SRS : Introduction

↳ Sounding Reference Signal

SRS is an Uplink signal, that is transmitted to find out the Uplink Channel Information.

Now the question comes, When we already have DMRS, then why do we need another Reference signal (SRS)? The DMRS signal which goes with PUSCH is used to estimate the channel for PUSCH.(i.e) only on the resources allocated for PUSCH, since the resources for DMRS and PUSCH are same.(i.e) same number of PRBS and Ports are allocated. But,

1. How gNB finds out what are the best uplink channels for a particular UE?
2. How gNB finds out How many uplink layers or Antenna Ports it can schedule?
3. How does gNB do Channel based Scheduling?
4. How gNB finds out what is the right MCS to use for a particular UE?

For all these different purposes, UE transmits SRS in the Uplink separately. And with the SRS, gNB will estimate the channel and finds out

- How many layers it should use.
- What are the PRBs that are best for a particular UE.

and then it can schedule accordingly as per SRS estimates.

Another purpose of SRS is that, it can also be used in Downlink. (ii).

- Whatever CSI-RS is doing for Downlink, SRS is doing the same for Uplink,
- It can give the Number of Layers (Rank)
- It can also provide the Precoding Matrix to the UE, that it can use to transmit PUSCH data
- Apart from PUSCH (uplink), it can also be used for downlink (only in TDD mode)

In TDD, lets say the Downlink and Uplink pattern is as below:

D	D	D	S	U	D	D	D	S	U

Lets say, SRS is transmitted in this UL slot. So, gNB estimates the channel information from SRS in this UL slot. Here, gNB assumes that the channel for UL and DL remains the same for the same antenna ports, and uses the same channel information to schedule PDSCH in the next DL slot. This is known as TDD Reciprocity. (cannot be done in FDD)

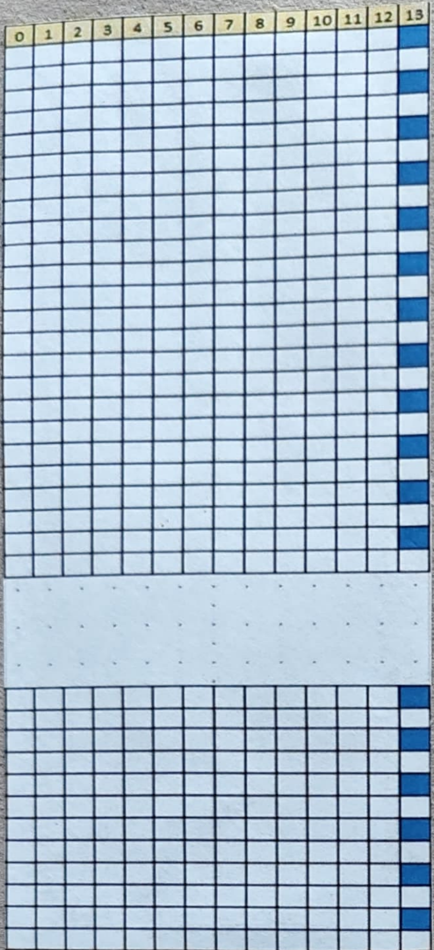
Note: If there is heavy interference in DL, in such case, the estimates of SRS may not be able to correctly schedule PDSCH.

SRS can be transmitted as periodic, aperiodic or semi-persistent (we'll look into these later in more detailed).

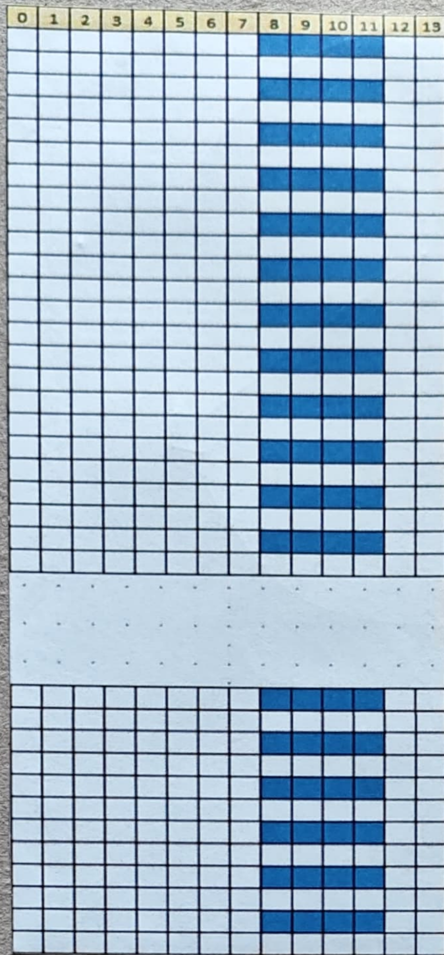
SRS is transmitted in the last OFDM symbols of the slots. SRS can take upto 4 OFDM symbols (1, 2, 3 or 4), and it can be transmitted in any of the last 6 symbols. (Symbols 8, 9, 10, 11, 12, 13). Out of these 6 symbols, any 4 symbols (maximum) can be given to SRS. (Refer Example 1 and Example 2)

SRS can be transmitted in Full band (272 PRBs). Normally, SRS resources are scheduled as multiple of 4 PRBs (min. 4 PRBs, max. 272 PRBs).

SRS signal is generated based on the ZC sequence. By providing different cyclic shifts of ZC sequence, we can multiplex multiple UE, or multiple antenna ports in the same SRS resources. (ie) Multiple UEs can transmit SRS on the same location (or) Multiple Antennas can transmit SRS at the same location. Like in Example 3., here SRS is taking 2 Symbols. One UE is allocated with these resources (Blue), and upto 8 UEs can use the same resources to send SRS. Also, some other UE may be allocated with these resources (Green). This is how, multiple UEs and multiple antenna ports can be multiplexed over the symbols.



Example 1



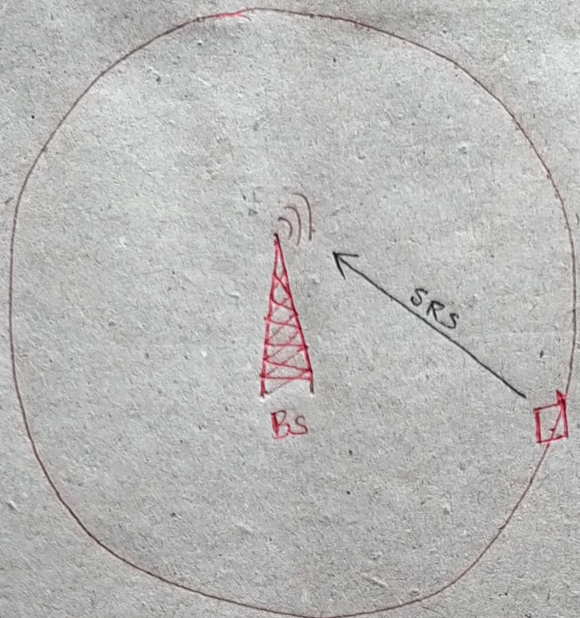
Example 2

Example 3

As already discussed, UE can send SRS on maximum 272 PRBs. So, gNB will estimate the channel on all 272 PRBs when BWP = 272 and SRS allocation is also on 272 PRBs.

gNB will estimate the channel (PRBs) when the channel is good as well as when the channel is bad. And the gNB schedules the resources for PUSCH transmission, when the channel is good.

