PRACH : What and Why ?

PRACH → Physical Random Access Channel.

This is the first UL signal that is sent by UE to gNB.

BS continuously broadcasts MIB / SIB1, which helps UE to send the PRACH.

SIB1 contains configuration for PRACH. Using this configuration, UE sends the PRACH.

Before PRACH, BS doesn't even know that there is a UE out there, which wants to connect.

Now, the UE can be anywhere. It can be close to the BS (150 meter, say) or can be far from the BS (20 to 30 km, say). So, PRACH signal has to be designed in a way that the BS should be able to decode PRACH signal irrespective of how far the UE is from the BS.

After PRACH, whatever the UL signals that we transmit (PUCCH / PUSCH) are always aligned in Uplink. (ie) Transmitted well in advance using the parameter 'Timing Advance'. This parameter 'TA' is calculated from PRACH.

So, once the UE sends PRACH, BS calculates TA and tells UE that, "This much time, well in advance, you should send further UL signals". So, after PRACH, whatever signals or channels UE transmits, they're transmitted by UE well in advance by TA.

For transmitting PRACH signal, TA is not required. So PRACH signal should be designed in a way that, even without TA, the BS should be able to decode it, no matter how far the UE is from the BS, no matter whether it takes 2 μs or 20 μs. To take care of such scenario, we have different PRACH formats.

1. Long PRACH
2. Short PRACH

Long PRACH signals are long in time and has smaller subcarrier spacing.

Short PRACH signals are short in time and has longer subcarrier spacing.

Long PRACH formats accommodate large cell radius, meaning if the UE is far away from BS (even upto 100 km), it can send PRACH, which can be successfully decoded at BS.

And for Short PRACH, the cell radius is small, meaning if the UE is near the BS (150 m to 5 km), the propagation delay can be handled. If the UE is outside this range, then the Short PRACH may not be successfully decoded.

This is why, PRACH is one of the most complicated signal in 5G.

WKT, BS provides UE with resources. (i.e.) Time, frequency and other configuration parameters where UE can transmit the data. So, when the UE does not have any of these resources, then the UE sends PRACH.

So, PRACH is also used when the UE does not have any uplink resources. That means, for any other UL signal (PUCCH/PUSCH/SRS), whether it is supposed to send ACK/NACK or control message or SR, UE needs to have resources.

Other use case of PRACH:

Consider the BS and UE are connected. But somehow the BS loses the UL synchronization with the UE, due to UE moving away/towards the BS. Then the propagation delay might change from say 5 μs to 2 μs. Hence, there will be an issue in decoding the UL signals.

In such case, the BS signal UE to send PRACH again so that it further synchronizes its TA values properly.

Another use case of PRACH:

Consider the UE is connected to BS 1, and it is moving towards BS 2. Now, the UE is supposed to connect to BS2 (handover scenario).

Since the UE is about to connect to BS2, it should know the propagation delay from UE to BS2.

(ii) how much time the signal would take to reach BS2. So, in that case, the UE will send PRACH first, calculates TA and then only it initiates further UL transmission.

So, basically, there are two divisions of usecases. One is, when the UE does not have any UL resources, the UE has to send PRACH again to get the resources.

Second is, Timing related information that UE needs to find out. (ii) UE moves and lost synchroni-zation, (or) UE moves from one cell to another (HO) (or) NSA scenario, where UE moves from 4G to 5G cell. For all the above cases, UE sends PRACH, get the TA, and then only initiates further UL transmission.

PRACH : Signal Generation and Mapping

Lets understand how PRACH signal is generated at the UE and being transmitted.

As we know, the Base Sequence for PRACH is Zad-off chu Sequence. We've seen the properties of ZC-sequence. For PRACH, one of the requirements is that, the signal should have very high Autocorrelation and very low cross-correlation.

When UE transmits PRACH, the BS has to detect which preamble was transmitted out of all the possible preambles. Since it is the first signal (initial access), the BS doesn't know which preamble was transmitted. So, the BS has to do the correlation and find out which preamble was transmitted, based on the threshold. (we'll look into the receiver in subsequent section).

$$x_u(i) = e^{-j\frac{\pi u i(i+1)}{L_{RA}}}, i = 0,1,\ldots, L_{RA}-1$$

This is the ZC sequence where,

$L_{RA} \rightarrow$ Sequence length

For Short format, $L_{RA} = 139$

For Long format, $L_{RA} = 839$

$u \rightarrow$ Root Sequence Index

So, for every different u, we generate different Zc sequence. (ie) we can have 138 different short sequences and 838 different long sequences.

This is how we generate the base sequence for PRACH. The Root Sequence Indices are conveyed as shown in table below.

Table 6.3.3.1-4: Mapping from *logical index* i to sequence number u for preamble formats with $L_{RA} = 139$.

i	Sequence number u in increasing order of i																			
0 – 19	1	138	2	137	3	136	4	135	5	134	6	133	7	132	8	131	9	130	10	129
20 – 39	11	128	12	127	13	126	14	125	15	124	16	123	17	122	18	121	19	120	20	119
40 – 59	21	118	22	117	23	116	24	115	25	114	26	113	27	112	28	111	29	110	30	109
60 – 79	31	108	32	107	33	106	34	105	35	104	36	103	37	102	38	101	39	100	40	99
80 – 99	41	98	42	97	43	96	44	95	45	94	46	93	47	92	48	91	49	90	50	89
100 – 119	51	88	52	87	53	86	54	85	55	84	56	83	57	82	58	81	59	80	60	79
120 – 137	61	78	62	77	63	76	64	75	65	74	66	73	67	72	68	71	69	70	-	-
138 – 837	N/A																			

The UE gets the logical index i, and then it maps the Root sequence number u.

This table is for Short PRACH format. For long PRACH format also, there is a similar table.

After generating the base sequence, we have an option to cyclically shift the sequence, to generate more no. of sequences.

$$x_{u,v}(n) = x_u((n + C_v) \bmod L_{RA})$$

where, $C_v \rightarrow$ Cyclic Shift size

Lets say, $L_{RA} = 139$ and $C_v = 20$. So, we can have $\left\lfloor \frac{139}{20} \right\rfloor = 6$ different cyclic shifts. If we change the C_v to 10, then we have double the no. of sequence. And, if we change the C_v to 40, then we have half the no. of sequence. So, as we change the C_v size, the no. of sequence will also change.

So, the total number of sequences that we have for a given C_v (say $C_v = 20$) is $6 \times 138 = 828$.

(i.e) in total, we have around 828 different sequences, given $C_v = 20$. This is how we do cyclic shift.

The cyclic shift C_v is given by

$$C_v = \begin{cases} vN_{CS} & v = 0,1,\ldots,\lfloor L_{RA}/N_{CS} \rfloor - 1,\ N_{CS} \neq 0 \quad \text{for unrestricted sets} \\ 0 & N_{CS} = 0 \quad \text{for unrestricted sets} \\ d_{start}\lfloor v/n_{shift}^{RA} \rfloor + (v \bmod n_{shift}^{RA})N_{CS} & v = 0,1,\ldots,w-1 \quad \text{for restricted sets type A and B} \\ \overline{d}_{start} + (v-w)N_{CS} & v = w,\ldots,w+\overline{n}_{shift}^{RA} - 1 \quad \text{for restricted sets type B} \\ \overline{\overline{d}}_{start} + (v - w - \overline{n}_{shift}^{RA})N_{CS} & v = w+\overline{n}_{shift}^{RA},\ldots,w+\overline{n}_{shift}^{RA}+\overline{\overline{n}}_{shift}^{RA} - 1 \quad \text{for restricted sets type B} \end{cases}$$

$$w = n_{shift}^{RA} n_{group}^{RA} + \overline{n}_{shift}^{RA}$$

The cyclic shift have impact on the frequency offset, due to high mobility and all. We'll look into this condition in next section. (ii) for restricted sets / non-restricted sets, how to choose the right C_v.

Once we have the signal $X_{u,v}(n)$, we convert it to frequency domain.

$$y_{u,v}(n) = \sum_{m=0}^{L_{RA}-1} x_{u,v}(m) \cdot e^{-j\frac{2\pi mn}{L_{RA}}}$$

(ii) Take FFT of size L_{RA} (839 or 139) to generate frequency domain signal.

$$a_k^{(p,RA)} = \beta_{PRACH}\, y_{u,v}(k)$$
$$k = 0,1,\ldots,L_{RA} - 1$$

- Then, UE will multiply $y_{u,v}(n)$ with the Power factor β_{PRACH}. The final signal $a_K^{(P,RA)}$ will be converted into OFDM symbols.

$$s_l^{(p,\mu)}(t) = \sum_{k=0}^{L_{RA}-1} a_k^{(p,RA)} e^{j2\pi(k+Kk_1+\overline{k})\Delta f_{RA}(t-N_{CP,l}^{RA}T_c-t_{start}^{RA})}$$
$$K = \Delta f / \Delta f_{RA}$$

$$k_1 = k_0^{\mu} + (N_{BWP,i}^{start} - N_{grid}^{start,\mu})N_{sc}^{RB} + n_{RA}^{start}N_{sc}^{RB} + n_{RA}N_{RB}^{RA}N_{sc}^{RB} - N_{grid}^{size,\mu}N_{sc}^{RB}/2$$
$$k_0^{\mu} = (N_{grid}^{start,\mu} + N_{grid}^{size,\mu}/2)N_{sc}^{RB} - \left(N_{grid}^{start,\mu_0} + N_{grid}^{size,\mu_0}/2\right)N_{sc}^{RB}2^{\mu_0-\mu}$$

