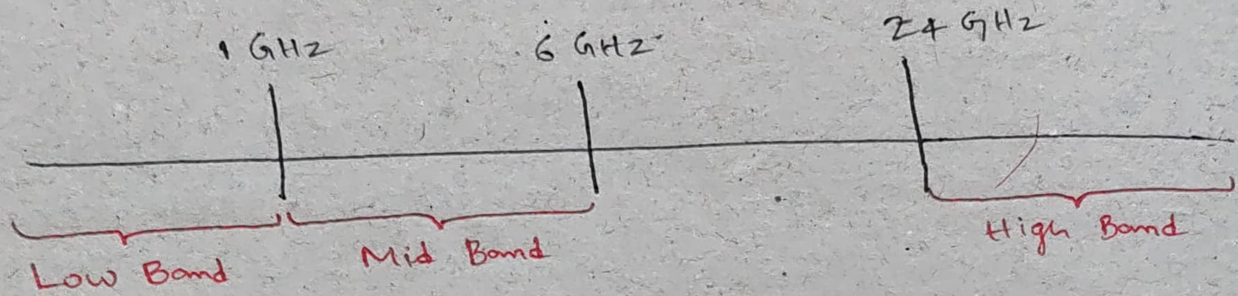
NR operating bands, Bandwidth, SDL and SUL

In 5G, the frequency bands are categorized as below.



Low Band :

- Signal travels far distance (Higher coverage)
- But the problem is, there exists very less number of freely available bands.

High Band :

- Signal travels shorter distance (Lower coverage)
- But the good part is, most of the bands are available for use.

Mid Band :

- There is trade-off between coverage and frequencies available.
- Most 5G operators are interested in these bands. Most deployments happens in this band. (around 3 GHz)

The 5G Bands are defined in Specification as below.

FR1 bands – n1, n2, . . . , n86.

FR2 bands – n257, n258, n260, n261

For each band, there is a frequency range associated.

Table 5.2-1: NR operating bands in FR1

NR operating band	Uplink (UL) operating band BS receive / UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating band BS transmit / UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
n2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
n3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
n5	824 MHz – 849 MHz	869 MHz – 894 MHz	FDD
n7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
n8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
n12	699 MHz – 716 MHz	729 MHz – 746 MHz	FDD
n20	832 MHz – 862 MHz	791 MHz – 821 MHz	FDD
n25	1850 MHz – 1915 MHz	1930 MHz – 1995 MHz	FDD
n28	703 MHz – 748 MHz	758 MHz – 803 MHz	FDD
n34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
n38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
n39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
n40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD
n41	2496 MHz – 2690 MHz	2496 MHz – 2690 MHz	TDD
n50	1432 MHz – 1517 MHz	1432 MHz – 1517 MHz	TDD[1]
n51	1427 MHz – 1432 MHz	1427 MHz – 1432 MHz	TDD
n66	1710 MHz – 1780 MHz	2110 MHz – 2200 MHz	FDD
n70	1695 MHz – 1710 MHz	1995 MHz – 2020 MHz	FDD
n71	663 MHz – 698 MHz	617 MHz – 652 MHz	FDD
n74	1427 MHz – 1470 MHz	1475 MHz – 1518 MHz	FDD
n75	N/A	1432 MHz – 1517 MHz	SDL
n76	N/A	1427 MHz – 1432 MHz	SDL
n77	3300 MHz – 4200 MHz	3300 MHz – 4200 MHz	TDD
n78	3300 MHz – 3800 MHz	3300 MHz – 3800 MHz	TDD
n79	4400 MHz – 5000 MHz	4400 MHz – 5000 MHz	TDD
n80	1710 MHz – 1785 MHz	N/A	SUL
n81	880 MHz – 915 MHz	N/A	SUL
n82	832 MHz – 862 MHz	N/A	SUL
n83	703 MHz – 748 MHz	N/A	SUL
n84	1920 MHz – 1980 MHz	N/A	SUL
n86	1710 MHz – 1780 MHz	N/A	SUL

NOTE 1: UE that complies with the NR Band n50 minimum requirements in this specification shall also comply with the NR Band n51 minimum requirements.
NOTE 2: UE that complies with the NR Band n75 minimum requirements in this specification shall also comply with the NR Band n76 minimum requirements.

4 different duplex modes (FDD/TDD/SDL/SUL)

n78 – widely used NR operating band.

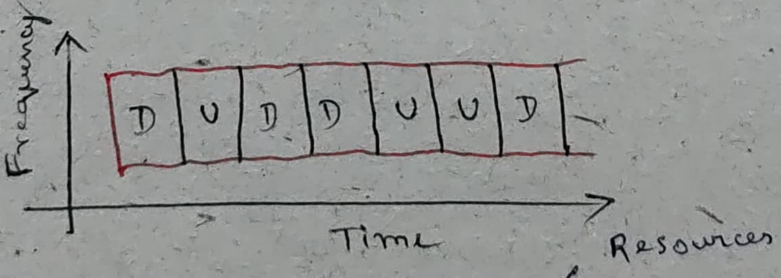
Table 5.2-1: NR operating bands in FR2

Operating Band	Uplink (UL) operating band BS receive UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating band BS transmit UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
n257	26500 MHz – 29500 MHz	26500 MHz – 29500 MHz	TDD
n258	24250 MHz – 27500 MHz	24250 MHz – 27500 MHz	TDD
n260	37000 MHz – 40000 MHz	37000 MHz – 40000 MHz	TDD
n261	27500 MHz – 28350 MHz	27500 MHz – 28350 MHz	TDD

Eg: For n1 band, there is an Uplink frequency and a downlink frequency.
UL frequency has range from 1920 MHz to 1980 MHz.
DL frequency has range from 2110 MHz to 2170 MHz.
And, it is a FDD band.

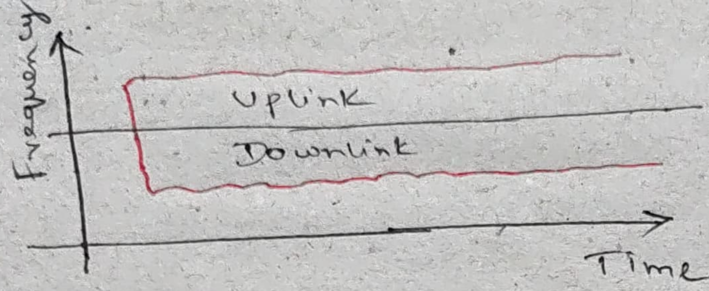
There are 4 different duplex modes specified here.

(i) TDD (Time Division Duplexing)



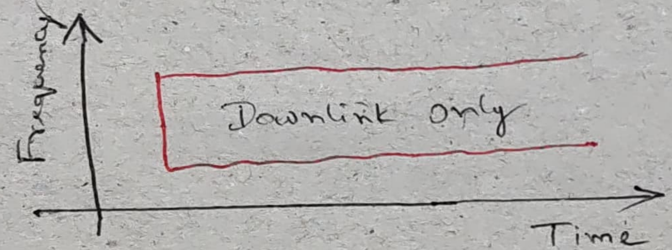
- In TDD, we divide the (DL and UL) in Time.
- Both DL and UL takes same frequency, but at different time.

(ii) FDD (Frequency Division Duplexing)

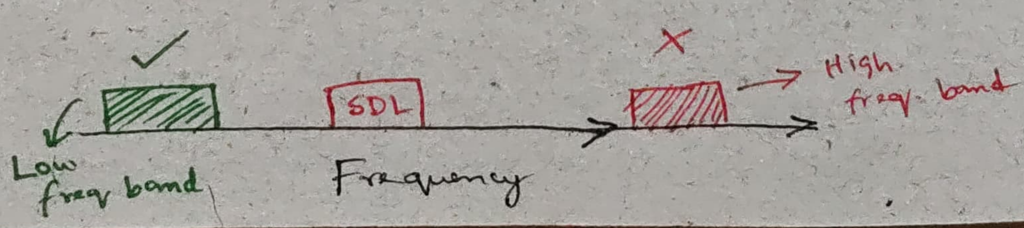


- In FDD, we divide the resources (UL and DL) in frequency.
- Both DL and UL happens at the same time, but at different frequencies.

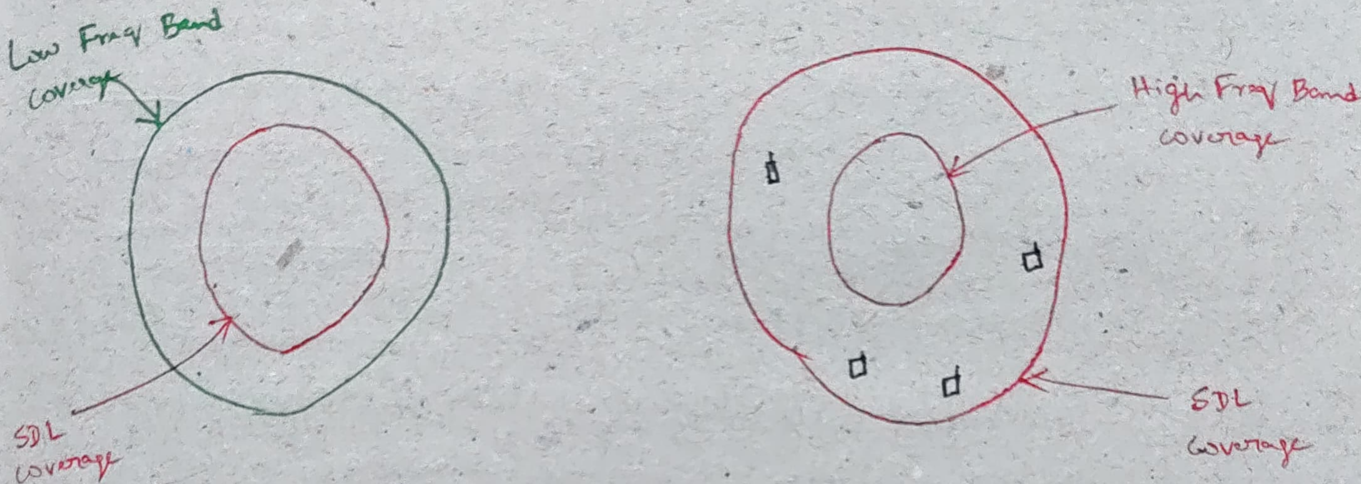
(iii) SDL (Supplementary Downlink)



- SDL is not so commonly used.
- In SDL, there is only DL. No UL neither in frequency nor in time.
- Main purpose of SDL is that, it is used to improve the DL data rate in low frequency bands.
- Mainly, the SDL bands are paired with low frequencies (say 1 GHz). So, if the DL data rate requirement is high, then we aggregate both the SDL and low frequency band, to increase the DL data rate.



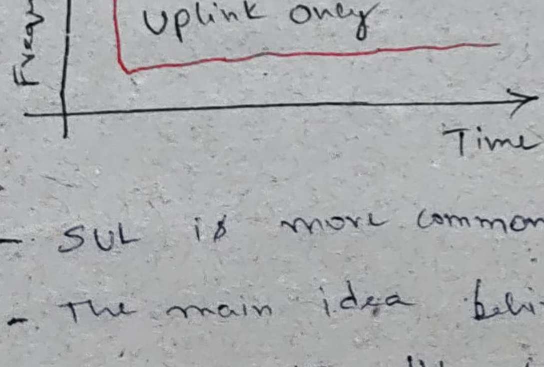
- Since the SDL is higher in frequency compared to the Low frequency band, its coverage is less. So, SDL cannot be paired with High frequency band.



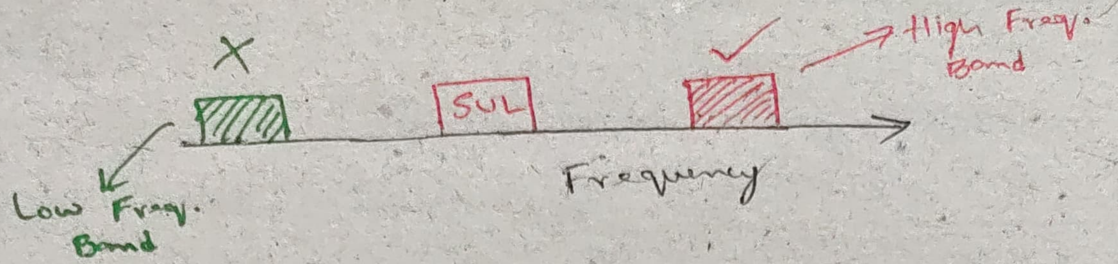
(a) ✓ (b) ✗

because, the UE's specified in Fig (b) only get the DL signal, but wont be able to do UL ACK/NACK transmission. So, SDL bands are always aggregated with the Low freq Bands.