Now, One of the problem in scheduling Full band is that, UE has limited Power. It can have upto 23 dBm (or) 26 dBm. This is the maximum power UE can transmit.

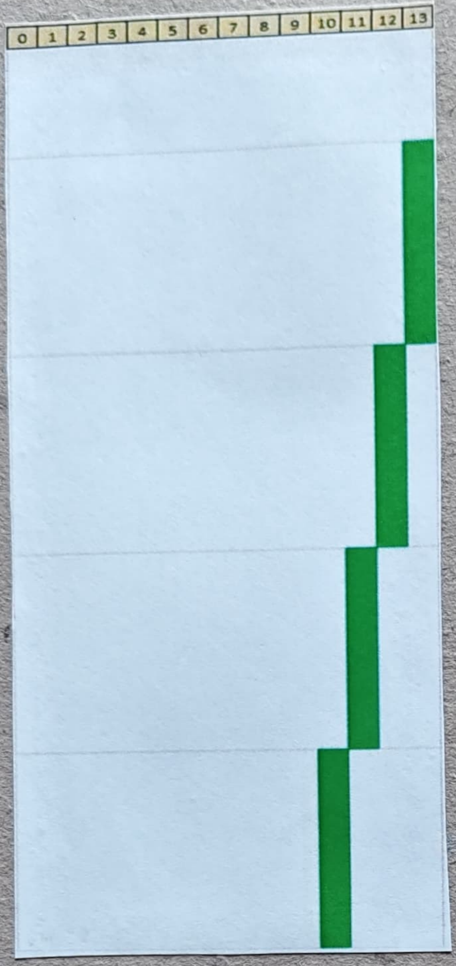


If the UE is very far from the BS (ie) at the edge of the cell, in that case, if UE schedules Full band (272 PRBs), then the SRS signal that is coming to the gNB will be very weak, because the full power that the UE can use is distributed across the full band (272 PRBs). Hence the power per subcarrier is very less. So, the signal reaching to the gNB is very weak and hence the channel estimates done by the gNB may not be proper.

So, in the case where UE is far from gNB, they can use something called "Frequency Hopping" to transmit SRS.

"Frequency Hopping" in SRS can be done in two ways.

1. Inter-slot Frequency Hopping
2. Intra-slot Frequency Hopping

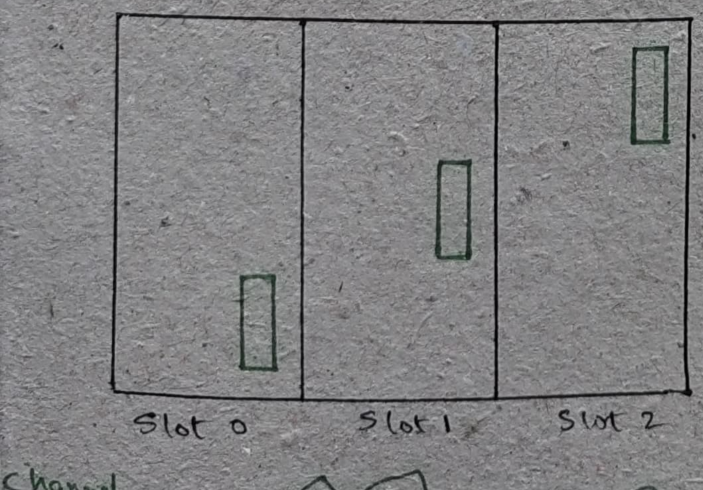


Example 4

Let's say, UE had the limited power. So, in this example, UE sends SRS across 4 symbols. This is called intra-slot frequency hopping. Here, one fourth of the allocation (SRS) goes on each symbol. This way, SRS can be estimated on the full Frequency band, by employing all the 4 symbols.

This frequency hopping is very useful for the UEs at the cell edge.

In Inter-slot frequency hopping, the same can be done across the slots. So, this increases the Uplink power. One of the drawback in inter-slot frequency hopping is "Channel Ageing".



That means, if SRS is scheduled in inter-slot fashion as shown in this figure, and if the channel is varying very fast, then the estimates of SRS in one slot may not be valid in the next slot.

This inter-slot frequency hopping in SRS may not hold valid for the channels where we want to schedule PUSCH next.

SRS : Sequence Generation

Lets understand the sequence generation for SRS. As we know, SRS is a ZC based sequence. We've already seen how to generate ZC sequence and what are the different inputs

$$r^{(p_i)}(n, l') = r_{u,v}^{(\alpha_i,\delta)}(n)$$

$$0 \le n \le M_{sc,b}^{SRS} - 1$$

$$l' \in \{0, 1, \dots, N_{symb}^{SRS} - 1\}$$

This is the base formula for the sequence generation,

where,

p_i → Antenna Port index (1/2/4).

n → Sequence index

l' → Symbols given to SRS

α_i → To provide cyclic shift

δ → Used for size calculation

u, v → For Group and Sequence Hopping.

$M_{sc,b}^{SRS}$ → Length of the SRS sequence generated

N_{symb}^{SRS} → No. of Symbols for SRS (1/2/3/4)

Two different ways of mapping SRS.

1

2

① ⇒

- Here, the comb size, $K_{TC} = 2$
- SRS is allocated one in every two subcarriers
- Here, the density of SRS REs is 1/2
- In single PRB, we have 6 SRS REs.

② ⇒

- Here, the comb size, $K_{TC} = 4$
- SRS is allocated one in every four subcarriers
- Here, the density of SRS REs is 1/4
- In single PRB, we have 3 SRS REs.

$$\delta = \log_2(K_{TC})$$

If $K_{TC} = 2$, $\delta = \log_2(2) = \underline{\underline{1}}$

$K_{TC} = 4$; $\delta = \log_2(4) = \underline{\underline{2}}$

$$r_{u,v}^{(\alpha,\delta)}(n) = e^{j\alpha n}\bar{r}_{u,v}(n), \quad 0 \le n < M_{ZC}$$

$$M_{ZC} = mN_{sc}^{RB}/2^{\delta}$$

This is how ZC sequence is generated, where

$e^{j\alpha n}$ → is to provide cyclic shift.