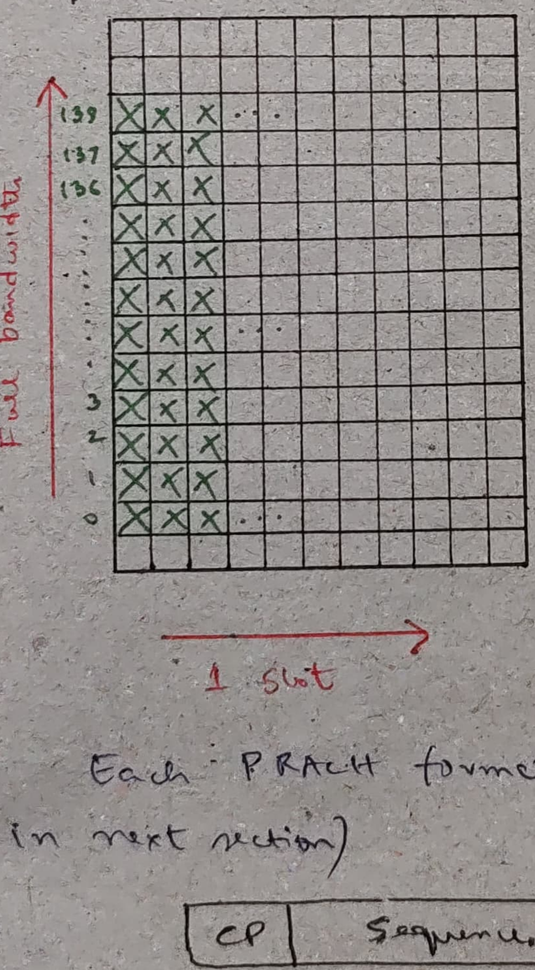
where $t_{start}^{RA} \le t < t_{start}^{RA} + (N_u + N_{CP,l}^{RA})T_c$

$S_l^{(p,\mu)}(t)$ is the final OFDM symbols in Time domain.

Now, PRACH has three different types of Subcarrier Spacings. Long formats has 1.25 KHz or 5 KHz. whereas the Short formats have Subcarrier Space same as PUSCH (15/30/60/120 KHz).

So, the final frequency domain sequence that is generated is mapped to the Resource Grid.

PRACH Short format



From the Starting subcarrier and Starting symbol, the 139 frequency domain signals is mapped on each subcarrier on a symbol. This is how we map a single sequence.

There could be repetition also in some PRACH formats. So the same sequence is repeated in the next coming symbols.

Each PRACH format has different CP (More details in next section)

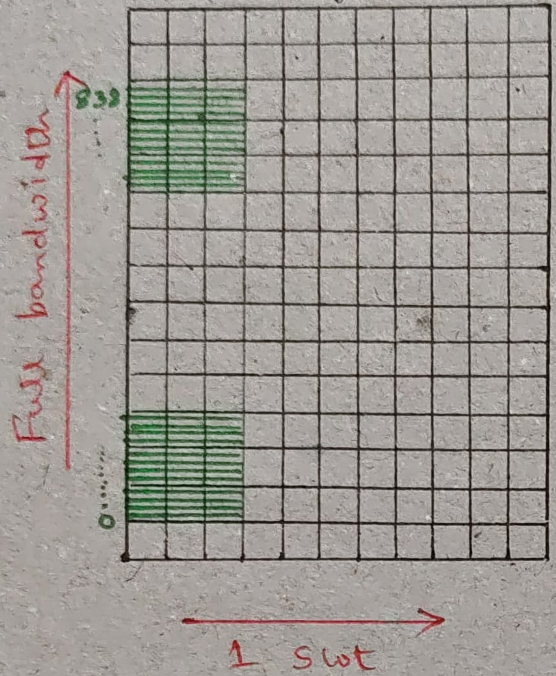
CP	Sequence	Guard

where, ⊙ the CP size is different for different formats. CP size will decide the cell radius that the PRACH format can support.

⊙ the sequence may have repetitions

⊙ Guard is to align the sequence to the symbol boundary of PUSCH.

PRACH Long format

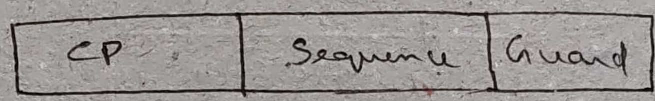


For PRACH Long format, the Subcarrier Spacing is quite less than the PUSCH SCS. Say,

PUSCH SCS → 30 KHz

PRACH SCS → 1.25 KHZ

then, the PRACH signal is mapped on the RE as shown here.



Here, we have big CP, which decides the cell size, and then we have sequence and Guard. (More detail in upcoming sections).

Table 6.3.3.1-1: PRACH preamble formats for $L_{RA} = 839$ and $\Delta f^{RA} \in \{1.25, 5\}$ kHz.

Format	L_{RA}	Δf^{RA}	N_u	N_{CP}^{RA}	Support for restricted sets
0	839	1.25 kHz	24576κ	3168κ	Type A, Type B
1	839	1.25 kHz	$2 \cdot 24576\kappa$	21024κ	Type A, Type B
2	839	1.25 kHz	$4 \cdot 24576\kappa$	4688κ	Type A, Type B
3	839	5 kHz	$4 \cdot 6144\kappa$	3168κ	Type A, Type B

For Long PRACH format.

Table 6.3.3.1-2: Preamble formats for $L_{RA} = 139$ and $\Delta f^{RA} = 15 \cdot 2^{\mu}$ kHz where $\mu \in \{0,1,2,3\}$.

Format	L_{RA}	Δf^{RA}	N_u	N_{CP}^{RA}	Support for restricted sets
A1	139	$15 \cdot 2^{\mu}$ kHz	$2 \cdot 2048\kappa \cdot 2^{-\mu}$	$288\kappa \cdot 2^{-\mu}$	-
A2	139	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$576\kappa \cdot 2^{-\mu}$	-
A3	139	$15 \cdot 2^{\mu}$ kHz	$6 \cdot 2048\kappa \cdot 2^{-\mu}$	$864\kappa \cdot 2^{-\mu}$	-
B1	139	$15 \cdot 2^{\mu}$ kHz	$2 \cdot 2048\kappa \cdot 2^{-\mu}$	$216\kappa \cdot 2^{-\mu}$	-
B2	139	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$360\kappa \cdot 2^{-\mu}$	-
B3	139	$15 \cdot 2^{\mu}$ kHz	$6 \cdot 2048\kappa \cdot 2^{-\mu}$	$504\kappa \cdot 2^{-\mu}$	-
B4	139	$15 \cdot 2^{\mu}$ kHz	$12 \cdot 2048\kappa \cdot 2^{-\mu}$	$936\kappa \cdot 2^{-\mu}$	-
C0	139	$15 \cdot 2^{\mu}$ kHz	$2048\kappa \cdot 2^{-\mu}$	$1240\kappa \cdot 2^{-\mu}$	-
C2	139	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$2048\kappa \cdot 2^{-\mu}$	-

For Short PRACH format.

Above tables gives the CP size, Sequence, Subcarrier Spacing and LRA lengths, for Long PRACH formats and Short PRACH formats.

This is how PRACH signal is generated at the UE side and transmitted...

PRACH : Cyclic Shift, Restricted Sets, and Timing offset.

WKT, $u \Rightarrow$ Root Sequence index

$C_v \rightarrow$ Cyclic Shift.

We have seen that, for different u, we generate different PRACH sequence. Also, for different C_v, we generate different PRACH sequence.

Lets understand how UE will generate a PRACH sequence and how it picks up a Preamble.

Consider the PRACH sequence (Long Format) of length $L_{RA} = 839$. The PRACH sequence indices ranges from 0, 1, 2, ..., 837, 838. These sequence indices also known as Logical Sequence ID.

There is a mapping from Logical Sequence ID to the actual sequence ID (u), which is given in table below.

Table 6.3.3.1-3: Mapping from *logical index* i to sequence number u for preamble formats with $L_{RA} = 839$.

i	Sequence number u in increasing order of i																			
0 – 19	129	710	140	699	120	719	210	629	168	671	84	755	105	734	93	746	70	769	60	779
20 – 39	2	837	1	838	56	783	112	727	148	691	80	759	42	797	40	799	35	804	73	766
40 – 59	146	693	31	808	28	811	30	809	27	812	29	810	24	815	48	791	68	771	74	765
60 – 79	178	661	136	703	86	753	78	761	43	796	39	800	20	819	21	818	95	744	202	637
80 – 99	190	649	181	658	137	702	125	714	151	688	217	622	128	711	142	697	122	717	203	636
100 – 119	118	721	110	729	89	750	103	736	61	778	55	784	15	824	14	825	12	827	23	816
120 – 139	34	805	37	802	46	793	207	632	179	660	145	694	130	709	223	616	228	611	227	612
140 – 159	132	707	133	706	143	696	135	704	161	678	201	638	173	666	106	733	83	756	91	748
160 – 179	66	773	53	786	10	829	9	830	7	832	8	831	16	823	47	792	64	775	57	782
180 – 199	104	735	101	738	108	731	208	631	184	655	197	642	191	648	121	718	141	698	149	690
200 – 219	216	623	218	621	152	687	144	695	134	705	138	701	199	640	162	677	176	663	119	720
220 – 239	158	681	164	675	174	665	171	668	170	669	87	752	169	670	88	751	107	732	81	758
240 – 259	82	757	100	739	98	741	71	768	59	780	65	774	50	789	49	790	26	813	17	822
260 – 279	13	826	6	833	5	834	33	806	51	788	75	764	99	740	96	743	97	742	166	673
280 – 299	172	667	175	664	187	652	163	676	185	654	200	639	114	725	189	650	115	724	194	645
300 – 319	195	644	192	647	182	657	157	682	156	683	211	628	154	685	123	716	139	700	212	627
⋮																				

Similarly, there is another table for PRACH short format sequence.