(iv) SUL (supplementary Uplink)



- SUL is more commonly used than SDL.
- The main idea behind SUL bands is to increase the UL coverage.
- SUL is used with the high frequency bands.
- Normally, the UE has limitations in UL power, because they are operated on battery and the UL transmit power is lot lower than the DL transmit power.



- So, to increase the UL coverage, we have SUL for UEs to transmit UL on a different frequency. So, the SUL is paired with high frequency band to increase the UL coverage.

- gNB signals UE through DCI. (i) gNB may ask UE to use SUL, when the signal quality is very poor. and UE can choose to transmit signal on SUL.

Table 5.3.2-1: Maximum transmission bandwidth configuration N_{RB}

FR1

SCS (kHz)	5MHz	10MHz	15MHz	20 MHz	25 MHz	30 MHz	40 MHz	50MHz	60 MHz	80 MHz	90 MHz	100 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}	N_{RB}
15	25	52	79	106	133	160	216	270	N/A	N/A	N/A	N/A
30	11	24	38	51	65	78	106	133	162	217	245	273
60	N/A	11	18	24	31	38	51	65	79	107	121	135

Table 5.3.2-1: Maximum transmission bandwidth configuration N_{RB}

FR2

SCS (kHz)	50 MHz	100 MHz	200 MHz	400 MHz
	N_{RB}	N_{RB}	N_{RB}	N_{RB}
60	66	132	264	N.A
120	32	66	132	264

3GPP have defined, for a particular SCS, what are the number of PRBs allocated, for different Bandwidth configuration.

Lets take a case where SCS = 30 KHz and 100 MHz BW.

As per the above table, there exists 273 PRBs for this case.

$\Rightarrow$ 273 PRBs $\times$ 12 Sub carriers $\times$ 30 KHz SCS

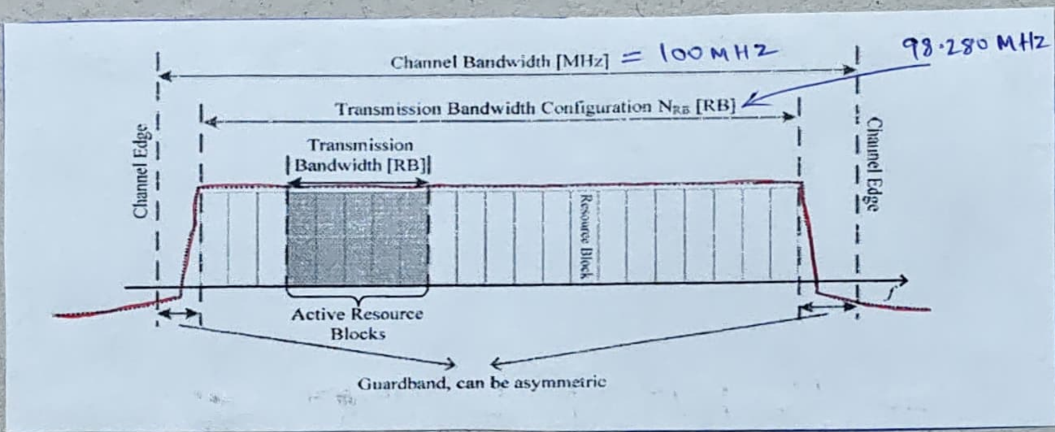
= 98.280 MHz.

Inference : Though the table specifies 100 MHz bandwidth, we don't use the full band to transmit the signals. We always leave guard bands both left and right.

The bandwidth that we use for signal transmission is 98.280 MHz only, where the full BW is 100 MHz.

Thus, Guard band = 100 - 98.280 = 1.720 MHz.

This Guardband may or may not be equal on both sides.



If the Guards are equal, then it can be 0.860 MHz. But it can be unequal as well.

3GPP have also defined, what are the different bandwidths that can be used in a particular NR band. For example, let's take n78 band, which has 3 different subcarrier spacings. (15 KHz, 30 KHz and 60 KHz).

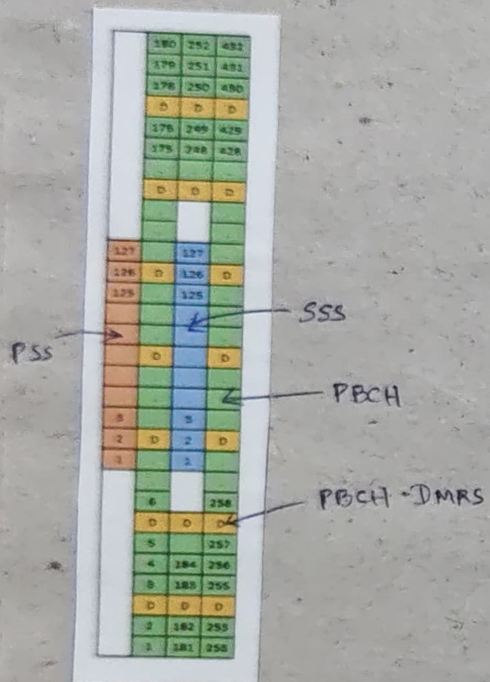
The table says, UE channel Bandwidth (i.e) UEs are supposed to support these channel bandwidths.

For n78, with 15 KHz SCS, UE supports 10/15/20/40/50 MHz bandwidth. With 30 KHz SCS, UE supports 10/15/20/40/50/60/80/90/100 MHz bandwidth. And with 60 KHz SCS, UE supports 10/15/20/40/50/60/80/90/100 MHz.

	NR band / SCS / UE Channel bandwidth												
NR Band	SCS kHz	5 MHz	10[1,2] MHz	15[2] MHz	20[2] MHz	25[2] MHz	30 MHz	40 MHz	50 MHz	60 MHz	80 MHz	90 MHz	100 MHz
n71	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n74	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n75	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n76	15	Yes											
	30												
	60												
n77	15		Yes	Yes	Yes			Yes	Yes				
	30		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes[4]	Yes
	60		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes[4]	Yes
n78	15		Yes	Yes	Yes			Yes	Yes				
	30		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes[4]	Yes
	60		Yes	Yes	Yes			Yes	Yes	Yes	Yes	Yes[4]	Yes
n79	15							Yes	Yes				
	30							Yes	Yes	Yes	Yes		Yes
	60							Yes	Yes	Yes	Yes		Yes
n80	15	Yes	Yes	Yes	Yes	Yes	Yes						
	30		Yes	Yes	Yes	Yes	Yes						
	60		Yes	Yes	Yes	Yes	Yes						
n81	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n82	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n83	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60												
n84	15	Yes	Yes	Yes	Yes								
	30		Yes	Yes	Yes								
	60		Yes	Yes	Yes								
n86	15	Yes	Yes	Yes	Yes			Yes					
	30		Yes	Yes	Yes			Yes					
	60		Yes	Yes	Yes			Yes					

RSRP (Reference Signal Received Power)

- As the name says, it is the received power on the Reference signals.
- This is calculated at the UE side from the SSS signal transmitted by the gNB.



SS-Burst

- Two different RSRP.
  - (i) SS-RSRP (calculated from SSS)
  - (ii) CSI-RSRP (calculated from CSI-RS Reference signals)

- RSRP tells the received power on particular REs.

- RSRP does not account for interference / noise, it just tells what is the received power on the given REs.

- SS-RSRP
  - ⊙ There are 127 SSS REs
  - ⊙ UE reads the received power of each SSS RE and then average them on linear scale. (i.e) the computed received powers of each SSS REs are averaged on Watt, not in dB.
  - ⊙ Lets say, the received power of SSS REs are $x_1, x_2, x_3, \ldots, x_{127}$. Then

$$RSRP = \left(\frac{x_1 + x_2 + \ldots + x_{127}}{127}\right) \text{Watt}$$

We later convert the RSRP to dBm.

- For FR1, we dont combine the Antenna Elements. So UE calculates RSRP from the Antenna Connector.

- Whereas in FR2, we assume many Antenna Elements are connected. So, UE calculates RSRP by combining signal strength from all Antenna Elements.

- The range of RSRP is from -44 dBm (highest) to -140 dBm.

- Highest power UE is expected to receive is -20 dBm.
  Highest RSRP is $-20 - 10\log_{10}(240 \text{ subcarriers})$
  $= -44$ dBm.

- Refer the screenshot captured from phone, showing RSRP / SINR / RSRQ

- If RSRP > -80, then it is good RSRP.
  If RSRP < -100, then it is poor RSRP.
  UE normally disconnects, if the RSRP < -110 or -115.

- Also, the screenshot shows Antenna Maximum / Minimum RSRP ranges between -44 to -114. Besides this range, UE wont receive the signal.

- dBm to watts

  -44 dBm $\rightarrow$ 40 nano watts (40×10^{-9} watts)

  (i.e) $10\log_{10}\left(\frac{40 \times 10^{-9}}{10^{-3}}\right) = -44$ dBm

ServiceMode

PCC MIMO Configured: 2
Tx Pwr : 18 dBm
UPPERLAYER_IND_R15 : Not Suppo
DCNR_RESTRICTION : FALSE
NR5G_RSRP : -94
NR5G_SINR : 8.0
NR5G RSRQ: -13
NR_SSB_Index: 0
NR_ARFCN: 629952
NR_PCI: 115
NR_RLF Count: --
SCGF Type: --
NR_BAND: n78
NR_CDRX: Active
NR_DL Scheduling: 0.00
NR_BLER: 0.00
NR_BW: 100
NR_SB Status: LTE+NR
NR_ANT MAX RSRP: -44
NR_ANT MIN RSRP: -114

ServiceMode

PCC MIMO Configured: 2
Tx Pwr : 14 dBm
UPPERLAYER_IND_R15 : Not Suppo
DCNR_RESTRICTION : FALSE
NR5G_RSRP : -99
NR5G_SINR : 0.5
NR5G RSRQ: -14
NR_SSB_Index: 0
NR_ARFCN: 629952
NR_PCI: 115
NR_RLF Count: --
SCGF Type: --
NR_BAND: n78
NR_CDRX: Active
NR_DL Scheduling: 0.00
NR_BLER: 0.00
NR_BW: 100
NR_SB Status: LTE+NR
NR_ANT MAX RSRP: -44
NR_ANT MIN RSRP: -114

ServiceMode

PCC MIMO Configured: 2
Tx Pwr : 3 dBm
UPPERLAYER_IND_R15 : Not Suppo
DCNR_RESTRICTION : FALSE
NR5G_RSRP : -90
NR5G_SINR : 1.5
NR5G RSRQ: -15
NR_SSB_Index: 0
NR_ARFCN: 629952
NR_PCI: 141
NR_RLF Count: --
SCGF Type: --
NR_BAND: n78
NR_CDRX: Active
NR_DL Scheduling: 0.00
NR_BLER: 0.00
NR_BW: 100
NR_SB Status: LTE+NR
NR_ANT MAX RSRP: -44
NR_ANT MIN RSRP: -114

RSRQ (Reference Signal Received Quality)

The difference between RSRP and RSRQ (considering SSS band) is that, RSRP is measured from SSS signals, whereas RSRQ is measured from any signal (need not be SSS). In fact, the gNB signals to the UE to measure RSRQ from SSB resources. (i.e) the symbols where RSRQ should be measured are signaled by gNB.

RSRP doesn't convey information about interference; it just conveys the received power. Whereas RSRQ conveys received quality along with the information about interference.