$\bar{r}_{u,v}(n)$ → This is again ZC sequence (the other exponential sequence that is generated)

δ → decides the length of the ZC sequence (M_{ZC})

$$\alpha_i = 2\pi \frac{n_{SRS}^{cs,i}}{n_{SRS}^{cs,max}}$$

$$n_{SRS}^{cs,i} = \left(n_{SRS}^{cs} + \frac{n_{SRS}^{cs,max}(p_i - 1000)}{N_{ap}^{SRS}} \right) \bmod n_{SRS}^{cs,max},$$

$$n_{SRS}^{cs} \in \{0, 1, \ldots, n_{SRS}^{cs,max} - 1\}$$

- For SRS, α_i is defined as above, where i is the antenna port index $(i = 1, 2, 3, 4)$.

$n_{SRS}^{cs,max} \rightarrow$ Maximum cyclic shift.

If comb size, $K_{TC} = 4$, then $n_{SRS}^{cs,max} = 12$

So, 12 cyclic shifts are possible.

If comb size, $K_{TC} = 2$, then $n_{SRS}^{cs,max} = 8$

So, 8 cyclic shifts are possible.

This cyclic shifts are used to multiplex multiple antennas or multiple UEs.

$$\Rightarrow \alpha_i = \frac{2\pi\, n_{SRS}^{cs,i}}{12} \text{ (or) } \frac{2\pi\, n_{SRS}^{cs,i}}{8}.$$

and, the parameter $n_{SRS}^{cs,i}$ can take values $\{0 \text{ to } 11\}$ if maximum cyclic shifts are 12. (or) $n_{SRS}^{cs,i}$ takes values $\{0 \text{ to } 7\}$ if maximum cyclic shifts are 8.

And, this portion $\frac{n_{SRS}^{cs,max}(p_i - 1000)}{N_{ap}^{SRS}}$ is to pick cyclic shift for different antenna port. The Antenna ports can be 1000, 1001, 1002 and 1003.

$N_{ap}^{SRS} \rightarrow$ Total No. of Antenna ports given to UE.

Lets say, the maximum cyclic shifts $n_{SRS}^{cs,max} = 12$,
and there are 4 Antenna ports,

$$n_{SRS}^{cs,i} = \left(n_{SRS}^{cs} + \frac{12\,(0/1/2/3)}{4} \right) \bmod 12$$

And, lets say, UE1 is given with cyclic shift of 1,

$$\Rightarrow n_{SRS}^{cs,i} = \left(1 + (0/3/6/9) \right) \bmod 12$$

$$= 1/4/7/10$$

These are the cyclic shifts that can be used for 4 different Antenna ports for that given UE. So, α_i becomes

$$\alpha_i = \frac{2\pi\,1}{12}, \frac{2\pi\,4}{12}, \frac{2\pi\,7}{12}, \frac{2\pi\,10}{12}$$ for 4

different Antenna Ports.

Now, lets say, UE 2 is given with cyclic shift of 2

$$\Rightarrow n_{SRS}^{cs,i} = \left(2 + (0/3/6/9) \right) \bmod 12$$

$$= 2/5/8/11$$

$$\alpha_i = \frac{2\pi\,2}{12}, \frac{2\pi\,5}{12}, \frac{2\pi\,8}{12}, \frac{2\pi\,11}{12}.$$

So, this is how different cyclic shifts are given to different UEs and to different Antenna ports. And, this is used to transmit multiple SRS sequences or the same SRS sequence, from different antennas and from different UEs.

Now, lets understand u and v.

u is for Group hopping (0 to 29)

v is for Sequence hopping (0 or 1)

$$u = \left(f_{gh}\left(n^{\mu}_{s,f}, l'\right) + n^{SRS}_{ID}\right) \bmod 30$$

The value of u depends on $f_{gh}(\cdot)$, which is a function of Slot number and Symbol number. This means, for every different Slot and Symbol number, a different SRS sequence can be generated.

n^{SRS}_{ID} → This ID can be specific to a cell, meaning, for every different cell, a different SRS sequence is generated. (to reduce interference across the cells)

→ Takes values from 0 to 1023.

- When both Group Hopping and Sequence Hopping are disabled, then

$$f_{gh}\left(n^{\mu}_{s,f}, l'\right) = 0$$
$$v = 0$$

So, u directly depends on n^{SRS}_{ID}. (ii)

$$u = n^{SRS}_{ID} \bmod 30$$

- When Group Hopping enabled and Sequence hopping disabled.

$$f_{gh}\left(n^{\mu}_{s,f}, l'\right) = \left(\sum_{m=0}^{7} c\left(8\left(n^{\mu}_{s,f} N^{slot}_{symb} + l_0 + l'\right) + m\right) \cdot 2^m\right) \bmod 30$$
$$v = 0$$

$$c_{init} = n^{SRS}_{ID}$$

- When Group Hopping disabled and Sequence hopping enabled.

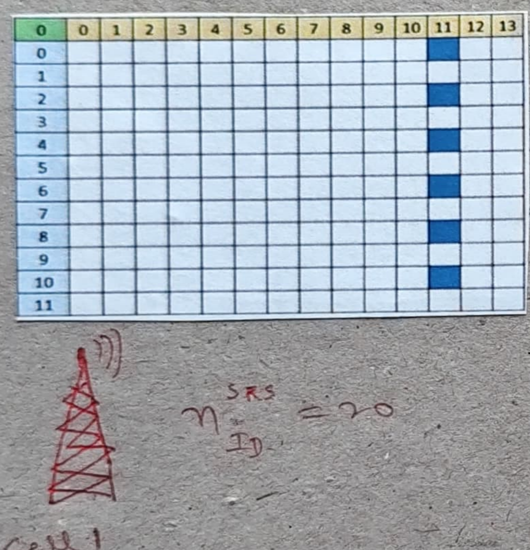
$$f_{gh}\left(n^{\mu}_{s,f}, l'\right) = 0$$
$$v = \begin{cases} c\left(n^{\mu}_{s,f} N^{slot}_{symb} + l_0 + l'\right) & M^{SRS}_{sc,b} \geq 6N^{RB}_{sc} \\ 0 & \text{otherwise} \end{cases}$$

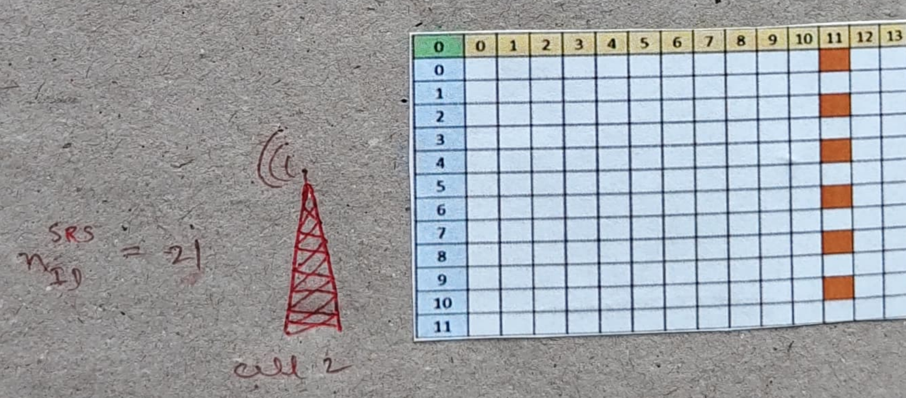
In this case, v takes value either 0 or 1.