In this table, for logical index $i = 4$, the sequence number $u = 120$. So, the actual root sequence index is according to this table.

Now, for each root sequence index, there can be multiple sequences, based on cyclic shifts.

- Lets assume, the Cyclic shift size, $N_{cs} = 209$.

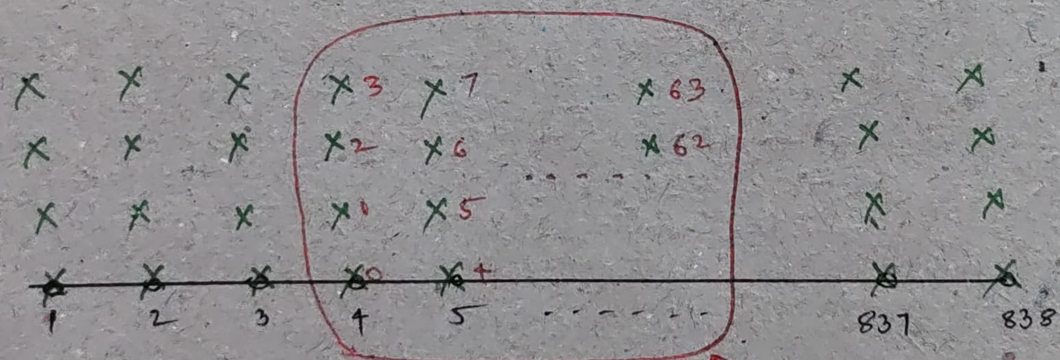
This Value is taken from Format 3 table, when $\Delta_f = 5$ KHz and $Z_c Z_c = 13$.

N_{cs} is Zero correlation zone size (ie) Shift size.

We have, total 839 different sequences.

So, $\left\lfloor \frac{839}{209} \right\rfloor = 4$ different cyclic shifts we can have.

So, for each root sequence index u, there can be 4 different cyclic shifts, when $N_{cs} = 209$.



So, we have, intotal $838 \times 4 = 3352$ different Preambles generated.

Now, UE is given with an starting root sequence index i, lets say $i = 4$. And, there can be 64 RACH preambles. So, UE picks the PRACH sequence with preamble ID 0 to 63. (as shown above)

Out of these 64 RACH preambles, UE pick one randomly, generates PRACH sequence, and transmits.

Lets understand, which is the impact of choosing Larger or Smaller cyclic shifts.

Properties of Z_c sequence.

① Two different sequences with different root sequence ID (say u_1 and u_2) have very low cross correlation. The normalized cross correlation is $\frac{1}{\sqrt{L_{RA}}}$.

② Two different sequences with different cyclic shifts (say C_{v_1} and C_{v_2}) are orthogonal.

In the previous example, we've assumed $N_{cs} = 209$, so we can generate 4 different cyclic shifts. 64 Preambles we need to generate; so, the root sequences that we need are $\frac{64}{4} = 16$.

	0	1	2	3
$i=4$	$v=0$	$v=1$	$v=2$	$v=3$

	4	5	6	7
$i=5$	$v=0$	$v=1$	$v=2$	$v=3$

...

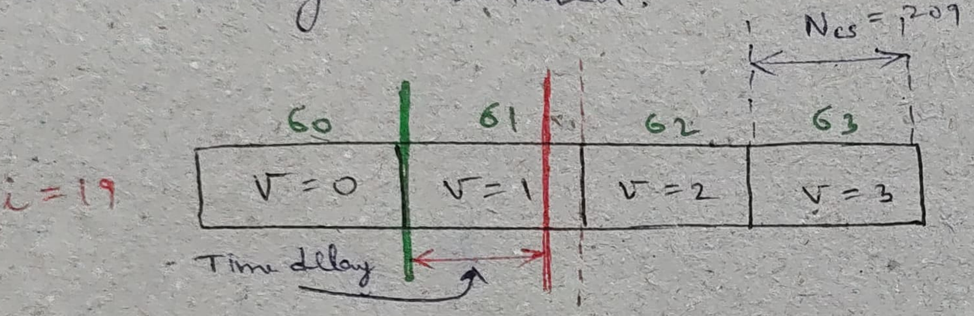
	60	61	62	63
$i=19$	$v=0$	$v=1$	$v=2$	$v=3$

$i \rightarrow$ root sequence index

$v \rightarrow$ cyclic shift index

Preamble ID

Now, at the receiver side, we dont know which preamble was transmitted. So, we try with each preamble and see where we get the highest correlation. There are different ways to correlate and do the peak search, to find out which Preamble was actually transmitted.



Lets say, Preamble ID 61 was transmitted. If there is no timing delay, then the peak will be here (Marked in Green), where we'll get the highest correlation (at the boundary).

But, because of timing delay, the peak wont be there, and it will be shifted here (Marked in Red), where the number of shifts depends on the timing delay. (ie) depends on how far the UE is from BS.

The dotted red line shows the maximum time delay that the receiver can support. (ie) the maximum distance of UE from gNB, which is nothing but the cell size.

If we decode the Preamble beyond the dotted red line (say on Preamble ID 62), meaning we are trying to decode wrong Preamble, and the decoding will fail.

The width (ie) $N_{cs} = 209$ in this example, decides the cell size. If we increase N_{cs} value, then the cell size increases. If we decrease N_{cs} value, then the cell size decreases.

$N_{cs} \rightarrow$ Zero correlation Zone size.

This is how the cyclic shift impacts the cell size, and we've to pick it appropriately (Precisely)

If the decrease N_{cs} value, the No. of cyclic shifts goes down, and the No. of Preambles that we generate will also reduce.

Lets understand Restricted and Unrestricted Set.

In 5G, we might have the situation where the UE Transmitter or BS Receiver Radio frequency is not well aligned. (ie) the Crystals are not working at the exact same frequency even though we configure it. Due to this, there is a frequency offset in transmitter and receiver.

Other reason for frequency offset is, UE moving at high speed.

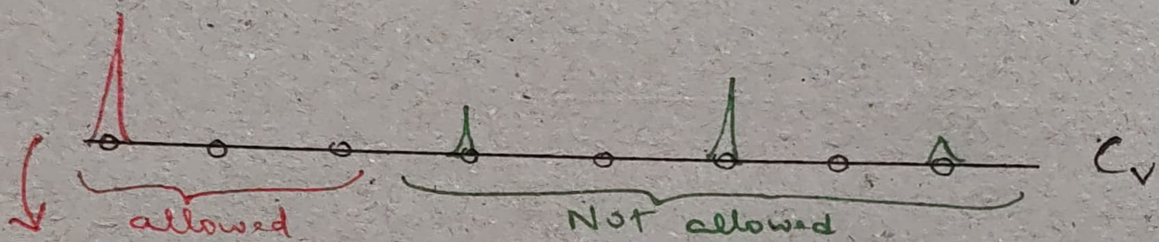
In both the cases, at the receiver end, we'll observe frequency offset.

WKT,

PRACH Long format have smaller SCS (1.25 KHz and 5 KHz). whereas PRACH short format have Larger SCS (15/30/60/120 KHz).

So, the frequency offsets will have higher impact on the PRACH long Format (which has smaller SCS). Let say the frequency offset is 600 Hz, and it has higher impact on 1.25 KHz and 5 KHz, not on 15/30/60/120 KHz.

What happens because of this Frequency offset?



Assume, this is where the correlation is supposed to be high and we supposed to get Peak. But, because of the frequency offset, as the energy gets distributed and we get peaks in different locations (green colored). So, we may decode False Preambles.

To overcome this, some of the N_{cs} values have been masked. (ie) we are only allowed to use certain cyclic shifts, not allowed to use other cyclic shifts, so that we can avoid false PRACH.

Table 6.3.3.1-5: N_{CS} for preamble formats with $\Delta f^{RA} = 1.25$ kHz. (Long Format)

zeroCorrelationZoneConfig	N_{CS} value		
	Unrestricted set	Restricted set type A	Restricted set type B
0	0	15	15
1	13	18	18
2	15	22	22
3	18	26	26
4	22	32	32
5	26	38	38
6	32	46	46
7	38	55	55
8	46	68	68
9	59	82	82
10	76	100	100
11	93	128	118
12	119	158	137
13	167	202	-
14	279	237	-
15	419	-	-

Table 6.3.3.1-6: N_{CS} for preamble formats with $\Delta f^{RA} = 5$ kHz. (Long Format)

zeroCorrelationZoneConfig	N_{CS} value		
	Unrestricted set	Restricted set type A	Restricted set type B
0	0	36	36
1	13	57	57
2	26	72	60
3	33	81	63
4	38	89	65
5	41	94	68
6	49	103	71
7	55	112	77
8	64	121	81
9	76	132	85
10	93	137	97
11	119	152	109
12	139	173	122
13	209	195	137
14	279	216	-
15	419	237	-

Table 6.3.3.1-7: N_{CS} for preamble formats with $\Delta f^{RA} = 15 \cdot 2^{\mu}$ kHz where $\mu \in \{0,1,2,3\}$.