RSRQ is used for Cell Selection and Cell Reselection. We have L3 RSRP and RSRQ as well, but those are derived from L1 RSRP and RSRQ, but they are not the same. Here we talk about L1 RSRP and RSRQ.

$$\boxed{RSRQ = \frac{RSRP}{(RSSI / N)}}$$

where, RSSI → Received Signal Strength Indicator

N → No. of PRBs where RSSI is measured

RSRQ measured from SSS resources

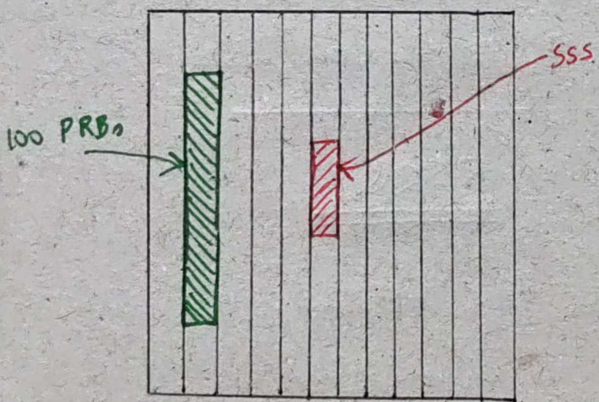
$$RSRQ = \frac{\overset{\text{per RE power}}{RSRP}}{\left(\frac{\overset{\text{Total power}}{\boxed{RSRP \times 12 \times N}}}{N}\right)}$$

$$= \frac{1}{12}$$

$$= -11 \text{ dB}$$

This can be one of the justification why RSRQ should not be calculated from SSS, because it won't give any additional information.

RSRQ measured from other resources



Assuming, there is no signal transmitted on these REs (100 PRBs) from that particular gNB, but there could be interference from other gNBs.

In this case, N = 100.

We are using this 100 PRBs to calculate RSSI.

And, lets say, the power per RE here is x. (i)

whatever received on these REs will be Interference or Noise. So,

$$RSRQ = \frac{RSRP}{\left(\frac{x \times 12 \times 100}{100}\right)} = \frac{RSRP}{12\,x}$$

Power received from other gNBs / Interference.

RSRP measured from SSS

$$= (RSRP)_{dB} - 10\log_{10}(12) - 10\log_{10}(x)$$

$$= (RSRP)_{dB} - 11 - 10\log_{10}(x)$$

For example,

$$RSRP = -80\ dBm$$

$10 \log_{10}(x) = -100\ dBm$ ($\because$ those are empty PRBs, so the power will be less)

So, $(RSRQ)_{dB} = (RSRP)_{dBm} - 11 - 10\log_{10}(x)$

$= -80 - 11 - (-100)$

$= +9$

RSRQ can be positive as well, and it can be used to give information about interference as well.

Case Study on RSRP and RSRQ

There are two cells with the following settings.

(1) cell A :

Bandwidth = 100 MHz

No. of PRBs = 273

Max. Tx. Power = 5 W

(2) cell B :

Bandwidth = 20 MHz

No. of PRBs = 52

Max. Tx. Power = 5 W

Consider a UE with equal path-loss 80 dBm from both the cells.

Measurement BW for RSSI == System BW.

(i) What is the SSB power per RE of cell A ?

$$\text{SSB power per RE} = \frac{\text{total power}}{N\_RE_0}$$

$$= \frac{5W}{(273 \times 12)} = 0.001526 \text{ W}$$

$$= 10 \log_{10}\left(\frac{0.001526}{10^{-3}}\right)$$

$$= 1.84 \text{ dBm.}$$

(ii) What is the SSB power per RE of cell B ?

$$\text{SSB power per RE} = \frac{\text{total power}}{N\_RE_0}$$

$$= \frac{5W}{(52 \times 12)} = 0.00801 \text{ W}$$

$$= 10 \log_{10}\left(\frac{0.00801}{10^{-3}}\right)$$

$$= 9.04 \text{ dBm.}$$

(iii) What is the SS-RSRP observed by UE from cell A ?

SS-RSRP = SSB transmit power per RE - pathloss

$= 1.84 - 80 = -78.16$ dBm

(iv) What is the SS-RSRP observed by UE from cell B ?

SS-RSRP = SSB transmit power per RE - pathloss

$= 9.04 - 80 = -70.96$ dBm.

(v) What is the SS-RSRQ observed by UE from cell A?

$$RSSI = \text{Total power} - \text{path loss}$$
$$= 10 \log_{10}(5000) - 80$$
$$\approx 37 - 80$$
$$= -43 \text{ dBm.}$$

$$RSRQ = \frac{RSRP \times N\_PRB_n}{RSSI}$$
$$= -78.16 \times 10 \log_{10}(273) - (-43)$$
$$= -78.16 + 24.36 + 43$$
$$= -10.8 \text{ dBm}$$

(vi) What is the SS-RSRQ observed by UE from cell B?

$$RSSI = \text{Total power} - \text{path loss}$$
$$= 10 \log_{10}(5000) - 80$$
$$\approx 37 - 80$$
$$= -43 \text{ dBm.}$$

$$RSRQ = \frac{RSRP \times N\_PRB_n}{RSSI}$$
$$= -70.96 \times 10 \log_{10}(52) - (-43)$$
$$= -70.96 + 17.16 + 43$$
$$= -10.8 \text{ dBm.}$$

(vii) What is the SS-RSRQ observed by UE from cell A when there is 10 dB of interference observed from cell B ?

RSSI = Total power - path loss + interference power

$= 10 \log_{10}(5000) - 80 + 10$

$\approx 37 - 80 + 10$

$= -33$ dBm

$$RSRQ = \frac{RSRP \times N\_PRBs}{RSSI}$$

$= -78.16 \times 10 \log_{10}(273) - (-33)$

$= -78.16 + 24.36 + 33$

$= -20.8$ dBm

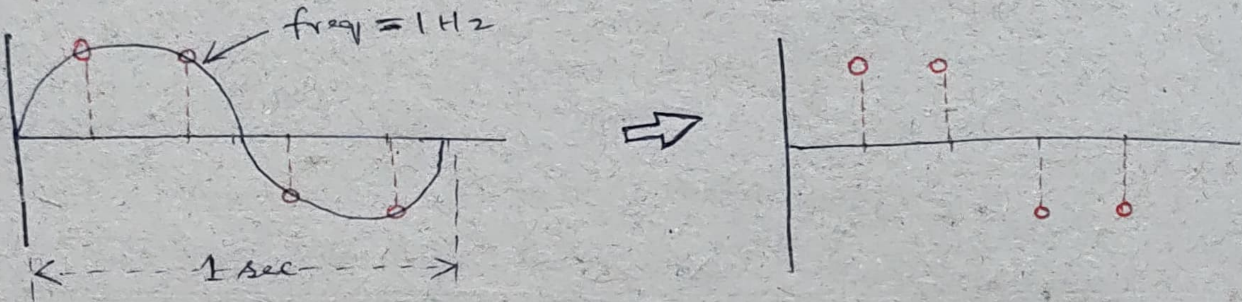
(viii) Based on the SS-RSRP and SS-RSRQ values calculated above, which cell UE should choose for better signal ?

UE should select cell B, as it receives better RSRP from it compared to cell A.

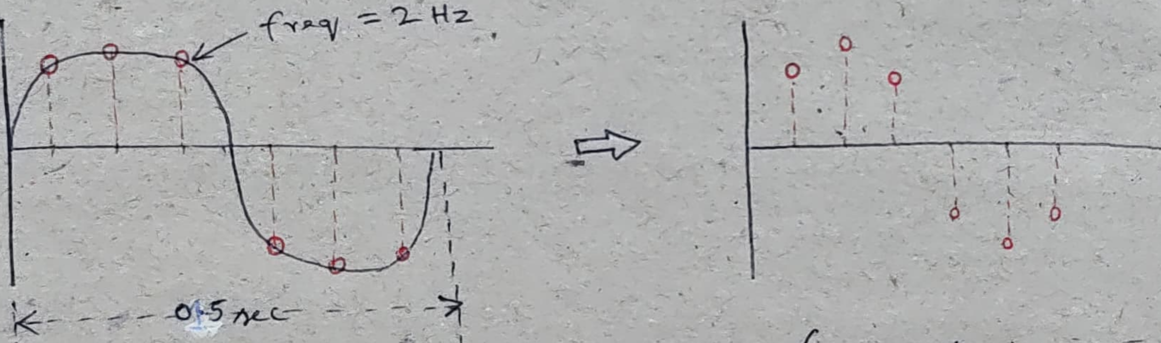
Sampling Rates in 5G

Sampling Rate = No. of Samples / sec.

How the signal is sampled ?



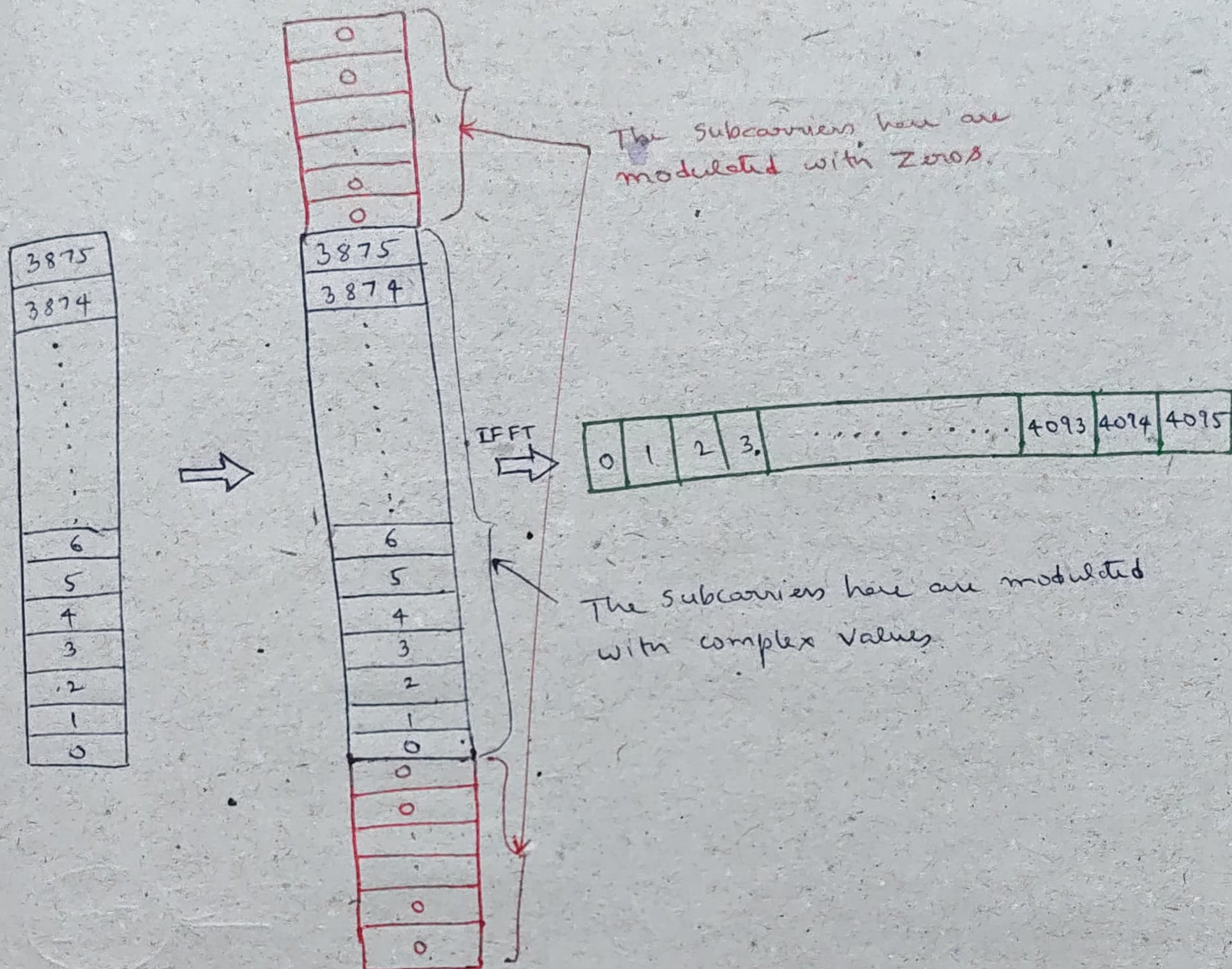
4 samples in 1 second
(ie) 4 sps.



6 samples in 0.5 second
(ie) 12 sps

Lets assume a system with 30 KHz Subcarrier spacing and 100 MHz bandwidth, having 3876 subcarriers.
(ie) There exists 3876 complex values that modulates 3876 subcarriers. So, we take 4096 point IFFT to do OFDM modulation.

We map this complex samples in the center, and put zeros in the remaining data points, and take IFFT.



After IFFT, the time domain samples (4096 samples) are as shown above.