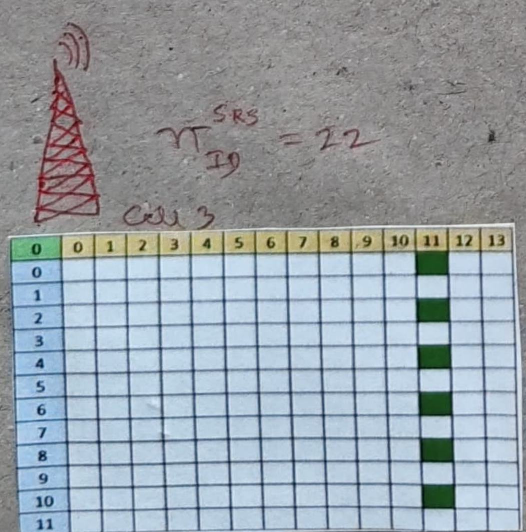
if the length of the sequence, $M_{sc,b}^{SRS}$ is greater than 6 PRBs, then there will be two sequences and the sequence index is given by

$$v = c\left(n_{s,f}^{\mu} N_{symb}^{slot} + l_0 + l'\right),$$

otherwise, $v = 0$.







Lets say, there are three cells, as shown in figure. These 3 cells generate different SRS signal on the same symbol (Symbol 11). The comb size, $K_{TC} = 2$ for all the 3 cells. And, we can still generate different SRS signals (orthogonal to each other) using different n_{ID}^{SRS} for each cell.

This is about the Sequence generation for SRS.

———×———

SRS : Mapping to Resource Grid :

Lets understand, how the ZC sequence that we have generated in the previous section, is mapped to the SRS resources:

WKT, SRS takes upto 4 Symbols and 4 Antenna Ports.

$$a^{(p_i)}_{K_{TC}k'+k_0^{(p_i)},\, l'+l_0} = \begin{cases} \dfrac{1}{\sqrt{N_{ap}}}\beta_{SRS}\, r^{(p_i)}(k',l') & k'=0,1,\ldots,M^{SRS}_{sc,b}-1 \quad l'=0,1,\ldots,N^{SRS}_{symb}-1 \\ 0 & \text{otherwise} \end{cases} \quad \text{—(1)}$$

This equation explains the SRS mapping, where

N_{ap} → No. of SRS Antenna Ports

$\frac{1}{\sqrt{N_{ap}}}$ → is for amplitude scaling, based on the No. of antennas.

β_{SRS} → SRS Power

$r^{(p_i)}(k', l')$ → ZC sequence that we've generated.

p_i → Port index

k' and l' → Frequency and Time index of the ZC sequence generated

$K_{TC}k' + k_0^{(p_i)}$ and $l' + l_0$ → Frequency and Time index where the sequence will be mapped.

$M^{SRS}_{sc,b}$ → Length of the ZC sequence

N^{SRS}_{symb} → No. of symbols for SRS. (4)

$$M_{sc,b}^{SRS} = m_{SRS,b} N_{sc}^{RB} / K_{TC}$$

where,

- $m_{SRS,b}$ → No. of PRBs allocated to SRS.

  N_{sc}^{RB} → No. of subcarriers in a PRB (12).

  k_{TC} → Comb size (2 or 4).

If $m_{SRS,b} = 1$, and $k_{TC} = 2$, then

- $M_{sc,b}^{SRS} = \frac{1 \times 12}{2} = 6$ subcarriers going to SRS (REs)

If $k_{TC} = 4$, then

$M_{sc,b}^{SRS} = \frac{1 \times 12}{4} = 3$ subcarriers given to SRS (REs)

---

l' → OFDM symbol index inside the SRS resources.

So, $l' = 0, 1, 2, 3$ (at max) $\because N_{symb}^{SRS} = 4$.

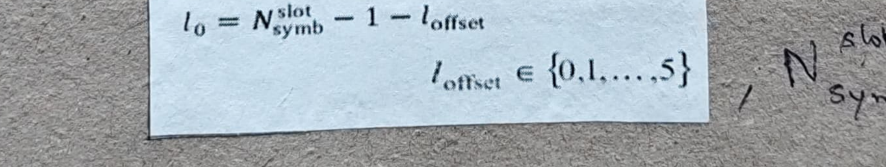
The symbol location is given as follows.

$$l_0 = N_{symb}^{slot} - 1 - l_{offset}$$

$$l_{offset} \in \{0, 1, \ldots, 5\}$$, $N_{symb}^{slot} = 14$

$\Rightarrow l_0 = 14 - 1 - l_{offset}$

As we know, the SRS takes 4 symbols (at max) in the last 6 symbols.



Lets rewrite the equation (1), dropping the amplitude scaling factor and SRS power. (for time being)

$$\underbrace{a^{(p_i)}_{K_{TC}k' + k_0^{(p_i)},\; l' + l^0}} = r^{(p_i)}(k', l')$$

This is where the ZC sequence that we've generated, will be mapped. The complex valued ZC sample (i) (k', l') is mapped to $(K_{TC}k' + k_0^{(p_i)}, l' + l^0)$ location of the resource grid.

$r(k', l')$

k'	0	1
11	a12	b12
10	a11	b11
	a10	b10
	a9	b9
	a8	b8
	a7	b7
	a6	b6
	a5	b5
	a4	b4
2	a3	b3
1	a2	b2
0	a1	b1

$l' = 0$ $l' = 1$

Lets say, this is the ZC sequence $r(k', l')$

And, below is the final Grid where the ZC sequence $r(k', l')$ should be mapped.

0	0	1	2	3	4	5	6	7	8	9	10	11	12	13
23														
22											a12	b12		
21														
20											a11	b11		
19														
18											a10	b10		
17														
16											a9	b9		
15														
14											a8	b8		
13														
12											a7	b7		
11														
10											a6	b6		
9														
8											a5	b5		
7														
6											a4	b4		
5														
4											a3	b3		
3														
2											a2	b2		
1														
0											a1	b1		
0	0	1	2	3	4	5	6	7	8	9	10	11	12	13

$2k'$

$l' = 10, 11$

Now, l' is mapped to $l' + l^0$

WKT, $l^0 = 14 - 1 - l_{offset}$.

