain) output to OFDM module. Now, the OFDM module gives output

Once again in Time Domain.



So, this multiplexing happens in Time Domain.

Here, we form PTRS in groups.

Table 6.2.3.2-1: PT-RS group pattern as a function of scheduled bandwidth

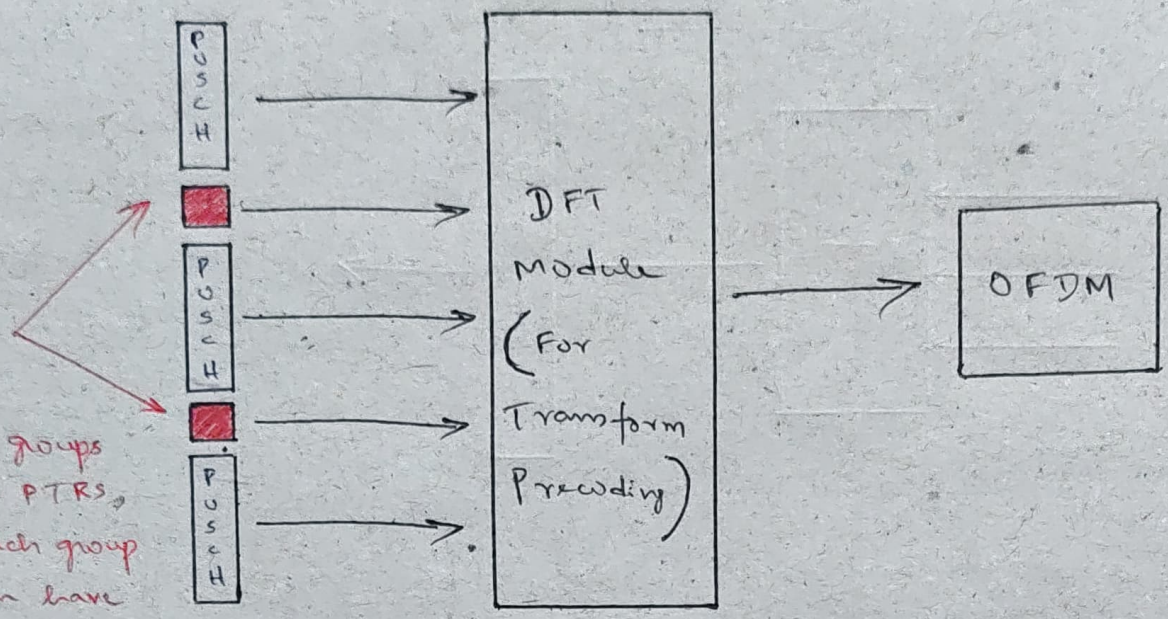
Scheduled bandwidth	Number of PT-RS groups	Number of samples per PT-RS group
$N_{RB0} \le N_{RB} < N_{RB1}$	2	2
$N_{RB1} \le N_{RB} < N_{RB2}$	2	4
$N_{RB2} \le N_{RB} < N_{RB3}$	4	2
$N_{RB3} \le N_{RB} < N_{RB4}$	4	4
$N_{RB4} \le N_{RB}$	8	4

There are two different group size, as shown in above table. ① No. of PTRS groups and ② Group size.

① ⇒ basically a set of PTRS samples

② ⇒ Either 2 samples or 4 samples.

There are multiple groups ① defined based on the PRBs allocated for PUSCH. There are 5 different levels defined in the Table. Higher the PRBs allocated for PUSCH, higher is the No. of PTRS groups.



2 groups of PTRS, each group can have either 2 or 4 samples.

Now, this 'Group size', 'where exactly PTRS is multiplexed with PUSCH', and 'how the sequence is generated' is explained as below.