∴ It is given 30 KHz SCS, so the symbol time is $\left(\frac{1}{30K}\right)$ seconds.

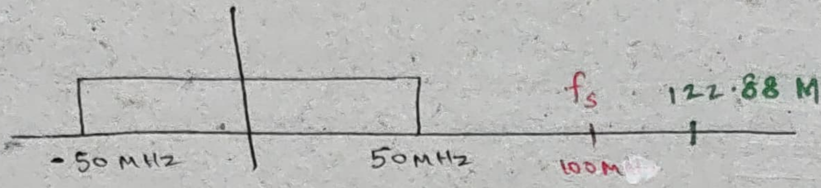
And the Sampling rate = No. of samples / sec

$$= \frac{4096}{(1/30K)} \text{ sps}$$

$$= 4096 \times 30K \text{ sps}$$

$$= 122.88 \text{ Msps}$$

This is the sampling rate in 5G for the given configuration of 30 KHz SCS and 100 MHz bandwidth. This sampling rate is much higher than the Nyquist rate.



- The Nyquist rate is approximately 100M, but we are sampling it at 122.88 Msps, which is much higher than the Nyquist rate.

- So, the Sampling rate in 5G depends on the
  * IFFT / FFT size
  * SCS
  * BW

15 KHz

Channel bandwidth (MHz)	FFT size
5	512
10	1024
15	1536
20	2048
25	2048
30	3072
40	4096
50	4096

30 KHz

Channel bandwidth (MHz)	FFT size
5	256
10	512
15	768
20	1024
25	1024
30	1536
40	2048
50	2048
60	3072
70	3072
80	4096
90	4096
100	4096

60 KHz

Channel bandwidth (MHz)	FFT size
10	256
15	384
20	512
25	512
30	768
40	1024
50	1024
60	1536
70	1536
80	2048
90	2048
100	2048

→ FR1

3GPP has defined these above tables (ie) FFT sizes for different channel bandwidths and SCS.

60 KHz

Channel bandwidth (MHz)	FFT Size
50	1024
100	2048
200	4096

120 KHz

Channel bandwidth (MHz)	FFT Size
50	512
100	1024
200	2048
400	4096

→ FR2

The FFT size is normally chosen as 2^n.
(ie) 256/512/1024/2048/4096. But, for certain cases, other FFT sizes are also chosen.

512 + 256 = 768

1024 + 512 = 1536

2048 + 1024 = 3072

Example :

Considering 60 MHz bandwidth and 30 kHz SCS.

No. of PRBs = 162 (as per spec)

No. of subcarriers = 162 × 12 = 1944 subcarriers.

So, here, 2048 point IFFT would have been enough. But in spec, 3072 point IFFT is defined.

Reason :

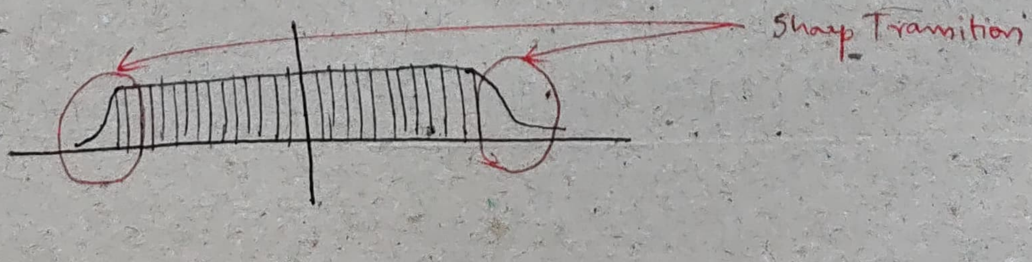
When higher IFFT size is chosen, the sampling rate also increases.

Sampling Rate for 2048 point IFFT } = 2048 × 30K

Sampling Rate for 3072 point IFFT } = 3072 × 30K

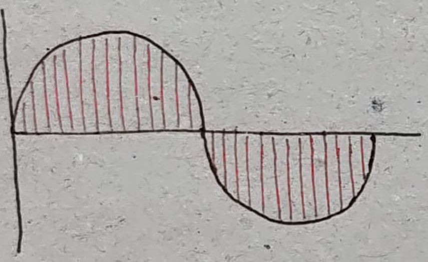
Here, the Sampling Rate increased 1.5 times.

The advantage is that, For 1944 subcarriers, 2048 point IFFT size is very close to the Nyquist rate. And for a real system, designing a filter for a very sharp transition is very difficult. So, having Larger FFT size is always useful when we are doing any Time domain estimation (or) Synchronization (or) similar such things...

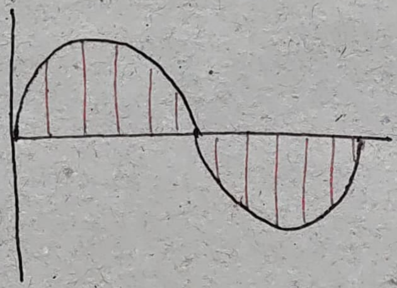


The disadvantage of using higher sampling rate is that, the BS (or) UE will have to process more number of samples. In our case, it has to process 1.5 times more number of samples.

One more thing that we need to understand is, the UE and gNB can work at different sampling rates. (ie) UE and gNB need not have same sampling rate. And, Also, the gNB never signals the sampling rate to the UE, as it is never required for the UE.



Sampling Rate S1



Sampling Rate S2

The signal transmitted by gNB might be sampled at rate S1, whereas the signal transmitted by UE might be sampled at rate S2.

Also, the gNB may operate at higher bandwidth and the UE may operate at Lower bandwidth. Lets say, the UE has a BWP, which is smaller than the bandwidth where BS is operating. In this case, UE operates at a much lower sampling rate than the BS.

ARFCN : Absolute Radio-Frequency Channel Number

ARFCN is basically a particular number (or) code, that specifies a pair of reference frequencies that are used for transmission and reception in a Radio frame.

If it is FDD, we have 2 ARFCN. One for downlink and one for uplink.

If it is TDD, then we have only one ARFCN.

So, ARFCN number is basically used to define,

- Where is the Point A
- Where is the, center

ARFCN can also be used to define the center of SSB, because, center of SSB also has a valid ARFCN.

In Specification, ARFCN numbers are defined as follows.

$$F_{REF} = F_{REF\text{-}Offs} + \Delta F_{Global} (N_{REF} - N_{REF\text{-}Offs})$$

Table 5.4.2.1-1: NR-ARFCN parameters for the global frequency raster

FR1

Frequency range (MHz)	ΔF_{Global} (kHz)	$F_{REF\text{-}Offs}$ (MHz)	$N_{REF\text{-}Offs}$	Range of N_{REF}
0 – 3000	5	0	0	0 – 599999
3000 – 24250	15	3000	600000	600000 – 2016666

If the Frequency range is 0 to 3GHz; then ARFCN takes values from 0 to 5,99,999. And if the frequency range is 3 GHz to 24.25 GHz, then ARFCN takes values from 6,00,000 to 20,16,666.

Table 5.4.2.1-1: NR-ARFCN parameters for the global frequency raster

FR2

Frequency range (MHz)	ΔF_{Global} (kHz)	$F_{REF\text{-}Offs}$ (MHz)	$N_{REF\text{-}Offs}$	Range of N_{REF}
24250 – 100000	60	24250.08	2016667	2016667 – 3279165

If the frequency range is 24.25 GHz to 100 GHz, then ARFCN takes values from 20,16,667 to 32,79,165.

Now, since the ARFCN maps to frequencies, so each band also has a range of ARFCN.

Table 5.4.2.3-1: Applicable NR-ARFCN per operating band

NR Operating Band	ΔF$_{Raster}$ (kHz)	Uplink Range of N_{REF} (First – <Step size> – Last)	Downlink Range of N_{REF} (First – <Step size> – Last)
n1	100	384000 – <20> – 396000	422000 – <20> – 434000
n2	100	370000 – <20> – 382000	386000 – <20> – 398000
n3	100	342000 – <20> – 357000	361000 – <20> – 376000
n5	100	164800 – <20> – 169800	173800 – <20> – 178800
n7	100	500000 – <20> – 514000	524000 – <20> – 538000
n8	100	176000 – <20> – 183000	185000 – <20> – 192000
n12	100	139800 – <20> – 143200	145800 – <20> – 149200
n20	100	166400 – <20> – 172400	158200 – <20> – 164200
n25	100	370000 – <20> – 383000	386000 – <20> – 399000
n28	100	140600 – <20> – 149600	151600 – <20> – 160600
n34	100	402000 – <20> – 405000	402000 – <20> – 405000
n38	100	514000 – <20> – 524000	514000 – <20> – 524000
n39	100	376000 – <20> – 384000	376000 – <20> – 384000
n40	100	460000 – <20> – 480000	460000 – <20> – 480000
n41	15	499200 – <3> – 537999	499200 – <3> – 537999
	30	499200 – <6> – 537996	499200 – <6> – 537996
n50	100	286400 – <20> – 303400	286400 – <20> – 303400
n51	100	285400 – <20> – 286400	285400 – <20> – 286400
n66	100	342000 – <20> – 356000	422000 – <20> – 440000
n70	100	339000 – <20> – 342000	399000 – <20> – 404000
n71	100	132600 – <20> – 139600	123400 – <20> – 130400
n74	100	285400 – <20> – 294000	295000 – <20> – 303600
n75	100	N/A	286400 – <20> – 303400
n76	100	N/A	285400 – <20> – 286400
n77	15	620000 – <1> – 680000	620000 – <1> – 680000
	30	620000 – <2> – 680000	620000 – <2> – 680000
n78	15	620000 – <1> – 653333	620000 – <1> – 653333
	30	620000 – <2> – 653332	620000 – <2> – 653332
n79	15	693334 – <1> – 733333	693334 – <1> – 733333
	30	693334 – <2> – 733332	693334 – <2> – 733332
n80	100	342000 – <20> – 357000	N/A
n81	100	176000 – <20> – 183000	N/A
n82	100	166400 – <20> – 172400	N/A
n83	100	140600 – <20> – 149600	N/A
n84	100	384000 – <20> – 396000	N/A
n86	100	342000 – <20> – 356000	N/A

FDD

TDD

Consider the n78 band (commonly used), where the ARFCN starts from 6,20,000 to 6,53,333 for 15 KHz for uplink. The ARFCN range is same for the Downlink, since it is a TDD band.

If it is a FDD band, lets say n1 band, then we have two diffrent ARFCNs coz there are two diffrent frequencies for uplink and downlink.

Table 5.4.2.3-1: Applicable NR-ARFCN per operating band

Operating Band	ΔF$_{Raster}$ (kHz)	Uplink and Downlink Range of N_{REF} (First – <Step size> – Last)
n257	60	2054166 – <1> – 2104165
	120	2054167 – <2> – 2104165
n258	60	2016667 – <1> – 2070832
	120	2016667 – <2> – 2070831
n260	60	2229166 – <1> – 2279165
	120	2229167 – <2> – 2279165
n261	60	2070833 – <1> – 2084999
	120	2070833 – <2> – 2084999

For a given ARFCN, how do we calculate the frequency? Say, for ARFCN of $\underbrace{6,43,222}_{N_{REF}}$, what is the corresponding frequency?

$$F_{REF} = F_{REF-Offs} + \Delta F_{Global} \left(N_{REF} - N_{REF-Offs} \right)$$

Refer Table 5.4.2.1-1

$$= 3000 \text{ MHz} + 15 \text{ KHz} \left(6,43,222 - 6,00,000 \right)$$

$$= 3000,000,000 + 15,000 \left(6,43,222 - 6,00,000 \right)$$

$$= 3,648,330,000$$

$$= 3648.33 \text{ MHz}$$

So, ARFCN of 6,43,222 means frequency of 3648.33 MHz. This particular frequency or ARFCN falls in n78 as well as n77.

Another thing that is defined in specification is the Step size. As we see, the step size is 20/6/3/2/1, which tells the valid ARFCNs. That means, considering n78 with 15 KHz aligned, step size of 1, the valid ARFCNs are 6,20,000, 6,21,000, ...