Assume $l^0 = 10$

And, we have $l' = 0$, $l' = 1$.

So, l' is mapped to Symbols 10 and 11.

Hence, the SRS ZC sequence will go on Symbols 10 and 11 for this particular configuration.

Now, inside these two symbols, at what frequency locations (k'), the SRS ZC sequence will be mapped?

k' is mapped to $K_{TC} k' + k_0^{(p_i)}$

WKT, $K_{TC} = 2$ (or) 4

Assume, $k_0^{(p_i)} = 0$

So, k' is mapped to $2k'$ (if $K_{TC} = 2$)

k' is mapped to $4k'$ (if $K_{TC} = 4$)

The corresponding frequency mapping (ie) $2k'$ is shown in the figure (Green), considering $K_{TC} = 2$. and $k_0^{(p_i)} = 0$.

$k_0^{(p_i)}$ is defined in the Specification as follows.

$$k_0^{(p_i)} = \bar{k}_0^{(p_i)} + \sum_{b=0}^{B_{SRS}} K_{TC} M_{sc,b}^{SRS} n_b$$

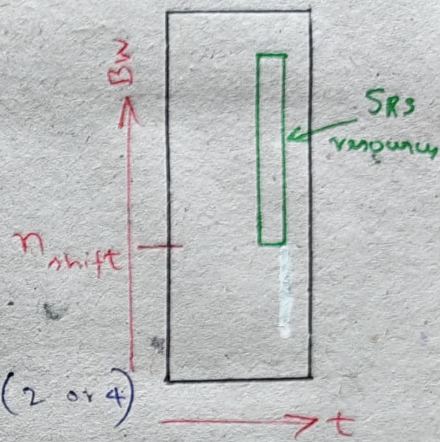
, where

$$\bar{k}_0^{(p_i)} = n_{shift} N_{sc}^{RB} + k_{TC}^{(p_i)}$$

$$k_{TC}^{(p_i)} = \begin{cases} (\bar{k}_{TC} + K_{TC}/2) \bmod K_{TC} & \text{if } n_{SRS}^{cs} \in \{n_{SRS}^{cs,max}/2, ..., n_{SRS}^{cs,max} - 1\} \text{ and } N_{ap}^{SRS} = 4 \text{ and } p_i \in \{1001, 1003\} \\ \bar{k}_{TC} & \text{otherwise} \end{cases}$$

$\bar{k}_{TC} \rightarrow \{0, 1, ..., K_{TC} - 1\}$

n_{shift} (in terms of PRBs) tells the starting point from where the SRS resources are allocated.



$k_{TC}^{(p_i)}$ will take values from 0 to K_{TC} (2 or 4)

$$\Rightarrow k_{TC}^{(p_i)} = \begin{cases} 0, 1, & \text{if } K_{TC} = 2 \\ 0, 1, 2, 3, & \text{if } K_{TC} = 4 \end{cases}$$

$\bar{k}_{TC}$ will take values $\{0, 1, \ldots, K_{TC}-1\}$

The BS provides this n_{shift} and K_{TC} to the UE. (Basically odd or even subcarrier index).

$$\sum_{b=0}^{B_{SRS}} K_{TC} M_{sc,b}^{SRS} n_b ,$$

where, $K_{TC} = 2$ or 4

$M_{sc,b}^{SRS} \rightarrow$ Length of ZC sequence

$n_b \rightarrow$ defined as follows.

As we know, SRS also supports Frequency Hopping. So, there are 3 parameters, C_{SRS}, B_{SRS} and B_{hop}, which are used to find out SRS location and frequency. B_{hop} along with B_{SRS} provides information on Freq. hopping.

If $B_{hop} \geq B_{SRS}$, then there is no hopping and

$$n_b = \lfloor 4 n_{RRC} / m_{SRS,b} \rfloor \bmod N_b$$

If $B_{hop} < B_{SRS}$, then hopping is enabled, and

$$n_b = \begin{cases} \lfloor 4n_{RRC}/m_{SRS,b} \rfloor \bmod N_b & b \le b_{hop} \\ \left(F_b(n_{SRS}) + \lfloor 4n_{RRC}/m_{SRS,b} \rfloor\right) \bmod N_b & \text{otherwise} \end{cases}$$

where N_b is given by Table 6.4.1.4.3-1.

$$F_b(n_{SRS}) = \begin{cases} (N_b/2)\left\lfloor \dfrac{n_{SRS} \bmod \prod_{b'=b_{hop}}^{b} N_{b'}}{\prod_{b'=b_{hop}}^{b-1} N_{b'}} \right\rfloor + \left\lfloor \dfrac{n_{SRS} \bmod \prod_{b'=b_{hop}}^{b} N_{b'}}{2\prod_{b'=b_{hop}}^{b-1} N_{b'}} \right\rfloor & \text{if } N_b \text{ even} \\ \lfloor N_b/2 \rfloor \left\lfloor n_{SRS} / \prod_{b'=b_{hop}}^{b-1} N_{b'} \right\rfloor & \text{if } N_b \text{ odd} \end{cases}$$

Here, n_b is a function of $F_b(n_{SRS})$,

Table below is given in the specification.

C_{SRS}	$B_{SRS}=0$		$B_{SRS}=1$		$B_{SRS}=2$		$B_{SRS}=3$	
	$m_{SRS,0}$	N_0	$m_{SRS,1}$	N_1	$m_{SRS,2}$	N_2	$m_{SRS,3}$	N_3
0	4	1	4	1	4	1	4	1
1	8	1	4	2	4	1	4	1
2	12	1	4	3	4	1	4	1
3	16	1	4	4	4	1	4	1
4	16	1	8	2	4	2	4	1
5	20	1	4	5	4	1	4	1
6	24	1	4	6	4	1	4	1
7	24	1	12	2	4	3	4	1
8	28	1	4	7	4	1	4	1
9	32	1	16	2	8	2	4	2
10	36	1	12	3	4	3	4	1
11	40	1	20	2	4	5	4	1
12	48	1	16	3	8	2	4	2
13	48	1	24	2	12	2	4	3
14	52	1	4	13	4	1	4	1
15	56	1	28	2	4	7	4	1
52	224	1	112	2	56	2	4	14
53	240	1	120	2	60	2	4	15
54	240	1	80	3	20	4	4	5
55	240	1	48	5	16	3	8	2
56	240	1	24	10	12	2	4	3
57	256	1	128	2	64	2	4	16
58	256	1	128	2	32	4	4	8
59	256	1	16	16	8	2	4	2
60	264	1	132	2	44	3	4	11
61	272	1	136	2	68	2	4	17
62	272	1	68	4	4	17	4	1

UE is always signalled with C_{SRS} (values between 0 and 62) and B_{SRS} (0, 1, 2, 3).

m_{SRS} is the bandwidth of SRS. If $B_{SRS} = 0$, then the bandwidth can go up to 272. This is the case when there is almost no hopping.