OCC

$$r_m(m') = w(k')\underbrace{\frac{e^{j\frac{\pi}{2}(m \bmod 2)}}{\sqrt{2}}\left[(1-2c(m'))+j(1-2c(m'))\right]}_{\frac{\pi}{2}\text{ BPSK}}$$

$$m' = N_{\text{samp}}^{\text{group}} s' + k'$$

$$s' = 0, 1, \ldots, N_{\text{group}}^{\text{PT-RS}} - 1$$

$$k' = 0, 1, N_{\text{samp}}^{\text{group}} - 1$$

This is the sequence generation part, where in we see the PN sequences $c(m')$. This PN sequence is generated with the c_{init} below.

$$c_{\text{init}} = (2^{17}(N_{\text{symb}}^{\text{slot}} n_{s,f}^{\mu} + l + 1)(2N_{\text{ID}} + 1) + 2N_{\text{ID}}) \bmod 2^{31}$$

This c_{init} depends on the N_{ID}, No. of symbols in a slot $(N_{symb}^{slot} = 14)$, slot number $(n_{s,f}^{\mu})$ and the symbol number (l). So, for each symbol number in a slot, we generate a different PN sequence.

This PN sequence is then modulated as per this formulla,

$$\frac{e^{j\frac{\pi}{2}(m \bmod 2)}}{\sqrt{2}}\left[\left(1-2c(m')\right)+j\left(1-2c(m')\right)\right]$$, which is nothing but $\frac{\pi}{2}$ BPSK.

So, basically, we generate PN sequence, and then we do $\frac{\pi}{2}$ BPSK modulation of that PN sequence, and then we multiply this modulated samples with an orthogonal cover code (OCC).

Table 6.4.1.2.1.2-1: The orthogonal sequence $w(i)$.

$n_{RNTI} \bmod N_{samp}^{group}$	$N_{samp}^{group} = 2$ $[w(0) \quad w(1)]$	$N_{samp}^{group} = 4$ $[w(0) \quad w(1) \quad w(2) \quad w(3)]$
0	$[+1 \quad +1]$	$[+1 \quad +1 \quad +1 \quad +1]$
1	$[+1 \quad -1]$	$[+1 \quad -1 \quad +1 \quad -1]$
2	-	$[+1 \quad +1 \quad -1 \quad -1]$
3	-	$[+1 \quad -1 \quad -1 \quad +1]$

This orthogonal sequence, defined in this table, depends on the UE ID (i). n_{RNTI}.

If the No. of samples in a group is 2, then there are two orthogonal sequences.

If the Group size is 4, then there are four orthogonal sequences.

So, based on the UE ID (i) n_{RNTI}, different orthogonal sequences can be picked for different UEs, which provides orthogonality across the UEs.

So, in a single symbol, for all the UEs, the slot number / Symbol number / N_{ID} may remain same. In that case, n_{RNTI} can provide orthogonality across the Users.

$$m' = N_{samp}^{group} \cdot s' + k'$$

where, $s' = 0, 1, \ldots, N_{group}^{PT\text{-}RS} - 1$

$k' = 0, 1, \ldots, N_{samp}^{group} - 1$

This is nothing but the indexing based on the group size and No. of samples in the group. For example, we consider 4 groups and each group size is 2.

1st group → Pick the sequence generated at index 0, 1

2nd group → 2, 3

3rd group → 4, 5

4th group → 6, 7

(ii) 2 samples for each group.

So, this is how the PN sequence generated, then $\frac{\pi}{2}$ BPSK modulated, then with the added orthogonality, we finally have the $r_m(m')$ for a particular symbol for all the groups and all the samples.

Now, how the symbol mapping is defined? (ii) basically we have generated the sequence. Now where exactly we map these samples? How to we multiplex them with the PUSCH?

These are defined in the below table.

Table 6.4.1.2.2.2-1: PT-RS symbol mapping.