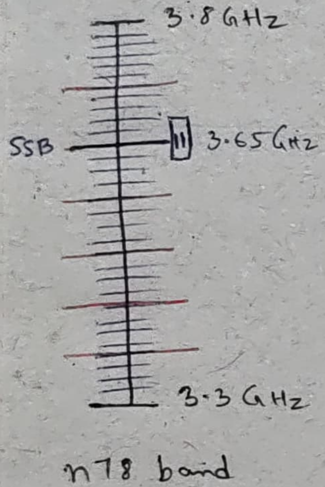
Also considering n78 with 30 KHz aligned, step size of 2, the valid ARFCNs are 6,20,000, 6,20,002, ...

So, we can assign a Center or also we can assign reference to Point A as well here.

GSCN : Global Synchronization Channel Number

The Question comes is,

- How the UE finds out the location of PSS / SSS / PBCH ?
- What are the different locations where UE should be searching for SS Burst ?



Let's say, UE search on band n78. (i) from 3.3 GHz to 3.8 GHz. Now, what are the different locations in this band where UE should try to search for SS Burst ?

WKT, in ARFCN number, the step size is very less. So, if the UE start searching using ARFCN number in order to find the SS Burst, which is transmitted at 3.65 GHz (say), it takes more time and many failed decodings for the UE, to reach the right SS Burst.

So, in order to avoid that, there is a different number, that is associated with the SS Burst location, known as GSCN number.

The difference between GSCN and ARFCN is that, the step size is more in GSCN compared to ARFCN.

GSCN will tell, what are the possible SSB locations where gNB might be broadcasting SS Burst.

The GSCN number is defined per deployment frequency range.

⟶

Table 5.4.3.1-1: GSCN parameters for the global frequency raster (FR1)

Frequency range	SS Block frequency position SS_{REF}	GSCN	Range of GSCN
0 – 3000 MHz	N * 1200kHz + M * 50 kHz, N=1:2499, M ∈ {1,3,5} (Note 1)	3N + (M-3)/2	2 – 7498
3000-24250 MHz	3000 MHz + N * 1.44 MHz N = 0:14756	7499 + N	7499 – 22255
NOTE 1: The default value for operating bands with SCS spaced channel raster is M=3.			

Table 5.4.3.1-1: GSCN parameters for the global frequency raster (FR2)

Frequency range	SS block frequency position SS_{REF}	GSCN	Range of GSCN
24250 – 100000 MHz	24250.08 MHz + N * 17.28 MHz, N = 0:4383	22256 + N	22256 – 26639

Table shows the GSCN parameters. (i) SS Block frequency position, GSCN and Range of GSCN for various frequency ranges.

→ For frequency range 0 to 3 GHz, the SSB frequency position is given by

$$SS_{REF} = N * 1200\text{ KHz} + M * 50\text{ KHz}$$

Assuming $N=1$,

$$SS_{REF} = 1200\text{ KHz} + M * 50\text{ KHz}, \quad \text{where } M = 1,3,5$$

So, it might happen that, the SS_{REF} may not be multiple of 15 KHz (or) 30KHz SCS. Hence, apart from the conditions specified in Table 5.4.3.1-1, the SSB should be frequency aligned with the PRBs in the channel bandwidth. (i) the subcarriers should be aligned with the channel subcarriers.

In order to align that, UE may not be allowed to pick any other position than that comes with this formula.

We see that, for a particular N (or) frequency, may be 1 or 2 of them may not align with SS Burst location with the PRB locations. So, we will have to pick N and M smartly.

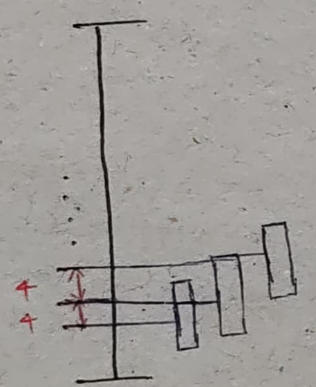
→ For frequency range 3 GHz to 24.25 GHz, the SSB frequency position is given by

$$SS_{REF} = 3\text{ GHz} + N * 1.44\text{ MHz}$$

Here, the steps between two SSB locations are 1.44 MHz. This 1.44 MHz and 3 GHz are multiples of SCS 15 KHz, 30 KHz, 60 KHz, 120 KHz and 240 KHz. So, the SS_{REF} that we get here will be aligned with the channel subcarriers.

If we look at 1.44 MHz with 30 KHz SCS, then it is around 4 PRBs. (ie) 30 KHz * 4 PRBs × 12 SC = 1.44 MHz

This means, the possible SSB locations are 4 PRBs apart.



→ For frequency range 24.25 GHz to 100 GHz, the SSB frequency position is given by

$$SS_{REF} = 24.25\text{ GHz} + N * 17.28\text{ MHz},$$ where N is 0 to 4383.

Here, 17.28 MHz is multiple of different SCS we have (60 KHz, 120 KHz, 240 KHz). So, the SSB locations always aligned with the channel subcarriers.

Table 5.4.3.3-1: Applicable SS raster entries per operating band

NR Operating Band	SS Block SCS	SS Block pattern[1]	Range of GSCN (First – <Step size> – Last)
n1	15 kHz	Case A	5279 – <1> – 5419
n2	15 kHz	Case A	4829 – <1> – 4969
n3	15 kHz	Case A	4517 – <1> – 4693
n5	15 kHz	Case A	2177 – <1> – 2230
	30 kHz	Case B	2183 – <1> – 2224
n7	15 kHz	Case A	6554 – <1> – 6718
n8	15 kHz	Case A	2318 – <1> – 2395
n12	15 kHz	Case A	1828 – <1> – 1858
n20	15 kHz	Case A	1982 – <1> – 2047
n25	15 kHz	Case A	4829 – <1> – 4981
n28	15 kHz	Case A	1901 – <1> – 2002
n34	15 kHz	Case A	5030 – <1> – 5056
n38	15 kHz	Case A	6431 – <1> – 6544
n39	15 kHz	Case A	4706 – <1> – 4795
n40	15 kHz	Case A	5756 – <1> – 5995
n41	15 kHz	Case A	6246 – <3> – 6717
	30 kHz	Case C	6252 – <3> – 6714
n50	15 kHz	Case A	3584 – <1> – 3787
n51	15 kHz	Case A	3572 – <1> – 3574
n66	15 kHz	Case A	5279 – <1> – 5494
	30 kHz	Case B	5285 – <1> – 5488
n70	15 kHz	Case A	4993 – <1> – 5044
n71	15 kHz	Case A	1547 – <1> – 1624
n74	15 kHz	Case A	3692 – <1> – 3790
n75	15 kHz	Case A	3584 – <1> – 3787
n76	15 kHz	Case A	3572 – <1> – 3574
n77	30 kHz	Case C	7711 – <1> – 8329
n78	30 kHz	Case C	7711 – <1> – 8051
n79	30 kHz	Case C	8480 – <16> – 8880

NOTE 1: SS Block pattern is defined in section 4.1 in TS 38.213 [8]

Table 5.4.3.3-1: Applicable SS raster entries per operating band

NR Operating Band	SS Block SCS	SS Block pattern[1]	Range of GSCN (First – <Step size> – Last)
n257	120 kHz	Case D	22388 - <1> - 22558
	240 kHz	Case E	22390 - <2> - 22556
n258	120 kHz	Case D	22257 - <1> - 22443
	240 kHz	Case E	22258 - <2> - 22442
n260	120 kHz	Case D	22995 - <1> - 23166
	240 kHz	Case E	22996 - <2> - 23164
n261	120 kHz	Case D	22446 - <1> - 22492
	240 kHz	Case E	22446 - <2> - 22490

NOTE 1: SS Block pattern is defined in subclause 4.1 in TS 38.213 [10].

If we look at 17.28 MHz with 120 KHz SCS, then it is around 12 PRBs. (i.e) 120 KHz * 12 PRBs x 12 SC = 17.28 MHz

This means, the difference between two possible SSB locations is 12 PRBs in this case.

Apart from these, there are few more conditions given.

(i) Not all the step size is allowed for every band. Lets say for n41 band, the GSCN possible locations have step size of 3. So, 6246, 6249, 6252, ... are the possible locations.

Also, for n79 band, the GSCN possible locations have step size of 16.

So, not all GSCN number that is calculated from the previous formulas are allowed to have SSB transmission. We will have to consider the step size, which gives final GSCN locations where SSB can be transmitted in a given band.

If the SS Burst is kept at the centre of the band, then the good part is that, the RSRP and RSRQ calculated by UE will be better, compared to the same calculated while keeping the SS Burst at the bottom or top.

And, the good part while keeping the SS Burst at the bottom or top is that, the CSI-RS will be continuous.

So, this trade-off we need to consider when we plan the SSB transmission.

TDD Slot Structure

- Distributing transmission in DL and UL across time slots. (i.e) When to transmit UL and when to transmit DL. Say,

Do not transmit anything

D	D	U	U	D	U	–	–	D

D	D	D	D	D	U	U	U	U	U

- Can we directly switch from DL to UL (or) UL to DL ?
- What are the different parameters to be considered when we have TDD slot structure ?

Lets consider few different slot formats (famous ones)

① ← Symbol Numbers in Slot

0	1	2	3	4	5	6	7	8	9
D	D	D	S	U	D	D	D	S	U

②

0	1	2	3	4	5	6	7	8	9
D	D	D	D	D	D	D	S	U	U

③

0	1	2	3	4	5	6	7	8	9
D	D	S	U	U	D	D	S	U	U

What is the right slot format that we should consider ?

What are the different parameters ?

Parameters

① Latency

- How much time the UE will take, to send the ACK / NACK, for the DL it received.
- In case ①, the UE cannot send ACK / NACK before slot 4 for all the DL. In case ②, the UE sends ACK / NACK earliest in slot 8 only. In case ③, UE sends ACK / NACK in slot 3 only.
- So, this parameter (Latency) decides, in TDD slot structure, whether we want fast communication (or) delay tolerable communication. (ii) whether the ACK / NACK to be sent fast (or) it is okay to get delayed by 4 or 5 slots.

② Cell Size / PRACH

- As we know, PRACH has two different formats.

(i) Long format
- It takes 2 to 3 slots
- Used for very large (or) Large cell size
- Eg. Rural area

(ii) Short format
- It takes only 1 slot
- Used for small cell size
- Eg. Indoor small cell (or) micro cell

- In case ①, Symbols 4 and 9 has UL.
In case ②, symbols 8 and 9 has UL.

If the cell deployment requires long PRACH formats, then case ② and ③ are preferred, as there exist consecutive ULs. If the cell deployment requires short PRACH formats, then case ① is preferred.

③ <u>SS Burst beams.</u>

- As we know, SS Burst has 4/8/64 Beams.
- we also know,

  In 1 slot, there are 2 SSBs

  In 2 slot, there are 4 SSBs

  In 3 slot, there are 6 SSBs

- Lets take 30 KHz scenario, where we have 8 beams. In the TDD slot structure case ①, we have 3 consecutive DLs, so we can have maximum of 6 SSBs. In case ②, we have 4 consecutive DLs, so we can have all 8 SSBs.

  Considering the above two cases, in case ①, we have less number of beams are wider. In case ②, we have more number of beams, which are less wider compared to case ①.

④ <u>DL/UL throughput</u>

- Heavy Downlink scenario : User wants to download more data.
- Heavy Uplink scenario : User wants to upload lots of data.

  For heavy downlink scenario, pick the TDD slot structure where there are more DLs in a slot. And, for heavy uplink scenario, pick the TDD slot structure where there are more ULs in a slot.

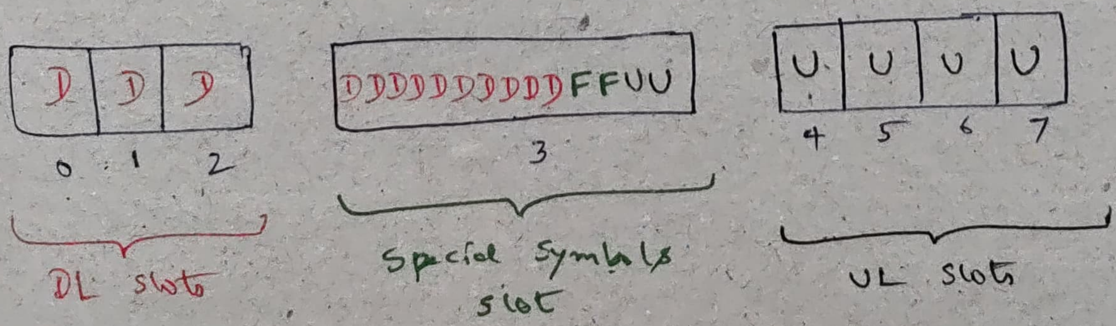
(5) Special Symbols for Switching.

