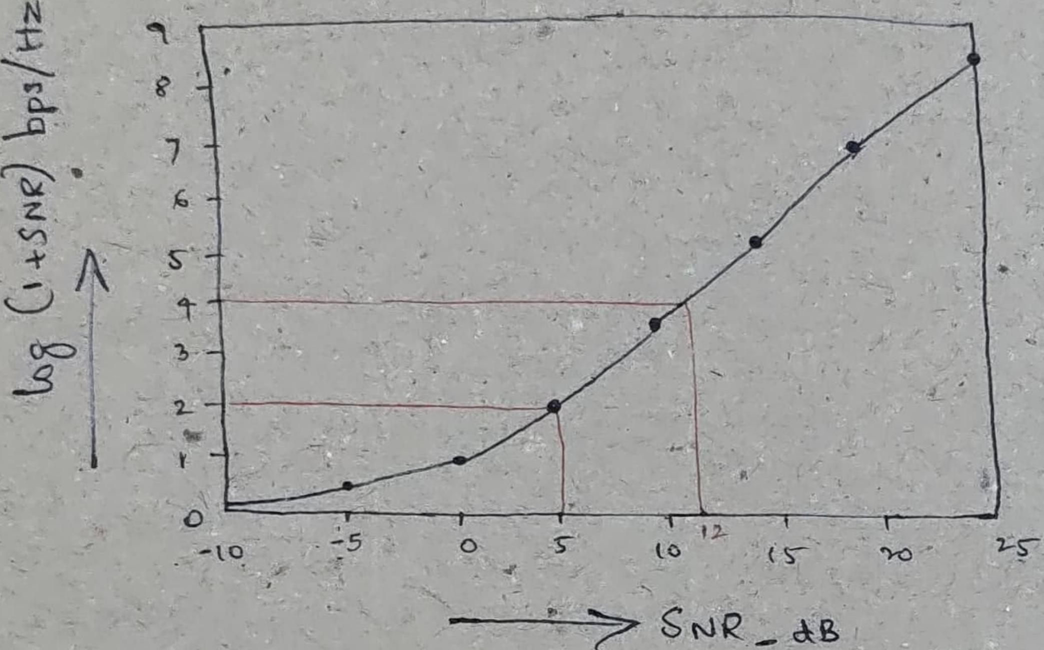
Key Technologies of 4G/5G systems

- Adaptive Modulation and Coding (AMC)
- OFDM
- MIMO
- Scheduling and Hybrid ARQ.

Adaptive Modulation and Coding (AMC)

Capacity of AWGN single-antenna channel, $y = x + n$ when x is Gaussian. $\Big\}$ $= \log(1 + SNR)$ bps/Hz



- AMC helps us achieve capacity using discrete constellations

Eg. M-QAM with $M = 2/4/16/64/256$

	No. of symbol (M)	No. of bits/symbol ($\log_2 M$)
BPSK ←	2	1
QPSK ←	4	2
16-QAM ←	16	4
64-QAM ←	64	6
256-QAM ←	256	8
1024-QAM ←	1024	10

→ Capacity

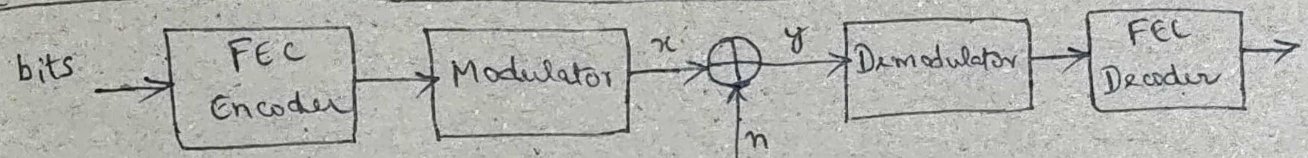
- If SNR is 5 dB, capacity would be 2 bps/Hz
  - → Using 4-QAM achieves the capacity
  - → BLER ≈ 0 is achieved

- If SNR is ≈ 12 dB, capacity would be 4 bps/Hz
  - → Using 16-QAM achieves the capacity
  - → BLER ≈ 0 is achieved

→ This idea of switching modulation according to SNR is called Adaptive Modulation

→ How to achieve other points on capacity curve?
For example, when SNR = 2.5 dB, capacity = 1.5 bps/Hz.