Number of PT-RS groups $N_{group}^{PT\text{-}RS}$	Number of samples per PT-RS group N_{samp}^{group}	Index m of PT-RS samples in OFDM symbol l prior to transform precoding
2	2	$s\lfloor M_{sc}^{PUSCH}/4 \rfloor + k - 1$ where $s = 1,3$ and $k = 0,1$
2	4	$sM_{sc}^{PUSCH} + k$ where $\begin{cases} s = 0 & \text{and} \quad k = 0,1,2,3 \\ s = 1 & \text{and} \quad k = -4,-3,-2,-1 \end{cases}$
4	2	$\lfloor s\, M_{sc}^{PUSCH}/8 \rfloor + k - 1$ where $s = 1,3,5,7$ and $k = 0,1$
4	4	$sM_{sc}^{PUSCH}/4 + n + k$ where $\begin{cases} s = 0 & \text{and} \quad k = 0,1,2,3 & n = 0 \\ s = 1,2 & \text{and} \quad k = -2,-1,0,1 & n = \lfloor M_{sc}^{PUSCH}/8 \rfloor \\ s = 4 & \text{and} \quad k = -4,-3,-2,-1 & n = 0 \end{cases}$
8	4	$\lfloor s\, M_{sc}^{PUSCH}/8 \rfloor + n + k$ where $\begin{cases} s = 0 & \text{and} \quad k = 0,1,2,3 & n = 0 \\ s = 1,2,3,4,5,6 & \text{and} \quad k = -2,-1,0,1 & n = \lfloor M_{sc}^{PUSCH}/16 \rfloor \\ s = 8 & \text{and} \quad k = -4,-3,-2,-1 & n = 0 \end{cases}$

Based on the No. of PT-RS groups and No. of samples per PT-RS group, there are different formulas defined.

Lets take a case!, where

$$\boxed{\begin{aligned} N_{group}^{PT\text{-}RS} &= 4 \\ N_{samp}^{group} &= 2 \end{aligned}}$$

Consider, PUSCH allocation = 20 PRBs

= 20 × 12 = 240 Subcarriers

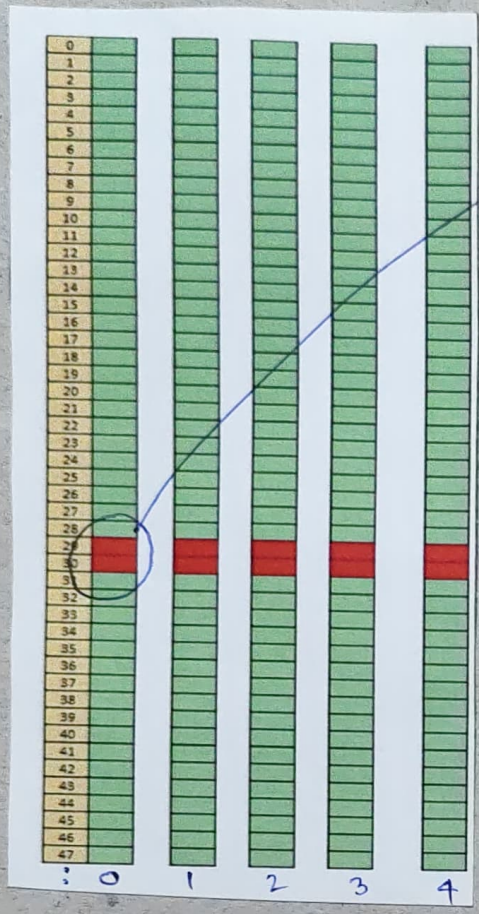
(i.e.) $M_{sc}^{PUSCH} = 240$

$\Rightarrow \left\lfloor s \cdot M_{sc}^{PUSCH} / 8 \right\rfloor + k - 1$

$\Rightarrow \lfloor 30\, s \rfloor + k - 1$, where $s = 1, 3, 5, 7$, $k = 0, 1$

$\Rightarrow$ 29, 30 ; 89, 90 ; 149, 150 ; 209, 210.

So, there are ten locations where PTRS will go along with PUSCH.



Case 1.

→ In this figure, only two PTRS indices are shown. (i.e) 29, 30. (Single group of PTRS).