- Special symbols are required whenever we switch from DL to UL.
- The special symbols adds overhead, because we do not transmit or receive any data there.
- The number of special symbols in a slot are decided based on the propagation delay.
- In TDD slot structure, S represents the special symbols. The number of symbols that are allocated in S as guard are decided based on the propagation delay and switching time.

There are the factors that we need to consider when we are deciding on the TDD slot structure.

In 5G, TDD slot structures are communicated in the following way.

- No. of DL slots = 3
- No. of DL symbols = 10
- No. of Special symbols = 2
- No. of UL symbols = 2
- No. of UL slots = 4

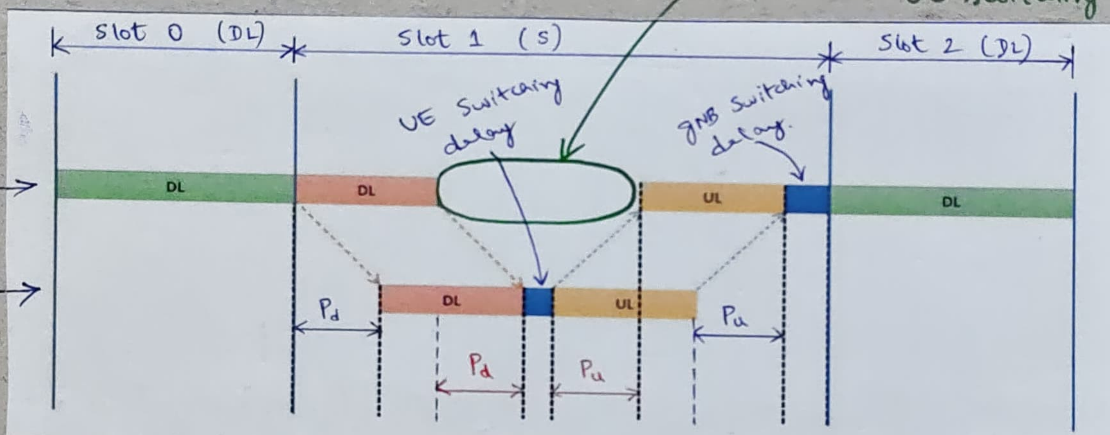


This is how the slot formats are communicated.

In most of the countries, the slot formats are fixed by government (or) Operators. In India, the slot format that is being used in 5G is DDDSU, where S has 10 D, 2 S and 2 U. Similarly in other countries also, the TDD slot format is fixed.

Now, lets look into the special slot or the switching between DL and UL.

Guard = P_d + P_u + UE switching delay



When the gNB transmits a DL, the signal takes some time to reach the UE. The time taken for the signal to reach the UE depends on how far the UE is from the BS. This is called the propagation delay for the DL signal (P_d).

Similarly, when the UE sends the signal to gNB, it will take similar amount of time for the UL signal to reach the gNB. This time window is called Uplink propagation delay (P_u)

Now, the gNB transmitted DL signal and UE received it. Now, UE needs to switch to UL, and there is a switching delay because UE need to switch its antennas from Receiving to transmitting. (ie) it needs to switch and start transmitting. This switching delay, as per 3GPP, for FR1 should be less than 10 µs; for FR2 should be less than 5 µs. This is the Maximum UE switching time.

Once UE switches, it starts transmitting the UL signal, which will take some time (P_u) to reach the gNB.

Now, after this Uplink, the gNB needs to switch from UL to DL. We call it gNB switching delay. As per 3GPP, the gNB switching delay (or) Radio ON OFF / OFF ON time for FR1 should be maximum 10 μs; for FR2 it should be maximum 5 μs. This is the gNB switching delay.

Now, the Guard is $P_d + P_u$ + UE switching delay. So, the number of symbols that we allocate for switching should be more than the Guard time.

So, the gNB Downlink is always aligned with the slot boundary. But the UE Uplink is not aligned, and is always in advance (ie) a fixed amount of delay is communicated to the UE. The UE should transmit well in advance including the Pu + gNB switching delay.

So, the number of symbols that we use in special slot should be more than the Guard period.

As we see, the Guard period heavily depends on the propagation delay. If the cell is large, then the propagation delay is large and the Guard time will be large. And if the cell is small, then the propagation delay will be less, guard time will be less, and the switching time would be less.

Apart from this, there is another parameter that is added in the switching time, called "BS to BS interference avoidance time". (ie) if there are 2 BS close by, they have a overlapping coverage area, being operated on the same frequency, they should have less than 3 μs accuracy.

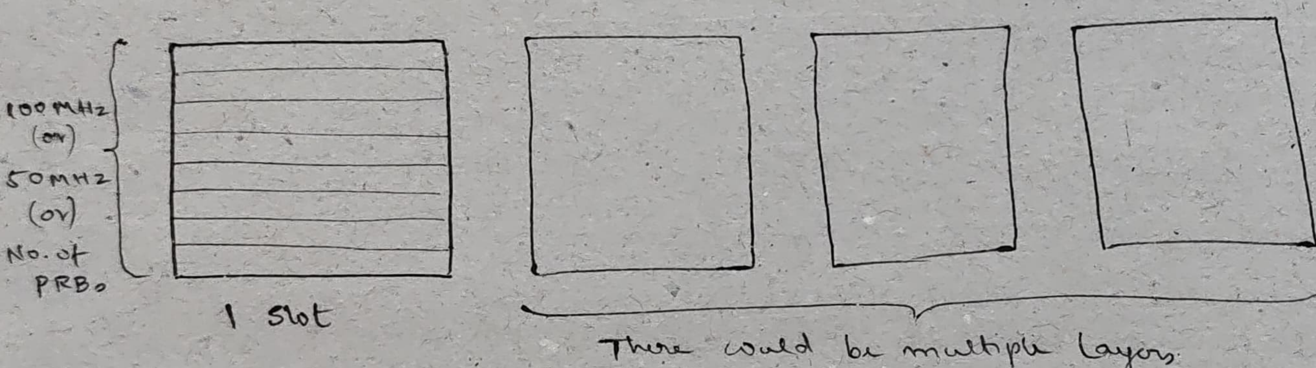
Quick throughput calculation

There are 3 steps that we normally follow, to calculate the throughput.

① Find out the total no. of REs allocated in a slot.

② Convert these REs (symbols) into bits, with the given MCS.

③ Convert these No. of bits per slot into No. of bits per second.



First we sum up all the REs allocated in a slot. There could be multiple layers as well (1/2/4/8 layers). We count all the REs, leaving the Reference Signals (RS), control REs (PDCCH), DMRS, ... Leaving those behind, we find the total no. of REs for the shared channel.

Once we have the total no. of REs, we multiply this with Modulation and Code Rate, to get the No. of bits in a slot.

Once we have the No. of bits in a slot, depending on the slot duration (1 ms/500 μs/250 μs/125 μs), we convert the No. of bits / slot into No. of bits / second.

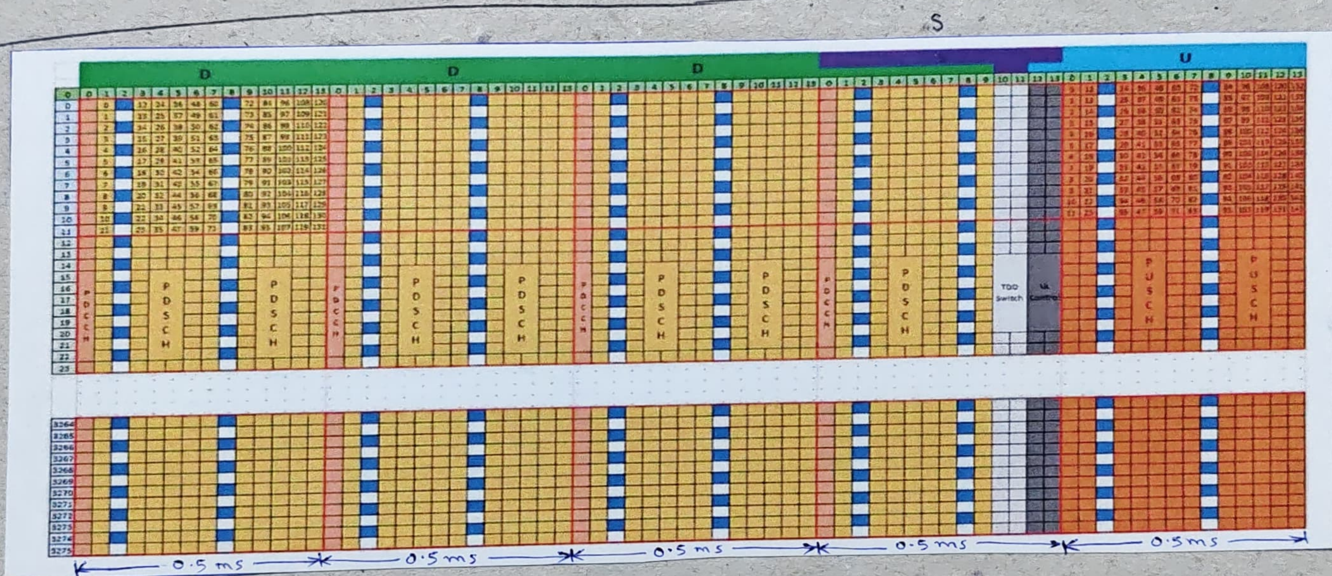
Consider X bits in a slot.

Assume slot duration = 250 μs

$\Rightarrow$ X bits in 250 μs

$$\boxed{1 \text{ second} \Rightarrow \frac{X}{250 \times 10^{-6}} \text{ bits}}$$

This is how we calculate No. of bits per second.



This is how a normal TDD allocation looks like. We assume the TDD format "DDDSU"; and in the special slot S, we assume 10 DL symbols, 2 special symbols for switching and 2 UL symbols.

In normal transmission, the first symbol is given to PDCCH at every DL slot (Not in UL slot). In the S slot, the last two symbols are utilized for control information (for PUCCH / for ACK/NACK / CSI Reportings / ...).

Here, we assume 100 MHz Bandwidth with 30 KHz SCS. So, total 273 PRBs. (i.e.) 273 × 12 = 3276 subcarriers. For throughput calculation, the only thing matters is the No. of PRBs allocated. So, we calculate the No. of PRBs from Bandwidth and Subcarrier Spacing.

- PDCCH on first few symbols, PDSCH on remaining symbols in Downlink;
- 2 Symbols for TDD switching (Based on the deployment - Large or small cell - this may vary)
- 2 Symbols for UL control
- Full Uplink slots is given to PUSCH.
- We assumed 2 DMRS symbols per slot, both for DL and UL slots.

This is for one layer. Similarly, the same allocation will be there if there are more than one Layer (2/4/8 layers). Of course, in more number of layers, the DMRS may change (ie) we may have more/less number of DMRS. Based on how the resource allocation is done, this picture may look different.

Now, for this particular case, lets calculate throughput. (Quick Calculation - Approximately calculate throughput)

(i) Total No. of REs allocated for PDSCH.

For 1 PRB, excluding PDCCH and DMRS, there are 11 symbols. So, the No. of REs in 1 PRB is $11 \times 12 = 132$ REs for PDSCH.

$$\begin{pmatrix}\text{Total No. of REs} \\ \text{in a DL Slot}\end{pmatrix} = \begin{pmatrix}\text{No. of REs} \\ \text{in a PRB}\end{pmatrix} \times \text{No. of PRBs}$$

There may be multiple layers. So, we multiply by No. of Layers. Assume, in this case, there are 2 layers.

$$\begin{pmatrix}\text{Total No. of REs}\\ \text{in a DL slot}\end{pmatrix} = \begin{pmatrix}\text{No. of REs}\\ \text{in a PRB}\end{pmatrix} \times \begin{pmatrix}\text{No. of}\\ \text{PRBs}\end{pmatrix} \times \begin{pmatrix}\text{No. of}\\ \text{Layers}\end{pmatrix}$$

$$= 132 \times 273 \times 2$$

$$= 72,072 \text{ REs.}$$

(ii) Convert these REs into bits, with the given MCS.

consider, MCS = 15

Modulation order = 6

Code Rate $= \frac{666}{1024}$

So, the approximate total No. of bits that are coming to PHY Layer is

$$\text{No. of bits} = \text{Total No. of REs} \times Q_m \times R$$

$$= (132 \times 273 \times 2) \times 6 \times \frac{666}{1024}$$

$$= 2,82,516.609 \text{ bits/slot}$$

Note: In this TDD format, not all the slots are given to DL. If it is a FDD case, the above No. of bits can be directly converted to Throughput. But, for this TDD case, where in every 2.5 ms, there is a full UL slot, and in the special slot, 4 symbols are not given to Downlink.