- The answer is "Adaptive modulation and (Error control) Coding".



- where, $y = x + n$
- FEC encoder rate, $r = \dfrac{\text{No. of FEC input bits}}{\text{No. of FEC output bits}}$
- 'r' is always ≤ 1.

Block diagram of Capacity achieving Transceiver

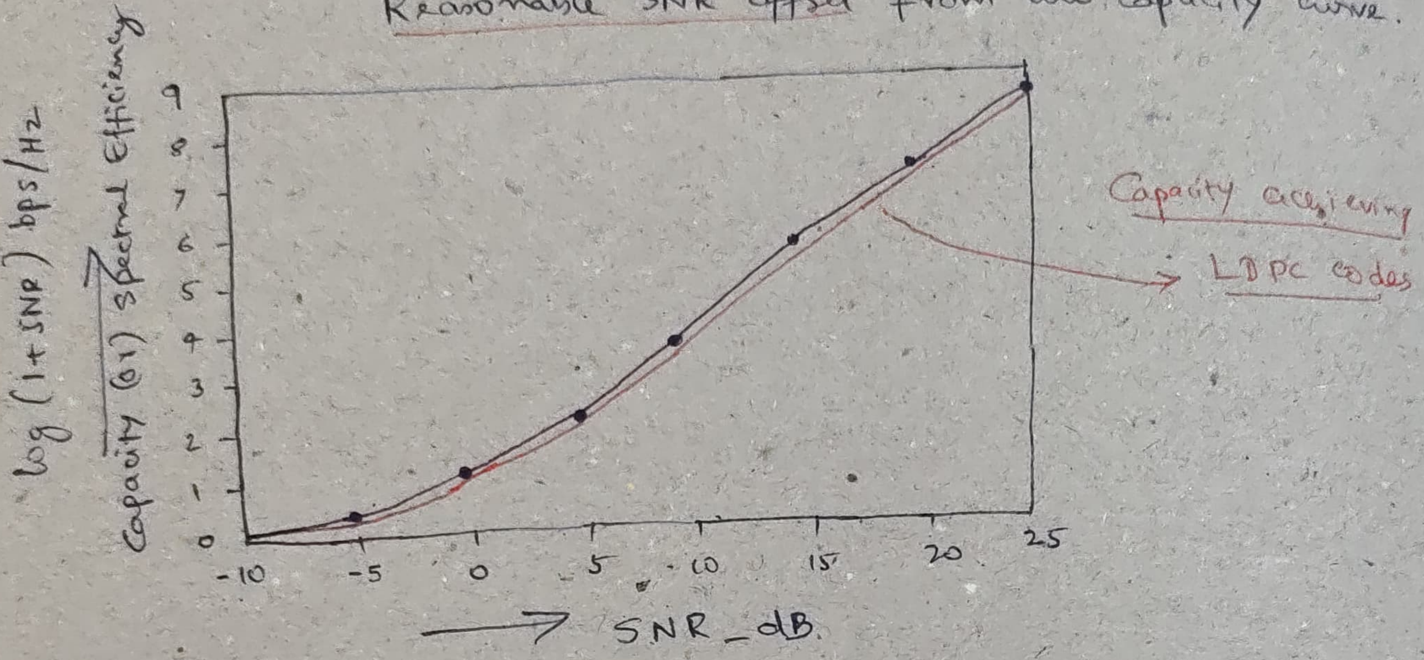
- FEC encoder adds parity bits to input message bits, in order to guarantee a low BLER.
- FEC encoder should use large code block lengths, in order to guarantee a low BLER

→ So, If SNR is 2.5 dB, Capacity is 1.5 bps/Hz,
  - → Using 4-QAM with code rate of 3/4 achieves the capacity
  - → (ie) 4-QAM capacity = 2 bps
    Desired capacity = 1.5 bps $\Rightarrow 2\text{ bps} \times \dfrac{3}{4} = 1.5\text{ bps}$

Capacity achieving Codes.