(Short Format)

zeroCorrelationZoneConfig	N_{CS} value for unrestricted set
0	0
1	2
2	4
3	6
4	8
5	10
6	12
7	13
8	15
9	17
10	19
11	23
12	27
13	34
14	46
15	69

As we see, for SCS of 1.25 KHz and 5 KHz (PRACH Long Format), we have Restricted sets Type A and Type B, and Unrestricted Set.

For SCS of 15/30/60/120 KHz (PRACH Short Format), we have Only Unrestricted Set.

The Restricted Sets Type A and Type B is basically depends on the Mobility or Amount of Frequency Offset. So, the thumb rule is, if the Frequency offset is less than half of SCS, then we can use Unrestricted Sets. (ie)

Freq. Offset < 625 Hz (for $\Delta f = 1.25$ KHz)

Freq. Offset < 2.5 KHz (for $\Delta f = 5$ KHz)

And, if the Frequency offset is less than SCS (or) 2 * SCS, then we can use Restricted Sets.

And, if the Freq. offset < SCS, then use Type A.
if the Freq. offset < 2* SCS, then use Type B.

This is how three different sets are defined, (Type A, Type B and Unrestricted Sets) and we are supposed to use them based on the mobility.

- If UE is moving very high speed, use Type B.
- If UE is moving at high speed, use Type A.
- If UE is moving at medium speed, use Unrestricted Set.

And; these are mapped with "ZeroCorrelationZoneConfig", aka ZcZc parameter.

This is all about PRACH cyclic shift, Restricted Sets and Timing calculations.

PRACH : Long Formats

The word 'Long' is associated with time. So, compared to the Short Format, they are Longer in time.

Table 6.3.3.1-1: PRACH preamble formats for $L_{RA} = 839$ and $\Delta f^{RA} \in \{1.25, 5\}$ kHz.

Format	L_{RA}	Δf^{RA}	N_u	N_{CP}^{RA}	Support for restricted sets
0	839	1.25 kHz	24576κ	3168κ	Type A, Type B
1	839	1.25 kHz	$2 \cdot 24576\kappa$	21024κ	Type A, Type B
2	839	1.25 kHz	$4 \cdot 24576\kappa$	4688κ	Type A, Type B
3	839	5 kHz	$4 \cdot 6144\kappa$	3168κ	Type A, Type B

There are 4 PRACH Long formats (Format 0, 1, 2, 3), and their SCS is different from what we have in Shared channels and other channels (1.25 KHz and 5 KHz):

If we take a subcarrier with 1.25 KHz, its symbol time will be $\frac{1}{1.25\text{ KHz}}$ = 800 μs (or) 0.8 ms

If we take a subcarrier with 5 KHz, its symbol time will be $\frac{1}{5\text{ KHz}}$ = 200 μs (or) 0.2 ms.

So, 0.8 ms and 0.2 ms are PRACH symbol duration. If it is PUSCH 15 KHz SCS, then this 0.8 ms is quite larger than PUSCH OFDM symbol time.

The No. of samples (N_u) also represents the PRACH sequence time. Let us take 24576 K, where K is Kappa

$\Rightarrow (24576 \times 64)\ T_c$

$\Rightarrow 24576 \times 64 \times 0.509 \times 10^{-6}$ ms

$\Rightarrow 800$ μs

$\Rightarrow$ 0.8 ms. (Same as what we've calculated using SCS).

Similarly; the Cyclic Prefix time is also given in the Table. Let us take $\left(N_{CP}^{RA}\right) = 3168\,K$

$\Rightarrow 3168 \times 64 \times 0.509 \times 10^{-6}$ ms

$\Rightarrow 103\ \mu s$

≈ 0.1 ms

And, as we know, $L_{RA} = 839$, for PRACH long formats.

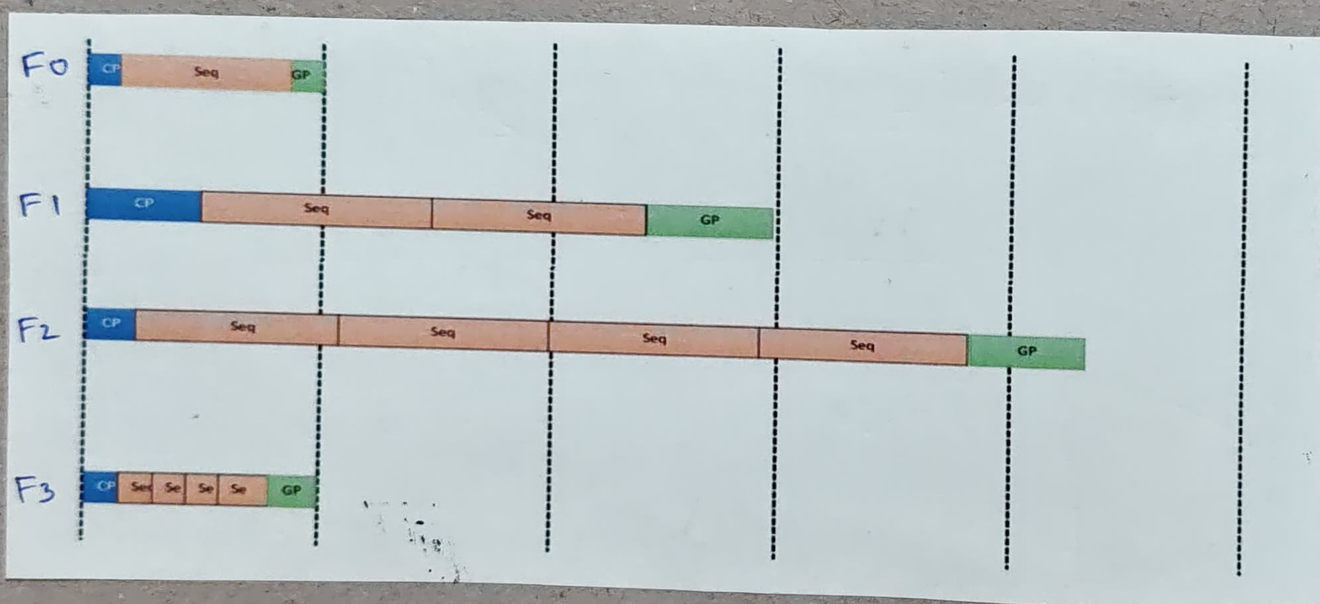


Figure illustrates the CP, Sequence and Guard Period (GP) for all the 4 different PRACH Long formats.

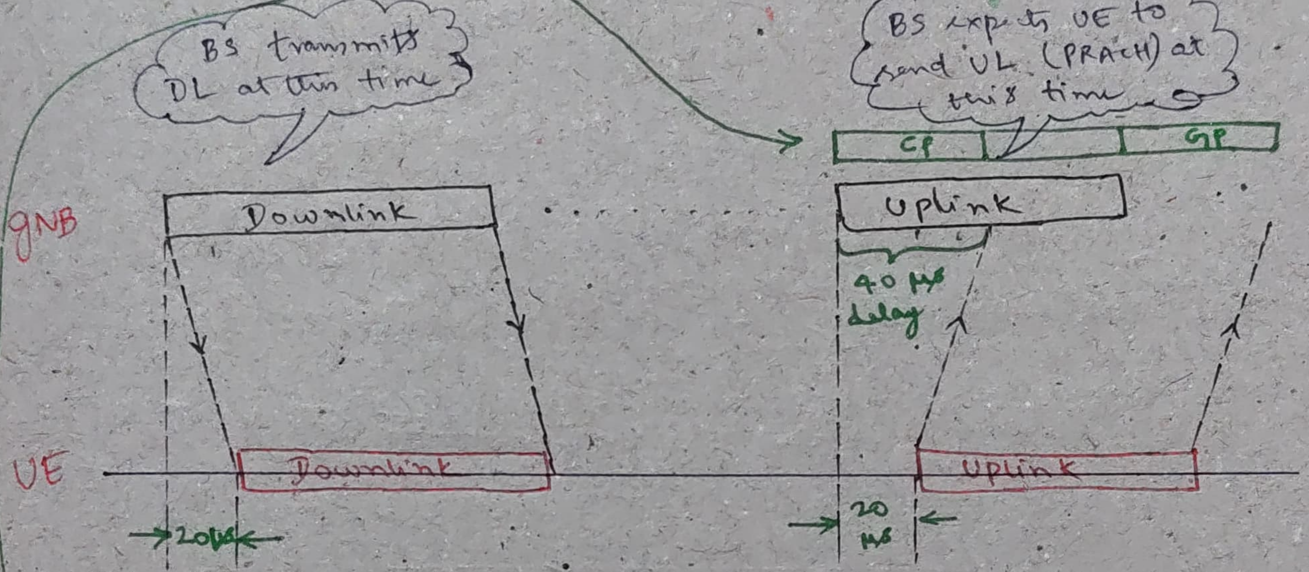
Guard Period (GP) is basically where we don't transmit anything.