→ Similarly, there are four groups at different symbols ($l = 0, 1, 2, 3, 4$)

→ Time density = 1.

(i.e) here, in transform precoding enabled case, the Time density doesn't depend on the MCS. It takes two values (either 1 or 2).

- 1 means, PTRS is going in every symbols
- 2 means, PTRS is going in alternative symbols.

Lets take another case (Case 2), where

$$N_{group}^{PT-RS} = 4$$
$$N_{samp}^{group} = 4$$

$\Rightarrow s \cdot M_{sc}^{PUSCH} / 4 + n + k$

$\Rightarrow s \cdot 240/4 + n + k$

$\Rightarrow 60 s + n + k.$

$\Rightarrow$ When $s = 0$, $n = 0$, $k = 0, 1, 2, 3$

$m = 0, 1, 2, 3$

When $s = 1$, $n = \lfloor M_{sc}^{PUSCH} / 8 \rfloor = \lfloor 240/8 \rfloor = 30$, $k = -2, -1, 0, 1$

$m = 88, 89, 90, 91$

→ Similarly, there are 4 groups, each taking 4 samples.

→ Figure shows its multiplexing with PUSCH. This is how it looks like.

→ Time density = 2

(i.e) PTRS is going in alternative OFDM symbols.

This is how the PTRS symbols are generated and mapped, when the Transform Precoding is enabled in PUSCH.

——— x ———

PTRS : Receiver Design

In the previous sections, we've seen Signal generation and Resource Mapping for PTRS. In this section, lets understand how do we design a receiver that correct the phase noise that have been added in the signal.

What happens when Phase noise is added to the Signal?

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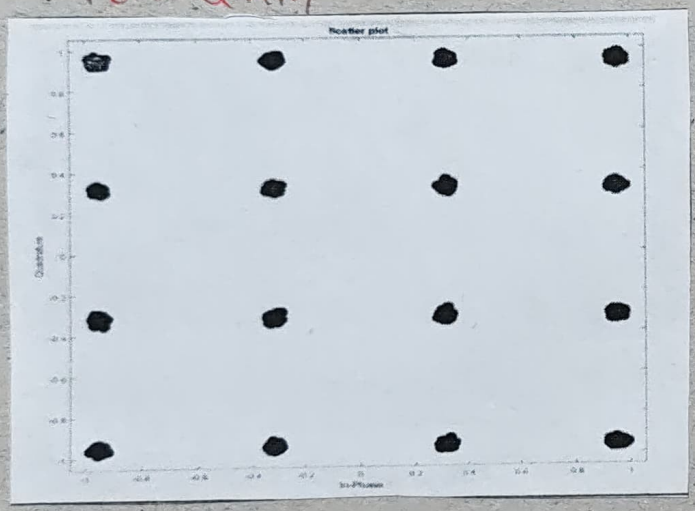
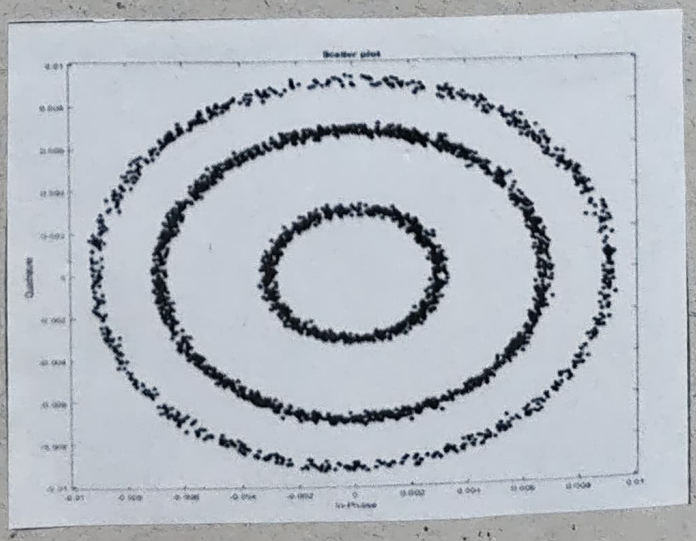


← This is how the Signal looks like, when there is No phase noise.