So, total No. of DL OFDM symbols in this case are

$$\text{TDD correction} = \frac{(14 \times 3) + 10}{(14 \times 5)} = \frac{52}{70}$$

We multiply this TDD correction with the above No. of bits,

$$\text{Total No. of bits} = \begin{pmatrix}\text{Total No. of}\\ \text{REs}\end{pmatrix} \times Q_m \times R \times \text{TDD correction}$$

$$= (132 \times 273 \times 2) \times 6 \times \frac{666}{1024} \times \frac{52}{70}$$

$$= 2,08,928.362 \text{ bits/slot.}$$

These are the No. of bits there in 1 slot (0.5 ms)

(iii) Convert the No. of bits per slot into No. of bits per second.

In this case, 1 slot = 500 μs

In 500 μs, we have X bits.

In 1 sec, we have $\frac{X}{500 \times 10^{-6}}$ bits (or) $\frac{X}{500}$ Mbps

$$\begin{pmatrix}\text{No. of bits} \\ \text{per second}\end{pmatrix} = \frac{\begin{pmatrix}\text{Total No.} \\ \text{of REs}\end{pmatrix} \times Q_m \times R \times \begin{pmatrix}\text{TDD} \\ \text{correction}\end{pmatrix}}{500} \text{ Mbps}$$

$$= (132 \times 273 \times 2) \times 6 \times \frac{666}{1024} \times \frac{52}{70} \times \frac{1}{500} \text{ Mbps}$$

$$= 417.856 \text{ Mbps}$$

This is how we can calculate the throughput for a given MCS and allocation.

Now, on top of this, if there are multiple carriers, then of course we multiply with the No. of carriers. Assume there are 2 carriers, then,

Throughput = 417.856 × 2 = 835.712 Mbps.

Note: All the calculations are done in multiplication. There is no addition / subtraction here.

Now, how to calculate the Exact throughput?

In order to calculate the exact throughput for a given system, there are few other things that we need to consider.

⟶

We should ideally consider

- RRC Message Overhead (MIB / SIB1 / other control information)
- DMRS / Data interleaving.
  (In the previous case, we have not considered the DMRS & Data interleaving. But we may have such interleaving as well)
- CRC overhead
- Other Reference Signals (CSI-RS / PTRS / ...)
  ($\because$ the PTRS and CSI-RS are not in every PRB, so it may not be symmetrical. In such case, we may not be able to calculate total NO. of REs in a PRB and directly multiply, to calculate for full bandwidth)
- BLER Rate

Exact throughput calculation

To calculate the exact throughput of the system, we need to consider the following.

- Get the exact TB size, considering the overhead of all Reference signals. (i.e) basically, calculation of the exact number of REs.
- We should consider overhead of RRC messages
  Eg. MIB, SIB1 and others
- We should also consider BLER rate, if we want to consider HARQ process also. Normally, we have 10% target BLER rate.

In this case, we considered two more Reference signals.

P → PTRS,

CSI-RS

This is just for example. This may not match with the exact allocation of PTRS and CSI-RS.

We also considered that, PTRS and CSI-RS are on alternative PRBs, not in every PRB.

As we see, there are 4 PTRS and 4 CSI-RS. So 8 REs are occupied by PTRS and CSI-RS in 1 PRB. But since they are on alternate PRB, so on an average, 4 REs are occupied per PRB in a slot.

(i) The No. of REs allocated for PDSCH in this case are 124 (excluding PTRS and CSI-RS) in 1 PRB.

But, since, the PTRS and CSI-RS are on alternative PRBs, so, on an average, there are 128 REs per PRB.

$$\begin{pmatrix}\text{Total No. of REs}\\ \text{in a DL Slot}\end{pmatrix} = \begin{pmatrix}\text{No. of REs}\\ \text{in a PRB}\end{pmatrix} \times \begin{pmatrix}\text{No. of}\\ \text{PRBs}\end{pmatrix} \times \begin{pmatrix}\text{No. of}\\ \text{Layers}\end{pmatrix}$$

$$= 128 \times 273 \times 2$$

$$= 69{,}888 \text{ REs}$$

(ii) NOW, with $\left\{\begin{array}{l}\text{MCS} = 15, \\ \text{Modulation order} = 6 \\ \text{code rate} = 666/1024\end{array}\right\}$, we should calculate the Transport Block size.

<u>Note</u>: For Quick throughput calculation, we just multiplied the Qm and R with total no. of REs, to get the round figure of the Transport block.

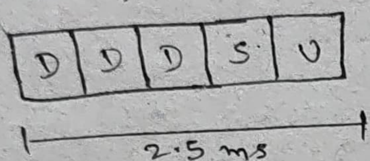
The Spec. has defined formulas to get the exact TB size for a slot, for the given resource allocation.

Using those complicated formulas, for 69,888 REs, we calculate the TB size as

TB Size = 2,70,576 bits/slot (for D-slot)

Here, in the S-slot, we have 10 Symbols for DL. Out of 10, 9 symbols are for PDSCH. And in those 9 symbols, we have PTRS, CSI-RS and DMRS. By using the spec. defined formula, which uses Total No. of REs in the S-slot, MCS, and all, we calculate the TB size as

TB size = 1,72,176 bits / slot. (for S-slot)



The complete TDD structure, which is 2.5 ms long, we have 3 DL slots and 1 S-slot. So, the total DL TB size in 2.5 ms would be

DL TB size = (270,576 × 3) + 1,72,176

= 9,83,904 bits per 2.5 ms slot

(iii) So, for 1 second,

$$\begin{pmatrix}\text{No. of bits}\\ \text{per second}\end{pmatrix} = \frac{\text{TB size}}{2.5\text{ ms}}\ \text{bps}$$

$$= \frac{9,83,904}{2.5 \times 10^{-3}}\ \text{bps}$$

$$= 393\ 561\ 600\ \text{bps}$$

$$= 393.56\ \text{Mbps}$$

This is the throughput.

Now, if we want to consider the RRC message overhead, which may vary based on the allocation. For example, let's consider,

In 1 Frame (20 slots), On an average 1 slot is given to RRC messages. (i.e) out of 20 slots, 1 slot is given to RRC messages. So, the throughput, considering this overhead would be,

$$\text{Throughput} = 393.56 \times \frac{19}{20}$$
$$= 373.88 \text{ Mbps}$$

Now, if we also want to consider the HARQ process and also account for the target BLER rate, say target BLER rate is 10%, the throughput would become

$$\text{Throughput} = 373.88 \times \left(\frac{9}{10}\right)$$
$$= 336.49 \text{ Mbps}$$

This throughput is the Physical Layer throughput, and may not match with the Application throughput.

These are the bits that are given in the Downlink from physical layer to Upper layers. (ie) These are the bits those have passed the CRC (correct bits). So, this is the throughput at the physical layer.

So, from the upper layers, if we remove all the overheads, the actual application throughput may go down further.

Uplink throughput:

UL throughput concept remains the same. (ie) we count the No. of bits in the UL slot. For this TDD structure, We have only one UL slot, and we assume that the UL control is on the S-Slot symbols 12 and 13 (This may not be the case and it may depend on the allocation)

So, for this particular example, we consider 1 UL slot. Once we calculate the total no. of REs, considering the MCS / No. of PRBs / No. of layers, we calculate the TB size using the same formula, and then we convert it to throughput.

Now, if we want to consider the PRACH overhead, say short format which takes 12 full PRBs (∵ for a single UE, we cannot allocate PUSCH on the remaining symbols at the end (start). And if there are multiple occasions of PRACH in frequency, then we have to consider those occasions, say if there are 3 occasions, then 3 x 12 = 36 PRBs are given to PRACH. Also if we want to consider PRACH aperiodicity (PRACH is not in every U slot) say the PRACH comes once in 5 ms / 10 ms / 20 ms.

Considering all the above, the PRACH overhead is calculated, and the throughput is calculated.

This is how we calculate the UL throughput as well (same as DL throughput).

Maximum Throughput:

Lets say, to calculate Maximum DL throughput, we need to maximize everything.

- Maximum No. of REs we can have
- Maximum No. of Layers in downlink (8 layers)

Now, PDCCH has to be there (we cant skip), atleast one DMRS has to be there (∵ there are 8 layers, there has to be 2 DMRS symbols). So, 3 symbols are gone out of 14.

So, in total, we have 11 x 12 = 132 REs in a PRB. This is the maximum REs we can have.

Of course, we can further optimize by having single PDCCH allocated for all the Downlink slots and we can fit all the DCIs in that PDCCH. But here, we consider that there is one PDCCH in every slot.

So, in our case, for PDSCH, the number of OFDM symbols available are 11 and No. of Sub carriers in a PRB is 12. So, 132 REs in a PRB.

(i) $\begin{pmatrix}\text{Total No. of REs} \\ \text{in a DL slot}\end{pmatrix} = \begin{pmatrix}\text{No. of REs} \\ \text{in a PRB}\end{pmatrix} \times \begin{pmatrix}\text{No. of} \\ \text{PRBs}\end{pmatrix} \times \begin{pmatrix}\text{No. of} \\ \text{Layers}\end{pmatrix}$

$$= 132 \times 273 \times 8$$

$$= 2,88,288 \text{ REs}$$

(ii) Maximum MCS = 27 (from 256 QAM Table)

Max. Modulation order, $Q_m = 8$ (256-QAM)

Max. code Rate, $R = \frac{948}{1024}$

With this MCS / Q_m / R, we calculate the TB size for DL slot. For S-slot also, we can calculate the same way.

Note: Other thing we can do, to maximize DL throughput in this particular case is, currently we have 10 DL symbols / 2 symbols for switching / 2 UL symbols in S-slot. Instead, we could have 12 DL symbols / 2 symbols for switching / Eliminate the UL symbol. (ie) we can put the UL symbols ~~at~~ the S-slot into the UL-slot itself. This way, we can increase the DL throughput.

Also, by minimizing the RRC overhead / BLER rate, we can increase the DL throughput.

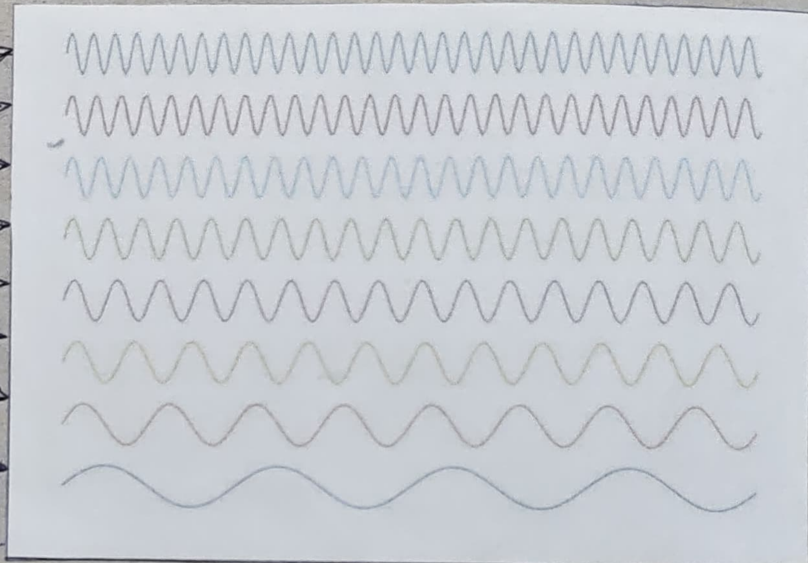
If there are multiple carriers (say 4 carriers), then the maximum throughput that we calculated for single carrier can be multiplied by 4, to get the maximum throughput.

PAPR in OFDM

PAPR $\rightarrow$ Peak to Average Power Ratio

Why PAPR is a problem in OFDM and how does it impact the System ?