CP decides the maximum cell radius.

The factors in (N_u) represents the No. of Sequences.

Format	N_u
0	24576 K
1	2·24576 K
2	4·24576 K
3	4·6144 K

CP decides the maximum cell range. So, CP should account for the propagation time in DL and UL both. When we send PRACH initially, UE doesn't know how far it is from the BS.



Lets say, it takes 20 μs for the DL signal to reach the UE. Now, the UE sends UL signal, which takes another 20 μs to reach gNB. Hence, the total round trip delay is 40 μs. (20 μs in DL and 20 μs in UL).

So, the CP should be designed in a way that, it takes care of Round Trip delay. And the Guard Period length should be similar to CP length. This ensures that, there is no ISI in PRACH.

This is how the CP lengths are designed. Longer the CP, longer is the cell radius.

The cell radius is calculated as follows.

$$\frac{(3 \times 10^{8}) \times \left[(\text{CP time}) - (\text{Delay spread})\right]}{2}$$

2 ← For Round trip.

So, for Format 0, the CP time is 103 μs, Delay spread is approximately 5 μs. So, the cell radius is calculated as

$$\frac{(3 \times 10^{8}) \times \left[(103 \times 10^{-6}) - (5 \times 10^{-6})\right]}{2} \approx 14.7 \text{ Km.}$$

Format	N_{CP}^{RA} (T_c)	N_{CP}^{RA} (s)	Cell Radius
0	3168 K	103 μs	14.7 Km.
1	21024 K	684 μs	100 Km
2	4688 K	152 μs	22 Km
3	3168 K	103 μs	14.7 Km.

Now, how do we pick which format to use, when we are using PRACH long format?

- Format 0 is mostly used for LTE like scenarios.
- Format 1 supports large cell size, since it has very large CP. say, if the cell size is beyond 20 or 30 Kms, then we should use Format 1.
- When we want to have better coverage, say we want to install a BS where the signal is not reaching all the points, then we can use Format 2, since

the cell radius is limited and the coverage is better, because of the repetition. Here, the signal repeats 4 times, meaning 6 dB gain at the receiver.

- Format 3 and Format 0 are similar, The difference is that, Format 0 has 1.25 KHz SCS whereas Format 3 has 5 KHz SCS. This higher SCS is ideal for high speed scenarios. So, when we have a deployment where we need to support PRACH for high speed moving UEs, we use Format 3 in such case.

---

other point to consider while picking the format is Overhead. Format 0 and Format 3 has 1 ms Overhead. Format 1 has 3 ms overhead. Format 2 has 4.3 ms overhead.

Another point to consider is the TDD pattern. As we see, in Format 0, we need 1 ms continuous UL slots. Whereas in Format 1, we need 3 ms.

If we use PUSCH with SCS 15 KHz, then we need 3 slots. And if we use PUSCH with SCS 30 KHz, then we need 6 slots (continuous UL slots) to use Format 1.

If we use PUSCH with SCS 30 KHZ, then we need 2 continuous UL slots to use Format 0.

These are the factors that we need to consider when we want to decide which Format to use.

Also, since the length of the sequence, $L_{RA} = 839$ for all the formats (Format 0, 1, 2, 3), and there are two variants of SCS (1.25 KHZ and 5 KHZ), the bandwidth that is being used for Formats 0, 1 and 2 is 1.25 KHZ × 839 = 1.048 MHZ.

Whereas, for Format 3, the Bandwidth is 5 KHZ × 839 = 4.195 MHZ.

These are the bandwidths that is being used.

PRACH : Short Formats

As the name implies, these PRACH formats are short in time. The sequence length, $L_{RA} = 139$. And the SCS followed by PRACH short Formats are 15/30/60/120 KHz.

15 KHz, 30 KHz $\longrightarrow$ FR1

60 KHz, 120 KHz $\longrightarrow$ FR2

Table 6.3.3.1-2: Preamble formats for $L_{RA} = 139$ and $\Delta f^{RA} = 15 \cdot 2^{\mu}$ kHz where $\mu \in \{0,1,2,3\}$.

Format	L_{RA}	Δf^{RA}	N_u	N_{CP}^{RA}	Support for restricted sets
A1	139	$15 \cdot 2^{\mu}$ kHz	$2 \cdot 2048\kappa \cdot 2^{-\mu}$	$288\kappa \cdot 2^{-\mu}$	-
A2	139	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$576\kappa \cdot 2^{-\mu}$	-
A3	139	$15 \cdot 2^{\mu}$ kHz	$6 \cdot 2048\kappa \cdot 2^{-\mu}$	$864\kappa \cdot 2^{-\mu}$	-
B1	139	$15 \cdot 2^{\mu}$ kHz	$2 \cdot 2048\kappa \cdot 2^{-\mu}$	$216\kappa \cdot 2^{-\mu}$	-
B2	139	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$360\kappa \cdot 2^{-\mu}$	-
B3	139	$15 \cdot 2^{\mu}$ kHz	$6 \cdot 2048\kappa \cdot 2^{-\mu}$	$504\kappa \cdot 2^{-\mu}$	-
B4	139	$15 \cdot 2^{\mu}$ kHz	$12 \cdot 2048\kappa \cdot 2^{-\mu}$	$936\kappa \cdot 2^{-\mu}$	-
C0	139	$15 \cdot 2^{\mu}$ kHz	$2048\kappa \cdot 2^{-\mu}$	$1240\kappa \cdot 2^{-\mu}$	-
C2	139	$15 \cdot 2^{\mu}$ kHz	$4 \cdot 2048\kappa \cdot 2^{-\mu}$	$2048\kappa \cdot 2^{-\mu}$	-

As given in table, we have 9 different PRACH short Formats (A1, A2, A3, B1, B2, B3, B4, C0, C2). All short formats have sequence length $L_{RA} = 139$.

The No. of samples (N_u) representing the PRACH short format sequence time, changes, but the base sequence length remains constant (ie) $2048K \cdot 2^{-\mu}$

And, we have cyclic Prefix length (N_{CP}^{RA}). For A1 and B1, it is very small. For A2, B2 and B3, it is bit higher. For A3 and B4, it is high. For C0 and C2, the CP length is very large. The CP length decides the cell radius or cell range.

For Format A1, cell radius is computed as follows.

$N_{CP}^{RA} = 288\,K \cdot 2^{-\mu}$ (considering SCS is 15 KHz)

$= 288 \times 64 \times 2^{0} \times 0.509 \times 10^{-6}$ ms

$= 9\,\mu s$.

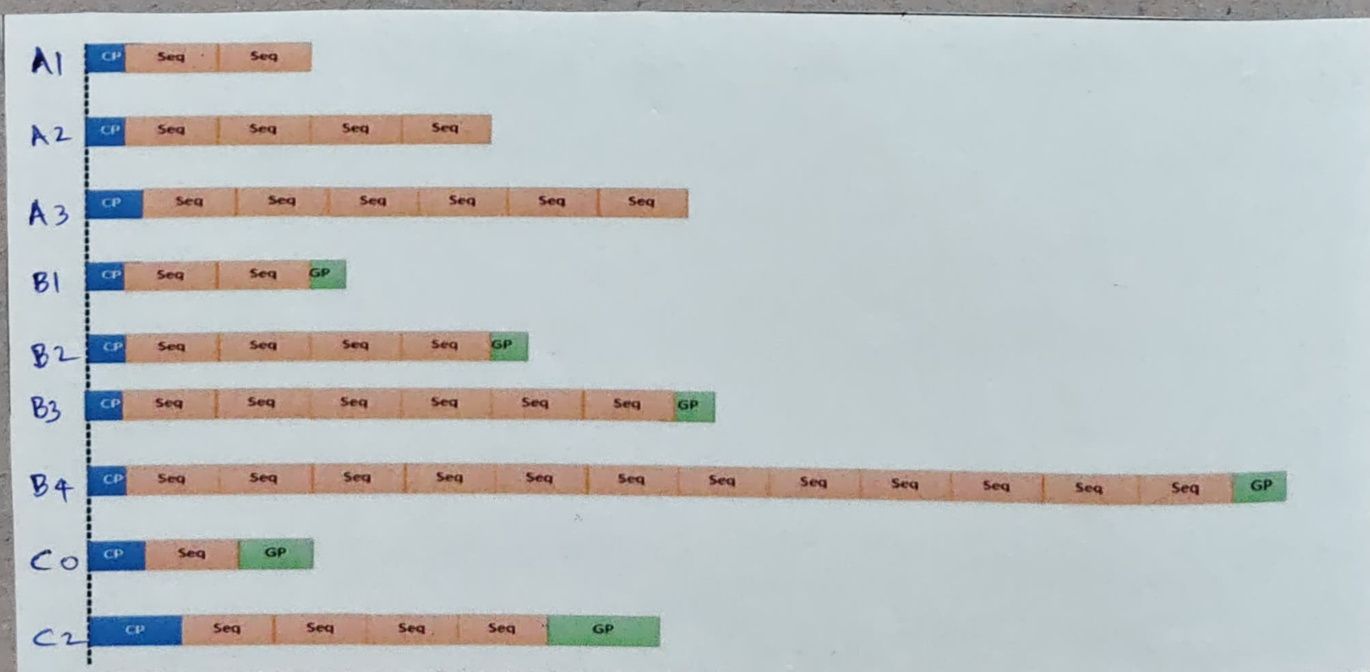
$$\text{cell radius} = \frac{(3\times10^{8}) \times [(9\times10^{-6}) - (3\times10^{-6})]}{2}$$

$$= 900 \text{ m}$$

Similarly, the cell radius for other Formats can be computed.