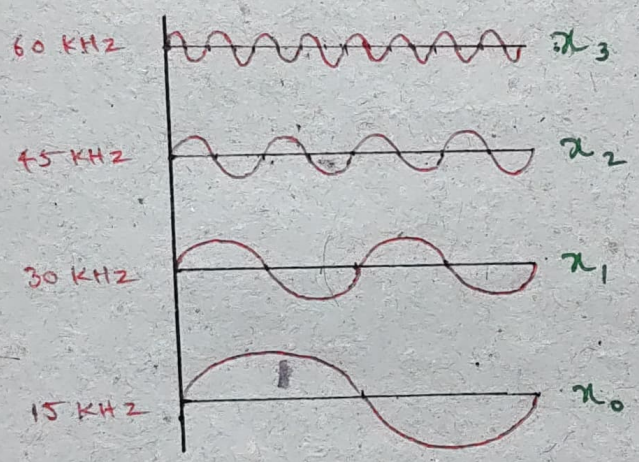
When phase noise is added, the signal may look as below. Based on the amount of Phase noise that is being added to the transmitted data, and the amount of noise that is there in the crystal, we see a rotation in the constellation points, as shown in figures below.



This rotation may be small or large, based on the phase noise.

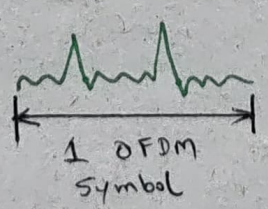
As we've seen previously that, the PTRS is less dense across the subcarriers, and highly dense across the OFDM symbols. This is because, the Phase noise is added because of the Crystal, and the variation across the subcarriers is less.

Recap OFDM, where we have different subcarriers, lets say 15 KHz, 30 KHz, 45 KHz, 60 KHz, and so on.

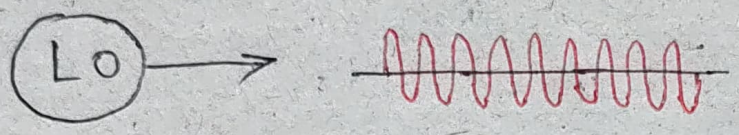


These subcarriers are modulated with data x_0, x_1, x_2, x_3, and so on.

And, when we add them up, the final signal (ie) 1 OFDM symbol with these many subcarriers modulated is shown below.



Now, with the local oscillator, we generate a carrier frequency (sine or cosine)

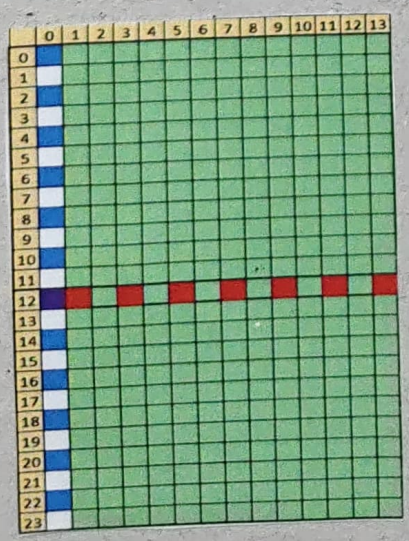


This carrier signal is modulated with the baseband signal (1 OFDM symbol), and transmitted.

Because of <u>imperfect</u> local oscillator, there is phase noise in the generated carrier signal, which in turn affects the baseband signal.

The phase noise due to imperfect LO, has variations across <u>time</u>, and does not have variations across <u>sub carriers</u>. Considering this in mind, the PTRS is designed. (i.e) PTRS is <u>lightly dense</u> across the sub carriers and <u>highly dense</u> across time.

Lets take an example (Case 1), where the assumption is that 'channel is stationary' (i.e) channel is not varying across time. So, 1 DMRS symbol is enough to estimate the channel, for the complete slot.