We see that, the bandwidth increases as the B_{SRS} decreases. This is how m_{SRS} is defined in this Table.

And here, N_0, N_1, N_2 and N_3 are given, to find out the frequency location where SRS is transmitted. (ie) N_b.

There is another parameter, n_{RRC}. As we know, SRS may not be transmitted in the full band. n_{RRC} is used to find out the frequency location where the SRS will be transmitted.

- n_b value ranges between 0 to $N_b - 1$, in both the cases when Frequency hopping is enabled / disabled, and N_b's are given in the above Table (N_0, N_1, N_2, N_3).

Also, note that, for $B_{SRS} = 0$, N_0 is always 1.

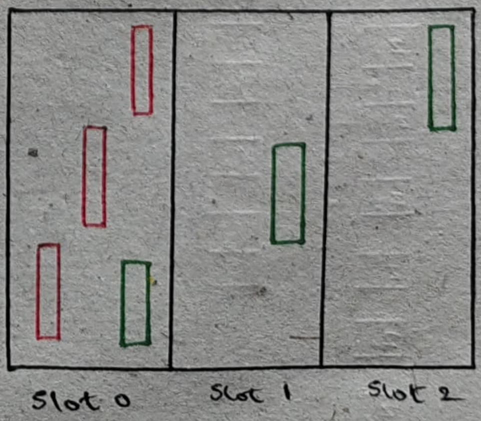
So, all these parameters decides where exactly we want to transmit SRS.

Lets say, if $C_{SRS} = 61$, $B_{SRS} = 0$, Full PRBs (272) are used to send SRS.

Lets say, if $C_{SRS} = 61$, $B_{SRS} = 3$, then $m_{SRS,3} = 4$ (ie) we send SRS in 4 PRBs only.

And, the location can be tuned using the parameter n_{shift} (tells the starting PRB from where SRS will be sent) (different UEs transmit SRS at different starting location).

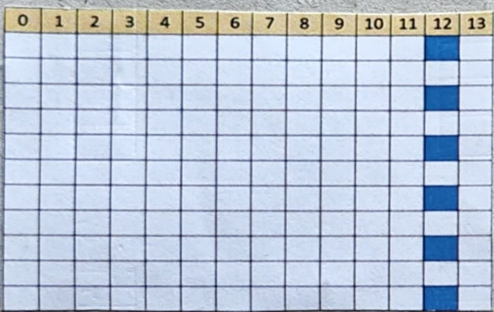
Also, SRS can have inter-slot and intra-slot Freq. Hopping, and the locations are given by the parameters $K_{TC} k' + k_0^{(p_i)}$, $l' + l^0$.



---x---

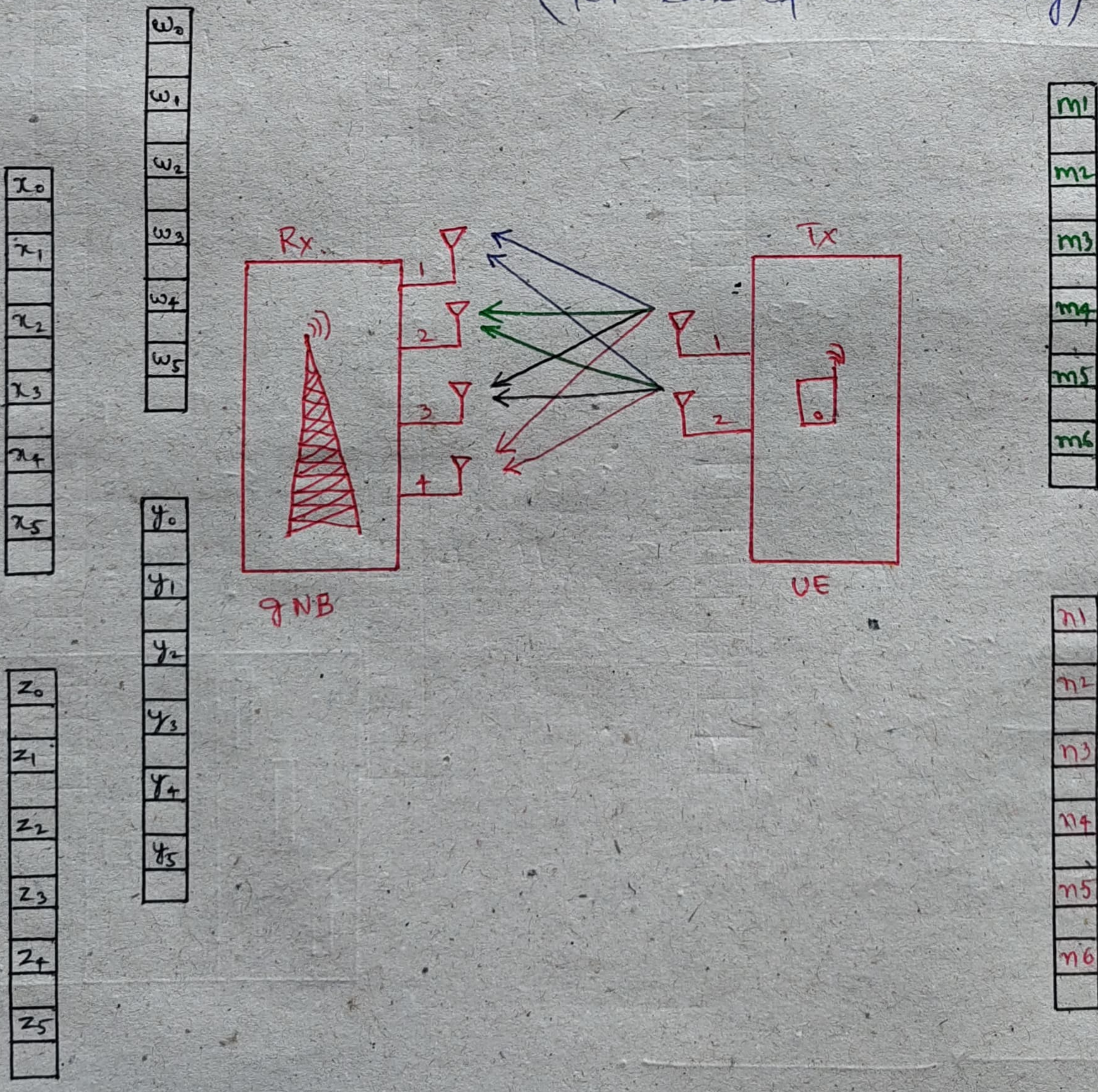
SRS : Receiver Processing, TDD Reciprocity and Antenna Switching

Lets understand how gNB receives SRS and how it takes the decision.



← Lets assume this SRS allocation, where $K_{TC} = 2$. (ie) SRS is transmitted on alternative subcarriers.