Format	Cell Radius
A1	900 m
A2	2 km
A3	3.5 km
B1	350 m
B2	1 km
B3	1.8 km
B4	4 km
C0	5 km
C2	10 km

So, based on the different use cases, different PRACH formats may be chosen. One of the criteria to select the PRACH format is the CP length or cell Radius.



The first 3 PRACH formats (A1, A2, A3) don't have the Guard Period (GP). This is because, these 3 PRACH formats always go with multiple RACH Occasions.
(ie) considering A1,

CP	Seq	Seq	CP	Seq	Seq	CP	Seq	Seq	...

Note: Format A1 always go with 6 RACH Occasions
Format A2 always go with 3 RACH Occasions
Format A3 always go with 2 RACH Occasions.

Formats B1, B2, B3, B4 have different CP lengths which implies different cell sizes. Also, each format has different No. of sequences (2, 4, 6, 12) respectively.

- Format B1 may be used either alone, or along with A1.

A1	B1

A1	A1	A1	B1

In this case, the cell radius is decided by the minimum among A1 and B1.

- Format B4 always goes alone
- Format B2 always go with A2
- Format B3 always go with A3

Formats C0 and C2 have large CP compared to all other formats. They also go with multiple RACH occasions.

The Sequence repetition in all the short Formats is used to increase the SNR.

For short Format, PRACH bandwidth depends on the SCS being used. (Assume SCS = 30 KHz)

$$\text{Bandwidth} = \text{SCS} \times L_{RA}$$

$$= 30 \text{ KHz} \times 139$$

$$= 4.32 \text{ MHz}$$

So, bandwidth varies as SCS changes.

PRACH : More on Resource Allocation & Scheduling

Lets understand PRACH time and frequency allocations (left over parameters)

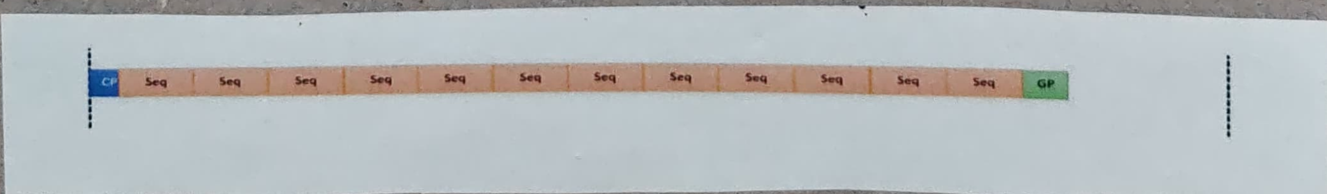
Table 6.3.3.2-3: Random access configurations for FR1 and unpaired spectrum.

PRACH Configuration Index	Preamble format	$n_{SFN} \bmod x = y$ (x)	(y)	Subframe number	Starting symbol	Number of PRACH slots within a subframe	$N_t^{RA,slot}$, number of time-domain PRACH occasions within a PRACH slot	N_{dur}^{RA}, PRACH duration
145	B4	16	1	9	0	2	1	12
146	B4	8	1	9	0	2	1	12
147	B4	4	1	9	2	1	1	12
148	B4	2	1	9	0	1	1	12
149	B4	2	1	9	2	1	1	12
150	B4	2	1	7,9	2	1	1	12
151	B4	2	1	4,9	2	1	1	12
152	B4	2	1	4,9	0	2	1	12
153	B4	2	1	8,9	0	2	1	12
154	B4	2	1	2,3,4,7,8,9	0	1	1	12
155	B4	1	0	1	0	1	1	12
156	B4	1	0	2	0	1	1	12
157	B4	1	0	4	0	1	1	12
158	B4	1	0	7	0	1	1	12
159	B4	1	0	9	0	1	1	12
160	B4	1	0	9	2	1	1	12
161	B4	1	0	9	0	2	1	12
162	B4	1	0	4,9	2	1	1	12
163	B4	1	0	7,9	2	1	1	12
164	B4	1	0	8,9	0	2	1	12
165	B4	1	0	3,4,8,9	2	1	1	12
166	B4	1	0	1,3,5,7,9	2	1	1	12
167	B4	1	0	0,1,2,3,4,5,6,7,8,9	0	2	1	12
168	B4	1	0	0,1,2,3,4,5,6,7,8,9	2	1	1	12

This particular table is for FR1 and Unpaired Spectrum. (There are couple of more tables as well). The PRACH Configuration index is what known to the UE, based on which the UE finds out

- Which PRACH format to use
- which Subframe, slot and Symbol
- How many RACH occasions to transmit.

Lets take an example. In this table, we picked PRACH format B4.



CP length, $N_{CP}^{RA} = 936\,K \cdot 2^{-\mu}$

All Seq. length, $N_u = 12 \cdot 2048\, \kappa \cdot 2^{-\mu}$

This is the Format B4, when there are 12 Sequences, a CP and a Guard period (GP).

Now, lets take PRACH configuration index 158.
There is a parameter which says

(1) $n_{SFN} \bmod x = y$

$\Rightarrow n_{SFN} \,\%\, x = y$.

Here $x = 1$, $y = 0$

$\Rightarrow n_{SFN} \,\%\, 1 = 0$

Which means, In <u>every frame</u>, B4 will be transmitted. (ie) what ever n_{SFN} be $(0, 1, 2, \cdots)$, mod with 1 will always be zero. So, we can transmit PRACH in every frame.

(2) Next column is Sub frame number. (ie) Inside the frame; in which Sub frame we are supposed to transmit. Assuming 30 KHZ SCS being used for PRACH, we have two Slots in a SF. So, Sub Frame No. 7 implies slot numbers 14 and 15.

(3) Start Symbol = 0.

(4) No. of <u>PRACH slots</u> within a SF = 1

if (SCS = 30 KHz (or) 120 KHz)

No. of PRACH slots within a SF = 1

else

No. of PRACH slots within a SF = 2.

So, in this case, PRACH will be transmitted on slot No. 15 only.

(5) No. of Time domain PRACH occasions within a PRACH slot $\}$ = 1.

Since, for B4, we only have single PRACH occasion, that can fit into a slot.

(6) PRACH duration (N_{dur}^{RA}) = 12 OFDM Symbols.

(i) it takes 12 OFDM symbols for complete PRACH transmission.

Note that, the Guard Period (GP) is never mentioned anywhere in the specification. It is calculated based on the PRACH duration. Lets calculate.

WKT, CP duration $= 936 \times K \times 2^{-\mu}$

$$= \frac{936 \times 64 \times 0.509 \times 10^{-6} \text{ ms}}{2}$$

$= 15.246\ \mu s$.

Seq. duration $= 12 \times 2048 \times K \times 2^{-\mu}$

$$= \frac{12 \times 2048 \times 64 \times 0.509 \times 10^{-6} \text{ ms}}{2}$$

$= 400.294\ \mu s$.

CP duration + Seq. duration $= 15.246\ \mu s + 400.294\ \mu s$

$= 415.54\ \mu s$.

We have, PRACH duration = 12 OFDM symbols

So, No. of samples in first 12 OFDM symbols $\}$ $= (320 + 4096) + (288 + 4096) \times 11$

$= 52640$ samples.

Total No. of Samples in 1 Slot = 61440 = 0.5 ms
(For 30 KHz SCS, Slot duration is 0.5 ms)
(Bandwidth is 100 MHz, so we've taken 4096 samples after IFFT)

61440 samples → 0.5 ms

52640 samples → $\frac{52640}{61440} \times 0.5$ ms
(12 OFDM symbols)

$= 428.38\ \mu s$

This is the time taken by 12 OFDM Symbols.

Since, PRACH is aligned with the Symbol boundary (start and end), so the PRACH has to end at 428.38 μs.

(CP + Seq) duration = 415.54 μs.

So, the remaining time will be the 'Guard Period.

(ie) GP = 428.34 μs − 415.54 μs

= 12.85 μs

This is all about understanding the table.

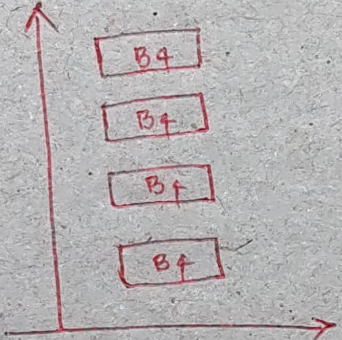
Now, there is Frequency domain PRACH allocation as well, that we need to understand.

There is a parameter called "msg1-FDM", that tells, how many PRACH allocations in Frequency domain at the same time allocation. (ie) No. of PRACH occasions in Frequency at the same time.

We've just seen different PRACH occasions in time domain. Now, lets see in frequency domain.