Case 1

Now, because of the multipath, reflections and all, the channel is varying across the frequency. So,

this is the reason that; in DMRS we have highly dense across the subcarriers. (ii) DMRS is there in every alternative subcarriers.

Lets say, $Y \rightarrow$ Received Signal

$X \rightarrow$ Transmitted Signal

Assume, the Transmitted signal has the phase noise effect in the channel (H_P).

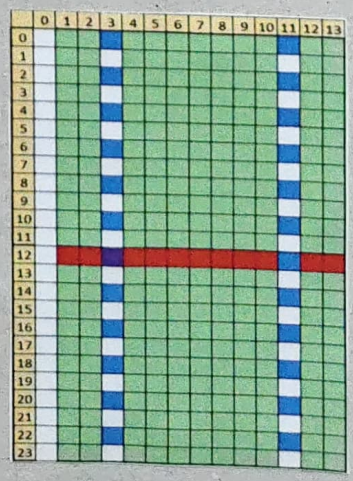
And, because of the multipath, reflections, and all, the Transmitted signal will have other channel effects like phase and amplitude variations (H_D).

Also, the white noise is being added.

$$\Rightarrow \boxed{Y = H_D H_P X + W}$$

So, the transmitted signal (X) has the effect of phase (H_P) because of the imperfect crystal, and other effects due to multipaths and all (H_D). And, thats how, we receive the final signal (Y) with the added White noise.

In case 1, we assumed that H_D is constant (not varying across the symbols). And, thats the reason we have only one DMRS symbol. If H_D is not constant (varies across the symbols), we'd have had multiple DMRS, like in case 2.



Case 2

Using the DMRS REs in Symbol 0, we first estimate the channel (i.e) H_{D1}. Now, there is no way to separate H_D and H_P.

H_{D1} has the estimation from both H_D and H_P.

Now, lets assume that, H_D is not varying across symbols, but H_P is varying across symbols. Assume that, there is phase change (rotation) of 2 degree on every OFDM symbol. (say Sym 1 → 2°, Sym 2 → 4°, Sym 3 → 6°, and so on).

So, first we apply the channel estimates that we've done on the DMRS symbol (Sym. 0) on the PTRS REs, and remove that channel effect.

Now, the only thing remains is the phase change w.r.t to the first symbol (DMRS) (Sym. 0). So, this phase change needs to be estimated.

We calculate the phase changes using the transmitted PTRS signal. WKT, the PTRS REs are repeated across the symbols. We also know the exact data that was transmitted on the PTRS REs. Now, using those two, we estimate the phase difference on the PTRS REs.

Now, we apply the phase estimates on top of the received data.

Now, on the PDSCH / PUSCH data (Sym. 1 to Sym. 13), we apply both the DMRS estimates and PTRS estimates to the received data. (ii) we equalize the received data with both the DMRS estimates and the PTRS estimates.

Finally, we get the equalized data, which we further pass it through different modules in the PDSCH or PUSCH chains.

This is how we do the phase noise estimation.

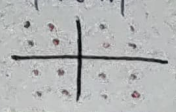
<u>Note</u>: When the channel (H_D) also varies across time, in that case, we use 2/3/4 DMRS symbols (ie) H_{D3}, H_{D11} (Case 2)

H_{D3} → Channel estimation using DMRS on symbol 3.

H_{D11} → Channel estimation using DMRS on symbol 11.

And, we can interpolate these channel estimates across the symbols allocated. and then we remove the channel effect from the PTRS REs.

Once we removed the channel effect from the PTRS REs, we have to calculate the phase variation across the OFDM symbols (PTRS REs), and then we apply H_D and H_P to equalize the data from Sym 1 to Sym 13. to get the Constellation back.



and then we pass it through different modules of PUSCH and PDSCH.

This is all about PTRS receiver design.

We can have very complex receivers to estimate the phase noise, and the DMRS estimates can be used with the PTRS estimates, to equalize the data.