← Bandwidth = 1 PRB (for ease of understanding)



Lets assume gNB has 4 Rx. Antennas and
UE has 2 Tx. Antennas

where, SRS is being sent from the two Tx. Antennas of the UE. (ii) UE generates two different ZC sequences with different cyclic shift.

Lets say, the ZC sequence $\{m1, m_2, m3, m4, m5, m6\}$ has cyclic shift of 1. And, the ZC sequence $\{n1, n2, n3, n4, n5, n6\}$ has cyclic shift of 5. (As we know, 8 different cyclic shifts are possible (0 to 7) for $K_{TC} = 2$).

So, Antenna 1 is transmitting $\{m1, m_2, \ldots, m6\}$ and
Antenna 2 is transmitting $\{n1, n_2, \ldots, n6\}$.

Now, at gNB, each antenna will receive all the transmitted sequences. The channel between each Rx. antenna and each Tx antenna is different.

Lets assume, the received sequences at

Rx. Antenna 1 → $\{w0, w1, w_2, w_3, w_4, w_5\}$

Rx. Antenna 2 → $\{x_0, x_1, x_2, x_3, x_4, x_5\}$

Rx. Antenna 3 → $\{y_0, y_1, y_2, y_3, y_4, y_5\}$

Rx. Antenna 4 → $\{z0, z1, z_2, z_3, z_4, z5\}$

So, each Rx. Antenna has both the transmitted sequences. Also, we assume, the channel is constant in 1 PRB.

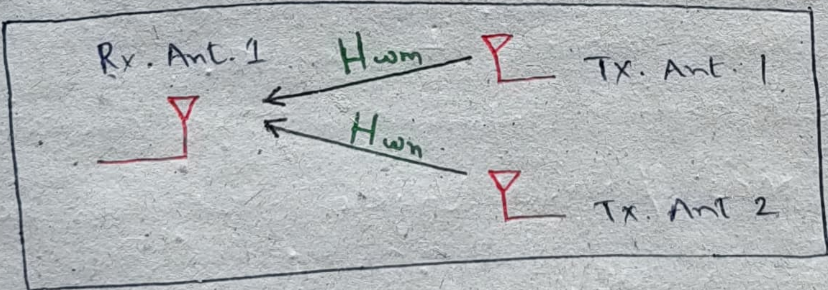
$$\begin{array}{ccccccc} \text{Rx.1} & & & \text{Tx.1} & & \text{Tx.2} & \\ \begin{bmatrix} w_0 \\ {} \\ w_1 \\ {} \\ w_2 \\ {} \\ w_3 \\ {} \\ w_4 \\ {} \\ w_5 \\ {} \end{bmatrix} & = & H_{wm} & \begin{bmatrix} m_1 \\ {} \\ m_2 \\ {} \\ m_3 \\ {} \\ m_4 \\ {} \\ m_5 \\ {} \\ m_6 \\ {} \end{bmatrix} & + \; H_{wn} & \begin{bmatrix} n_1 \\ {} \\ n_2 \\ {} \\ n_3 \\ {} \\ n_4 \\ {} \\ n_5 \\ {} \\ n_6 \\ {} \end{bmatrix} & + \; n \end{array}$$

$$\begin{array}{ccccccc} \text{Rx.2} & & & \text{Tx.1} & & \text{Tx.2} & \\ \begin{bmatrix} x_0 \\ {} \\ x_1 \\ {} \\ x_2 \\ {} \\ x_3 \\ {} \\ x_4 \\ {} \\ x_5 \\ {} \end{bmatrix} & = & H_{xm} & \begin{bmatrix} m_1 \\ {} \\ m_2 \\ {} \\ m_3 \\ {} \\ m_4 \\ {} \\ m_5 \\ {} \\ m_6 \\ {} \end{bmatrix} & + \; H_{xn} & \begin{bmatrix} n_1 \\ {} \\ n_2 \\ {} \\ n_3 \\ {} \\ n_4 \\ {} \\ n_5 \\ {} \\ n_6 \\ {} \end{bmatrix} & + \; n \end{array}$$

$$\begin{array}{ccccccc} \text{Rx.3} & & & \text{Tx.1} & & \text{Tx.2} & \\ \begin{bmatrix} y_0 \\ {} \\ y_1 \\ {} \\ y_2 \\ {} \\ y_3 \\ {} \\ y_4 \\ {} \\ y_5 \\ {} \end{bmatrix} & = & H_{ym} & \begin{bmatrix} m_1 \\ {} \\ m_2 \\ {} \\ m_3 \\ {} \\ m_4 \\ {} \\ m_5 \\ {} \\ m_6 \\ {} \end{bmatrix} & + \; H_{yn} & \begin{bmatrix} n_1 \\ {} \\ n_2 \\ {} \\ n_3 \\ {} \\ n_4 \\ {} \\ n_5 \\ {} \\ n_6 \\ {} \end{bmatrix} & + \; n \end{array}$$

$$\begin{array}{c} Rx.4 \\ \begin{bmatrix} z0 \\ \\ z1 \\ \\ z2 \\ \\ z3 \\ \\ z4 \\ \\ z5 \\ \\ \end{bmatrix} \end{array} = H_{zm} \begin{array}{c} Tx.1 \\ \begin{bmatrix} m1 \\ \\ m2 \\ \\ m3 \\ \\ m4 \\ \\ m5 \\ \\ m6 \\ \\ \end{bmatrix} \end{array} + H_{zn} \begin{array}{c} Tx.2 \\ \begin{bmatrix} n1 \\ \\ n2 \\ \\ n3 \\ \\ n4 \\ \\ n5 \\ \\ n6 \\ \\ \end{bmatrix} \end{array} + \eta$$

WKT, these two transmitted sequences are cyclic shifted version, and are orthogonal with each other. Since they're orthogonal, on each Rx. Antenna, we can estimate the channel between that particular Rx. Antenna and the Tx. Antenna. (ie)



H_{wm} and H_{wn} can be estimated at Rx. Ant. 1, since both the Tx. Antenna sequences are orthogonal to each other.

This way, we can have the channel information between all Rx. Antennas and all Tx. Antennas.

We have estimated the channel on each PRB or a group of PRBs. Similarly, SNR can be estimated on a group of PRBs.