"msg1-FDM" = 1/2/4/8

Assume, msg1-FDM = 4, then there will be 4 occasions in frequency.

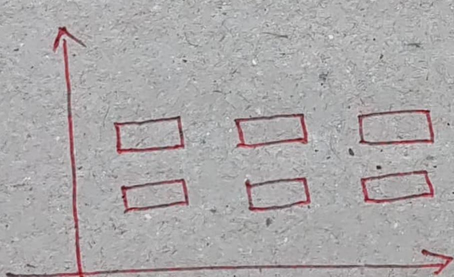


→ 4 PRACH Occasions

If msg1-FDM = 2, and

No. of Time domain PRACH occasions within a PRACH slot, $N_t^{RA,slot}$ } = 3.

→ 6 PRACH Occasions



This is how the PRACH allocation in Time and Frequency.

Now, these RACH allocations has association with the transmitted SSB, which is given by another parameter called "ssb-perRACH-OccasionAndCB-PreamblesPerSSB".

This seems like a single parameter, but there are two parameters. Lets understand both of them separately.

```
ssb-perRACH-OccasionAndCB-PreamblesPerSSB   CHOICE {
    oneEighth      ENUMERATED {n4,n8,n12,n16,n20,n24,n28,n32,n36,n40,n44,n48,n52,n56,n60,n64},
    oneFourth      ENUMERATED {n4,n8,n12,n16,n20,n24,n28,n32,n36,n40,n44,n48,n52,n56,n60,n64},
    oneHalf        ENUMERATED {n4,n8,n12,n16,n20,n24,n28,n32,n36,n40,n44,n48,n52,n56,n60,n64},
    one            ENUMERATED {n4,n8,n12,n16,n20,n24,n28,n32,n36,n40,n44,n48,n52,n56,n60,n64},
    two            ENUMERATED {n4,n8,n12,n16,n20,n24,n28,n32},
    four           INTEGER (1..16),
    eight          INTEGER (1..8),
    sixteen        INTEGER (1..4)
}
```

We'll first see "ssb-per-RACH-Occasion". As the name implies, it says the No. of SSBs per PRACH occasion. This parameter can take the following values:

$$\text{ssb-per-RACH-Occasion} = \frac{1}{8}, \frac{1}{4}, \frac{1}{2}, 1, 2, 4, 8, 16$$

where, $\frac{1}{8}$ → One SSB going over 8 RACH occasions

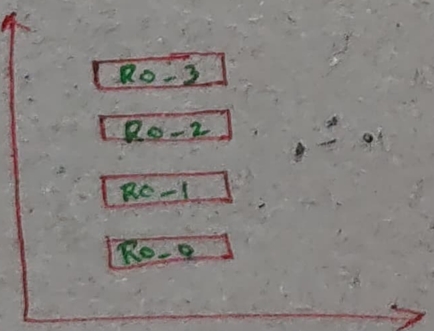
1 → One SSB per RACH occasion

16 → 16 SSBs per RACH occasion

Lets say, in FR1, we have maximum 4 and 8 SSBs. We assume, we have 8 SSBs, and

msg1-FDM = 4

ssb-per-RACH-occasion = 2



RO → Rach occasion

Here, we have 4 PRACH occasions, and each PRACH occasion will has two SSB.

(SSB 0 and SSB 1) in RO-0

(SSB 2 and SSB 3) in RO-1

(SSB 4 and SSB 5) in RO-2

(SSB 6 and SSB 7) in RO-3

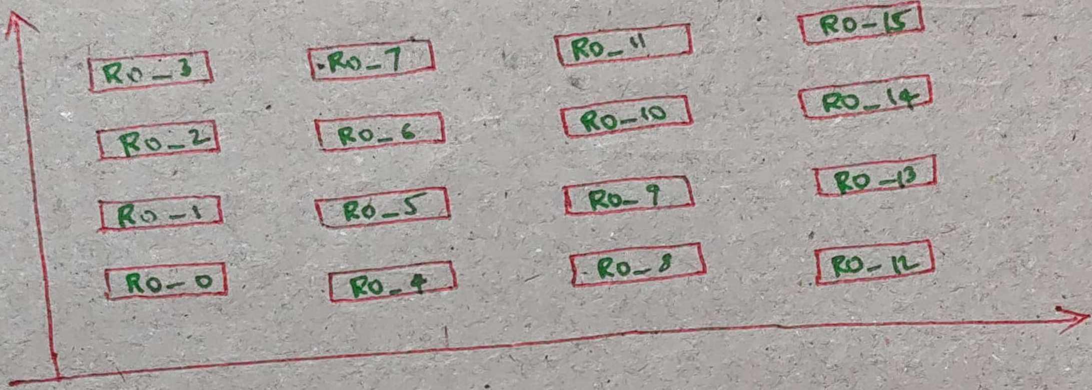
Lets take another example where, we have,

8 SSBs ;

ssb - per - RACH - occasion = $\frac{1}{2}$

(i) One SSB going over 2 RACH occasions.

msg1 - FDM = 4.



Here, we have 16 PRACH occasions, and 2 PRACH occasions will have single SSB.

(RO_0 and RO_1) associated with SSB 0

(RO_2 and RO_3) associated with SSB 1

(RO_4 and RO_5) associated with SSB 2

(RO_6 and RO_7) associated with SSB 3

(RO_8 and RO_9) associated with SSB 4

(RO_10 and RO_11) associated with SSB 5

(RO_12 and RO_13) associated with SSB 6

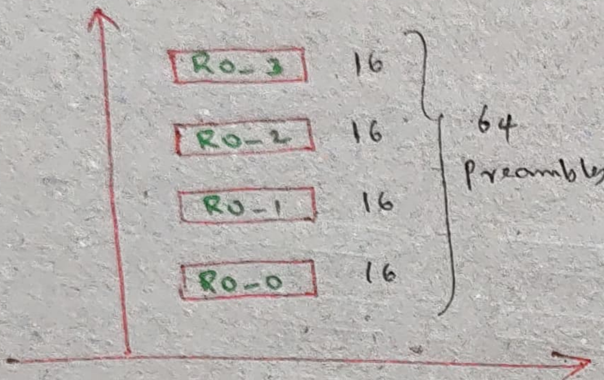
(RO_14 and RO_15) associated with SSB 7

Lets now see "CB - Preambles Per SSB" (i) contention based preambles per SSB. As we know, the maximum no. of preambles is 64. This parameter takes the values as shown in ASN-1. (i)

It ssb-per-RACH-occasion is $\frac{1}{8}$ or $\frac{1}{4}$ or $\frac{1}{2}$ or 1, CB-Preambles Per SSB takes values upto n64. Similarly, if it is 2, it takes upto n32. For 4, it takes upto n16. For 8, it takes upto n8. And For 16, it takes upto n4.

Lets take our previous example. where

msg1-FDM = 4,
No. of SSBs = 8,
ssb-perRACH-Occasion = 2

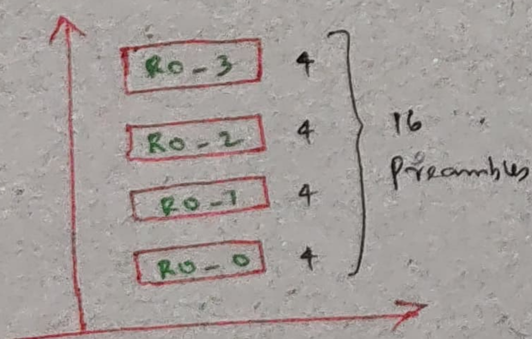


If No. of Preambles per SSB (i) CB-PreamblesPerSSB = 16,
(ii) ssb-perRACH-Occasion And CB-PreamblesPerSSB CHoice {
two. ENUMERATED { n16 }
}

So, Each Rach occasion will have 16 Preambles, and in total, there are 64 preambles.

- Single RACH occasion will have 16 contention based Preambles.

If CB-PreamblesPerSSB = 4, then we will have 4 preambles per Rach occasion and in total, there'll be 16 preambles.



This is how the Preambles are mapped with RACH occasions.

PRACH : Receiver Processing

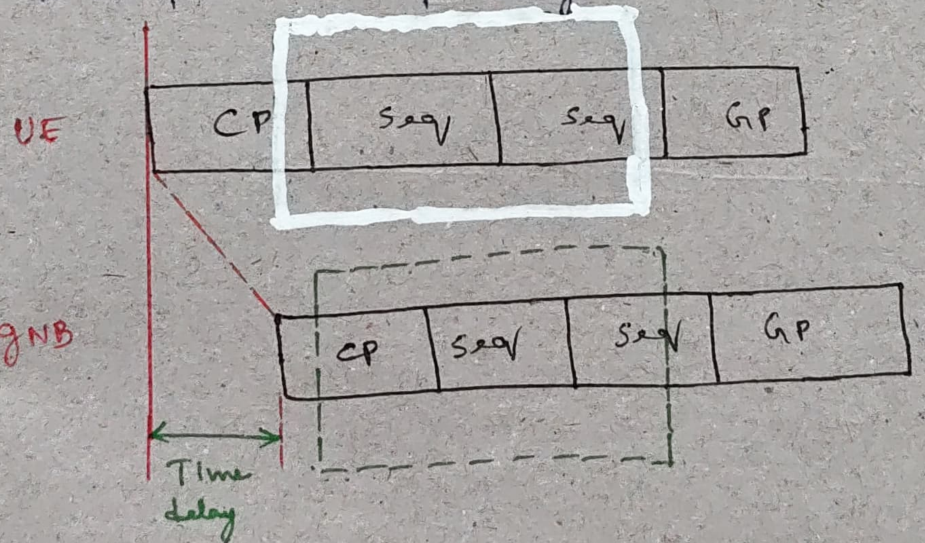
Lets understand, what happens at gNB side, when a UE or multiple UEs transmit PRACH.