0.7071 - 0.7071 i →
- 0.7071 + 0.7071 i →
0.7071 - 0.7071 i →
0.7071 + 0.7071 i →
0.7071 + 0.7071 i →
- 0.7071 + 0.7071 i →
0.7071 - 0.7071 i →
- 0.7071 - 0.7071 i →



Assume, the figure shows the orthogonal subcarriers. The subcarrier spacing can be 15 / 30 / 60 / 120 KHz.

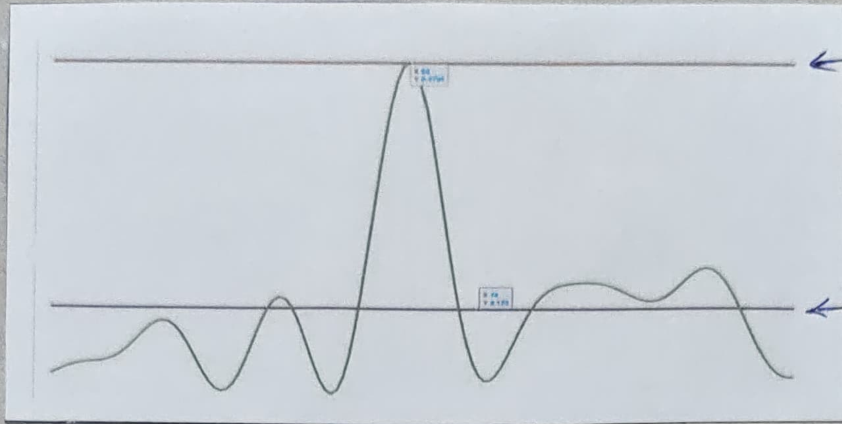
WKT, say if 16 bits are QPSK modulated, we get 8 complex valued modulated samples.

16 bits
↓
QPSK Modulation
↓
8 modulated samples

These 8 modulated samples have same amplitude but different phases.

With these modulated samples, we modulate the sine and cosine waves. Here only sine is shown in figure, but there could be cosine as well.

Now, each sample modulates each orthogonal subcarrier. After modulating each orthogonal subcarriers, if we add them up, we get a single final OFDM waveform as shown in figure below.



Peak Power 0.4725

Average Power 0.125

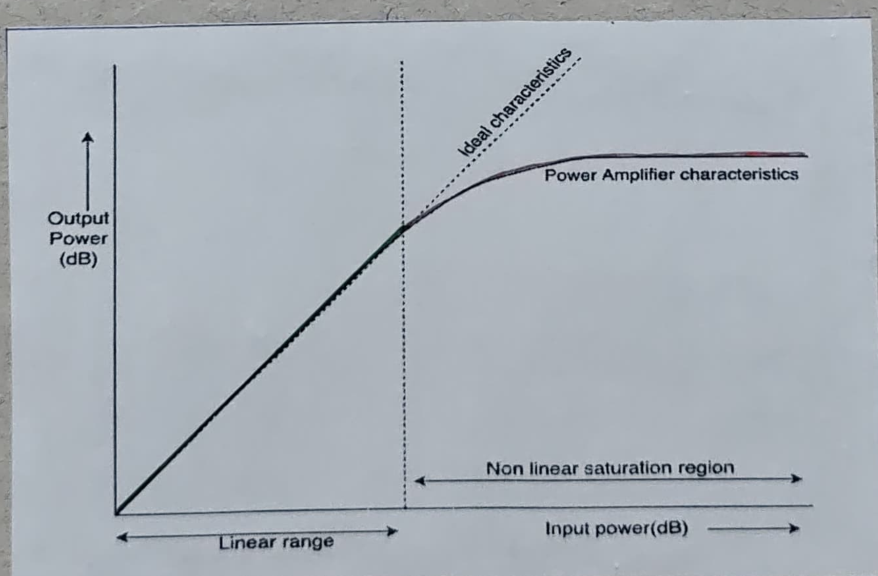
The ratio of this Average Power and Peak power is called as PAPR.

$$PAPR = 10 \log_{10}\left(\frac{0.4725}{0.125}\right) \approx 5.78 \text{ dB}$$

Based on the input bits / samples / No. of subcarriers, this PAPR will vary.

Now, how does the PAPR impact the system?

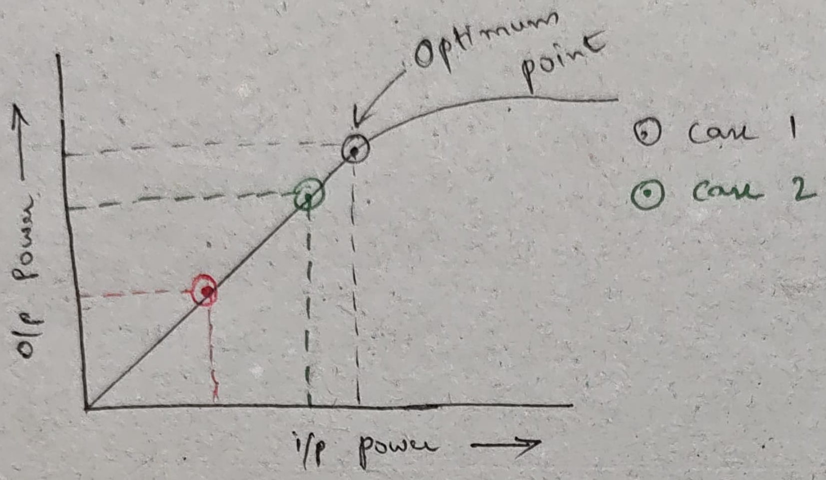
For that, lets look into how the Power Amplifier works in the radio part. The Graph below shows the normal power amplifier input power vs output power.



Linear range : The o/p power scales exactly with the i/p power

Non-linear range : The o/p power wont scale with the i/p power (aka) Saturation region.

Whether it is in the UL or DL, we want the Power amplifier to operate at higher power.



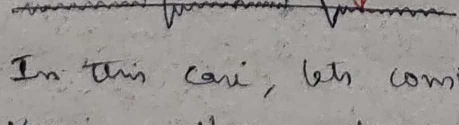
Different Cases :

① Figure shows the optimum point where the power Amplifier want to operate (ideal case). Here, the input power is constant (not fluctuating), and we want the Power Amplifier always radiate at higher power.

② In this case, lets consider the input is sligtly varying.

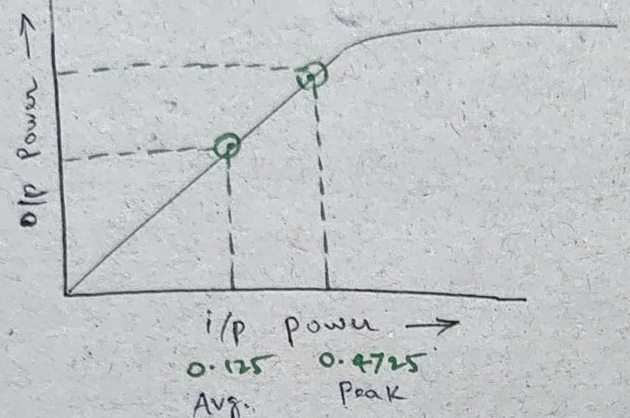
And, we cant operate at the optimum point. we'll have to operate sligtly lower power, so that the Peak doesn't go in the non-linear / saturated region.

③



In this case, lets consider the input power is extremely varying. Here, we'll have to operate at much lower power in order that the peak doesn't go to the non-linear/ saturated region.

Now, coming back to our example, where the Average power was at 0.125, Peak power was at 0.4725.



So, the transmitter have to back-off i/p power.

Higher the Peak power, compared to the Average power, Lower would be the Output Power.

The Maximum power defined as per UE class is 23 dBm / 26 dBm. Since, there is PAPR, UE wont be able to transmit at this power. It will always radiate the lower power.

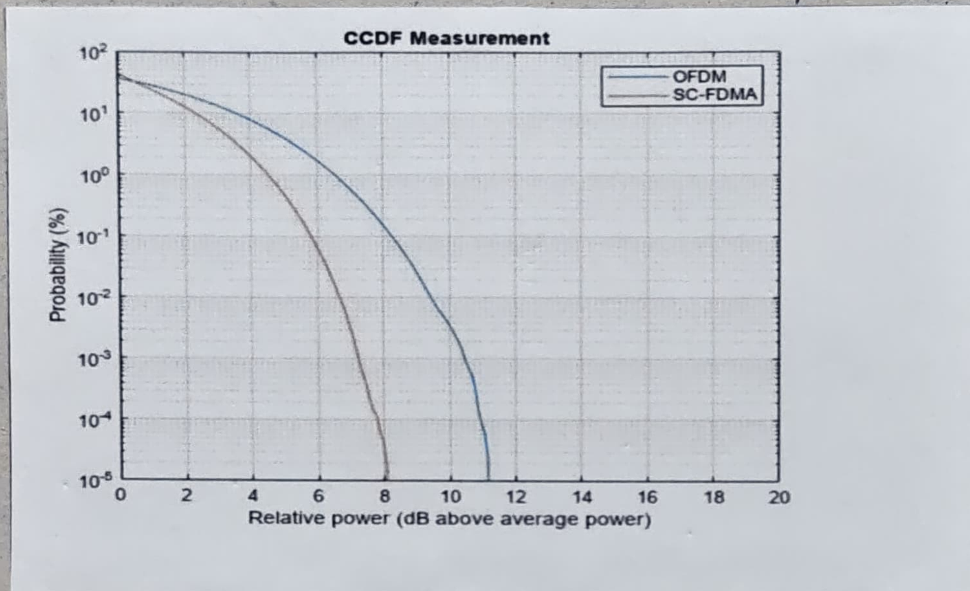
Similarly, if the gNB is supposed to operate at 40 watts / 46 dBm, it will never be operating at this power. It will always Operate at lower power. due to PAPR.

For this reason, we use DFT-S-OFDM (or) SC-FDMA in most of the UL signals, as they give us low PAPR.

What happens if we still operate at the optimum point and the peak goes on the non-linear region? In this case, the waveform will be distorted as the power wont be transmitted for those peaks. It can damage the Power amplifier, and wont transmit the expected power, and may result in high packet loss.

The other option is, still operate at the optimum point and just clip off the peaks at a certain level. Here also, the waveform will be distorted, and there will be out of band emission which will also result in higher packet loss.

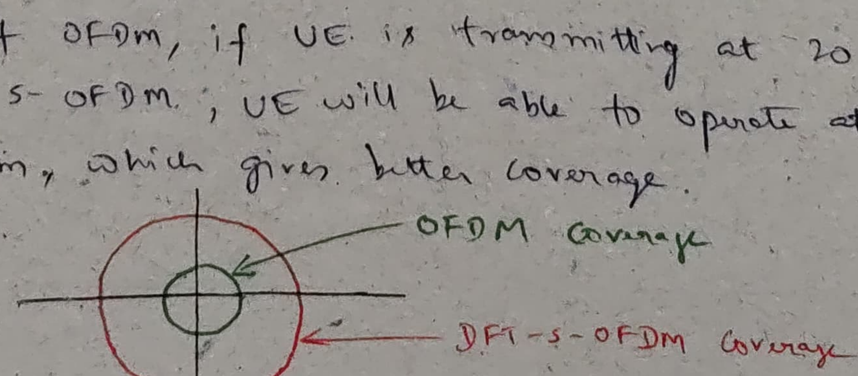
So, we always operate at a lower power than the optimum, making sure that the peak falls in the linear region and the average also falls in the linear region, which doesn't allow us to operate at higher power.



Graph shows the CCDF measurement of OFDM (uncoded) vs DFT-S-OFDM. As it can be seen that, in OFDM, the PAPR is 2 to 3 dB higher than that in DFT-S-OFDM.

Also, the graph says that; the probability that the Average power will be above 8 dB is 10^{-5}.

SC-FDMA is always better and gives better performance.
(i) When we use SC-FDMA (2 to 3 dB better), UE will always be able to operate at 2 to 3 dB more than OFDM.
(ii) In case of OFDM, if UE is transmitting at 20 dBm, then in DFT-S-OFDM, UE will be able to operate at 22 to 23 dBm, which gives better coverage.



And, for this reason, $\frac{\pi}{2}$ BPSK is the new waveform that is used in 5G, which has even lower PAPR, and gives further better coverage in OFDM.