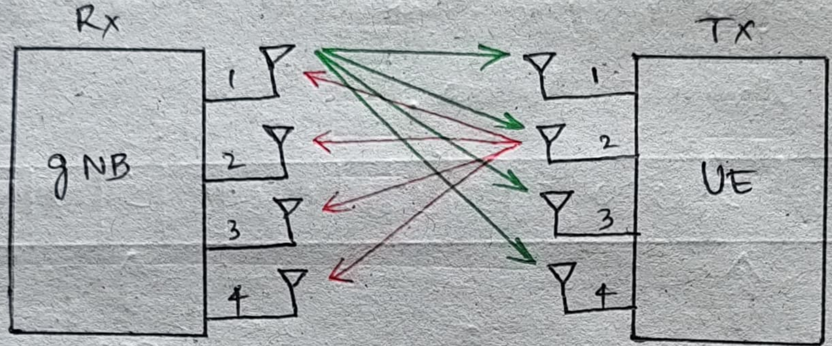
In the previous example, we have considered one PRB for SRS transmission. Now, lets say, SRS is transmitted on 272 PRBs. So, we estimate channel on each PRB (0, 1, 2, ..., 272) between each receive antenna and Transmit antenna. So, we can have Channel H on each PRB. or we can have channel H for a group of PRBs. (based on the receiver implementation).

Now, we have the channel and SNR estimated, and based on the channel and SNR information we can find which PRB has the better channel / SNR for a particular UE. So, the gNB schedules those PRBs for that UE. Lets say, gNB has the channel information for Full band (272 PRBs), picks the best 20 PRBs where the channel was good, and allocate those resources to the UE.

Based on SNR and channel information, gNB can also find out the best MCS / No. of Layers that can be allocated to a particular UE.

Lets say, its a TDD system, we assume that the channel between the Tx. and Rx. Antennas is same for the DL and UL (both). So, we can Precode the DL signal (for better SNR in DL) and Cancel the channel effect in the DL using the SRS channel estimates. This is known as TDD reciprocity.

Normally, a UE don't have same number of Tx. and Rx. Antennas. (ie) a UE might have 4 Rx. Antennas and 1 or 2 Tx. Antennas (of course, UE might have 4 Tx. Antennas as well, but its not useful).



For DL, UE might have all 4 antennas, but for UL, UE might have 1 or 2 antennas.

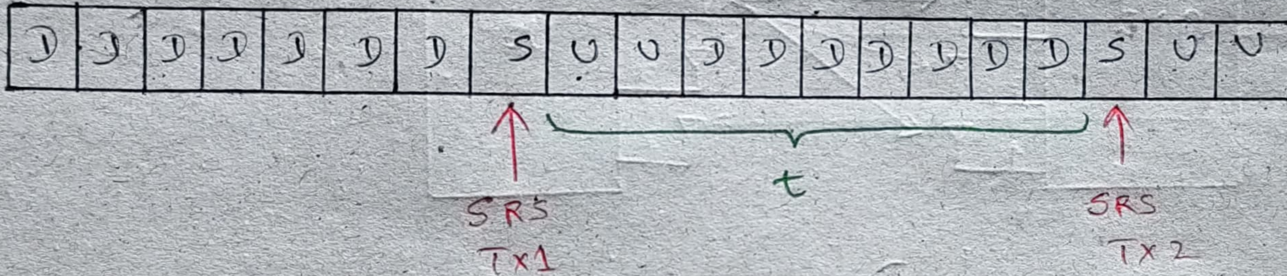
In such case, it is difficult for UE to have all the DL channel information (H). So, what gNB can do is, it can ask UE to change the antenna for SRS at different time instances (ie) at one instance, gNB can ask UE to use Tx. Antenna 1 to send SRS. At another instance, UE can use Tx. Antenna 2 to send SRS. Similarly, UE can use Tx. Antenna 3 and 4 at different instances.

This way, gNB will have information between all Rx. and Tx. Antennas, which helps gNB to schedule the DL and UL data accordingly.

This procedure has a downside. It takes long time for gNB to have the complete information between each Rx. and Tx. Antennas. So, by the time gNB gets the information from Tx. Antenna 4 from UE, the

Channel might have changed, and the information (H) from Tx. Antenna 1 from UE may expire (no longer useful).

This may happen if the channel is changing quite fast. This downside may also happen when in TDD structure, there is a huge gap between the continuous Uplink. (ie) Consider the TDD structure below.



Assume, we schedule UL transmission on Special slots, in the last symbols. The SRS for Tx.1 and Tx. 2 are scheduled as shown above. By the time, gNB has the channel information (H) for SRS Tx 2, the channel information for SRS TX1 may not hold True, since the channel have changed in the time t.

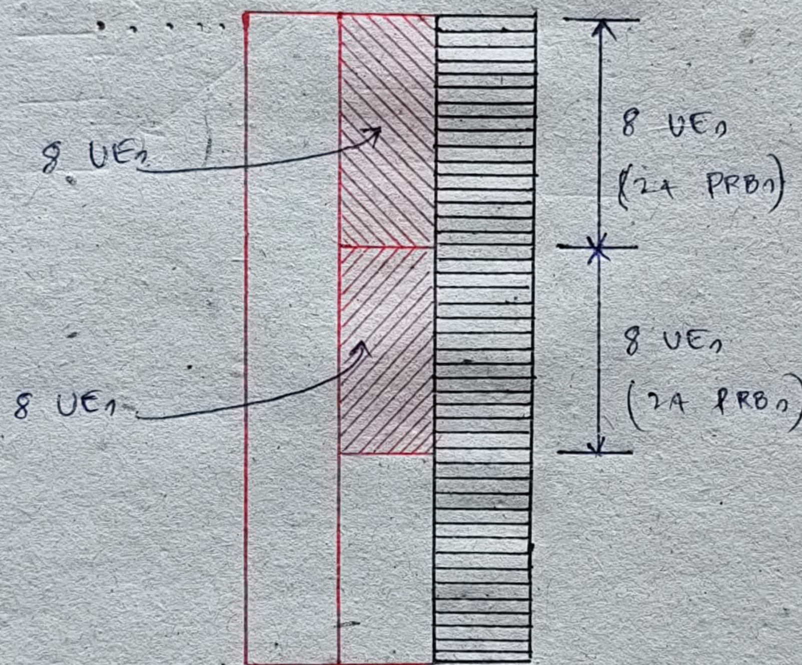
The above discussion holds true when

UE uses 4 Rx. Antennas
UE uses 2 Tx. Antennas (SRS)
gNB uses 4 Rx. Antennas.

In this case, there are two instances to send SRS to the gNB, to have complete information (H) across all the UE Tx. antennas.

In SRS, UEs can be multiplexed (i) Multiple UEs can be multiplexed across frequency and using different cyclic shift. We've seen the cyclic shift w.r.t K_{TC} (i) we can have 8 or 12 cyclic shift.

We can also multiplex UEs across sub-bands.



(i) as shown above, we can schedule a UE or a bunch of UEs (say 8 UEs) in, lets say 24 PRBs. And next 8 UEs are scheduled using the next 24 PRBs. This way multiple UEs can be frequency multiplexed across the full band.

UEs can also be multiplexed across the symbols as well. This way, we can schedule many many UEs or UEs with multiple antennas, to estimate the SRS channel.