Lets take a PRACH sequence.

CP	Seq	Seq	GP

This is how normally a PRACH sequence looks like. We may have different CP lengths, different no. of repetition of Seq., different time durations of the Seq., based on the SCS. But in general, this is how the PRACH sequence looks like.

The PRACH processing at the receiver is different from other channels. One of the reason is that, PRACH SCS may not be same as the data channels. So, it has to be processed separately.



The sequence could be delayed at the receiver (gNB). At the receiver, the CP is removed and the Seq. part alone extracted, as shown above.

Though, the extraction of Seq. is incorrectly done, it is fine, since CP is the last part of the Seq. So, gNB has all the samples of Seq.

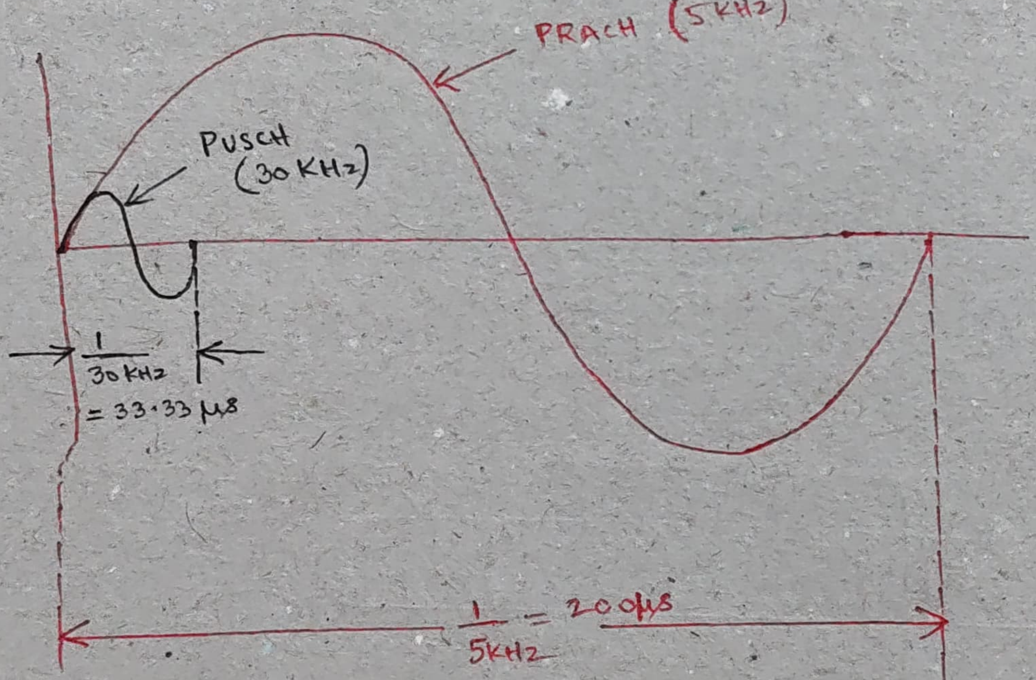
After extracting the seq, gNB (receiver) down sample it. How ?

Lets consider, for example, where PRACH and PUSCH are transmitted with different SCS.

PRACH (configured with Format 3) – 5 KHZ

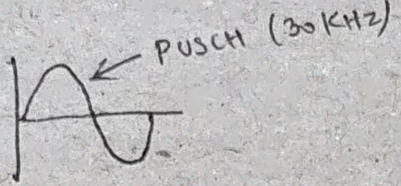
PUSCH – 30 KHZ

System Bandwidth = 100 MHZ.



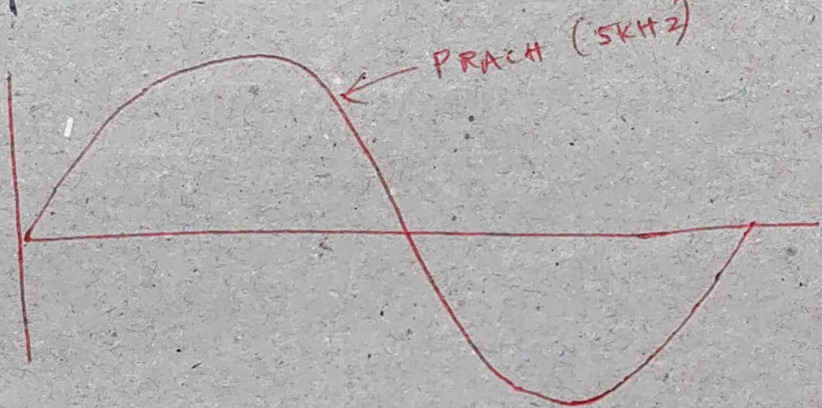
⊙ PUSCH is sampled at 122.88 Msps.

* SCS, $\Delta f = 15 \times 2^{\mu}$ KHz = 30 KHz
* BW = 100 MHz = 273 PRBs = 273 × 12 Sub carriers
  = 3276 Subcarriers
* FFT size must be a power of 2, large enough to cover 3276 subcarriers. So, $N_{FFT} = 4096$.
* Sampling Rate, $f_s = N_{FFT} \times \Delta f$
  $= 4096 \times 30$ KHz
  = 122.880 Msps.



* So, in PUSCH, one cycle has 4096 samples.

6. As we know, for PRACH (Format 3), the No. of samples = 839.



* But, the No. of samples that we received here is 4096 × 6 = 24,576 samples.

(i) $4096 \times \left(\frac{200\ \mu s}{33.33\ \mu s}\right) = 24{,}576$ samples

(ii) $4096 \times \left(\frac{30\ KHz}{5\ KHz}\right) = 24{,}576$ samples.

* So, we need to do Decimation (down sampling) from 24,576 samples to 839 samples.

Next step is, convert the down sampling output (839 samples) into frequency domain. How?

By taking FFT.

Remember, in the transmitter, we do IFFT for the OFDM conversion.

Now, we have the received signal in frequency domain of length L_{RA} (Sequence length).

The receiver generates locally, the base sequence (ZC sequence) in time domain, for different root sequences, convert it to frequency domain.

Since, both the Received signal and the locally generated signal are in frequency domain, the receiver correlates the base sequence generated for each u with the received signal.

Since, the receiver don't know which Preamble is transmitted by the UE or how many UE's have transmitted Preamble in that RACH occasion, the receiver needs to find this out.

So far, what the receiver does is, it has taken the received signal (it doesn't know the cyclic shift, u being used), it has taken the base sequence, correlate them for each u, and taken the output for each root sequence (u). (ie) Correlated output.

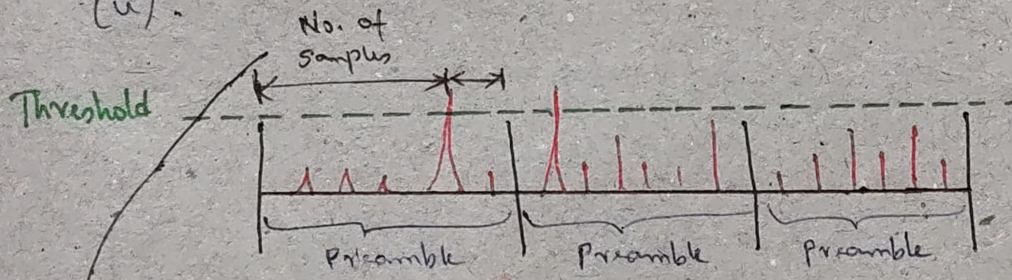
Now, the receiver takes IFFT (correlated output sequence is of length 839/139. So, it may take any larger IFFT (1024/512/256 point IFFT)), and convert it to Time domain, for all the root sequence (u). This IFFT is done for each repetition also.

CP	Seq.	Seq	GP

In case of multiple antennas, the receiver combines all the energies, and then average it.

Now, after summing up the correlation outputs, or the energies, the receiver divides this output into different bins, based on the number of cyclic shifts being used.

Lets say, there were 3 cyclic shifts. So, whatever the output length (1024/512/256), the receiver divides them into 3 parts for each root sequence (u).



And, in each bin, the receiver finds whether there is a peak. We see that, there are 2 values that are above threshold. (i.e) Two Preambles are detected which are above the Threshold.

Now, the No. of samples will be counted, to convert the delay into Timing Advance (TA). (i.e) Convert the sample delay into Timing Advance (TA). How? By considering the IFFT factors. Lets say we've taken 1024 point IFFT while down sampling output is converted to frequency domain. And, the received PRACH has 4096 samples per cycle (4096 point IFFT).

Lets say, the Sample delay = 10, then

$$TA = \underbrace{10 \times \left(\frac{4096}{1024}\right)}_{\text{No. of Samples}} \times (\text{Each sample Time})$$

This is how, the receiver finds the Peak and detect a Preamble.