⑤ 5G NR uses Capacity achieving LDPC Codes

→ Provides low BLER
Reasonable code block length
Reasonable SNR offset from the capacity curve.



⑥ 4G uses Capacity achieving Turbo codes.

Adaptive Modulation and Coding in 5G NR

MCS Index I_{MCS}	Modulation Order, Q_m ($\log_2 M$)	Target Code Rate ($1024 \times R$)	Spectral Efficiency (or) Capacity $R \times Q_m$
0	2	120	0.2344
1	2	157	0.3066
2	2	193	0.3770
3	2	251	0.4902
4	2	308	0.6016
5	2	379	0.7402
6	2	449	0.8770
7	2	526	1.0273
8	2	602	1.1758
9	2	679	1.3262
10	4	340	1.3281
11	4	378	1.4766
12	4	434	1.6953
13	4	490	1.9141
14	4	553	2.1602
⋮	⋮	⋮	⋮
27	6	910	5.3320
28	6	948	5.5547
29	2	Reserved	
30	4	Reserved	
31	6	Reserved	

$1024 \times R = 120$

$\Rightarrow R = \frac{120}{1024}$

$SE = R \times Q_m$

$= \frac{120}{1024} \times 2$

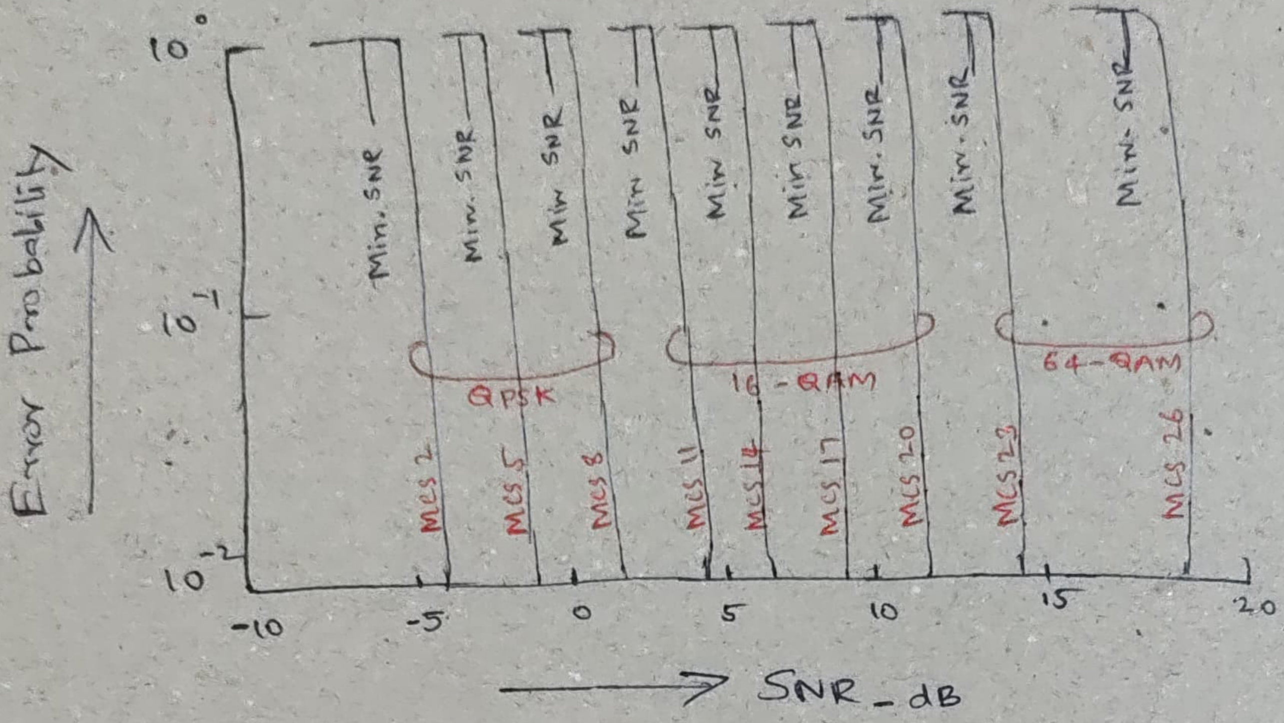
$= 0.2344$

MCS – Modulation and Coding Scheme

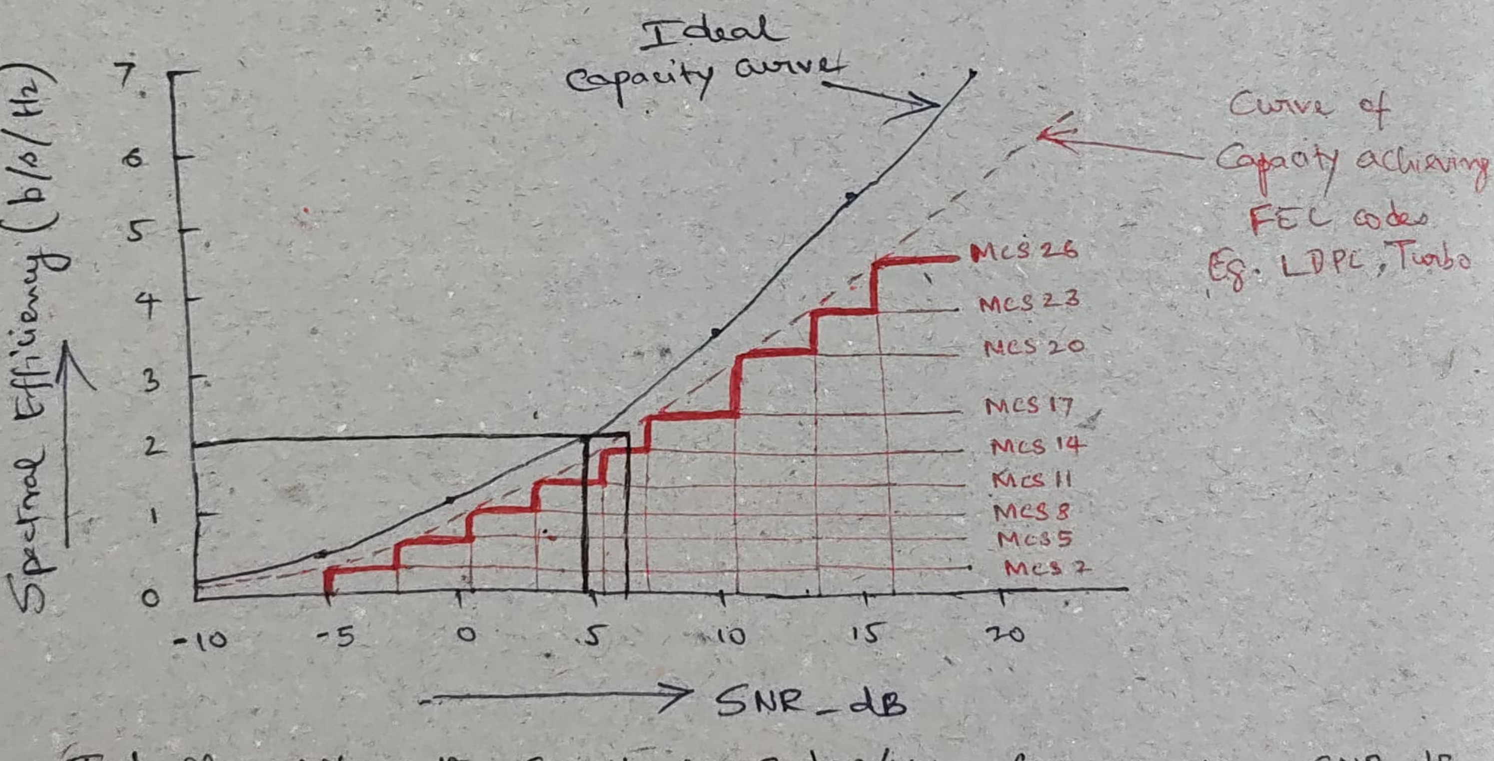
→ UE computes the SNR and its corresponding capacity, in other words Spectral Efficiency.

→ The corresponding MCS Index is reported to the BS by the UE.

→ Hence, the BS chooses appropriate modulation scheme for transmission.



Plot: BLER for LDPC with code block length of N = 6000.



Ideally, when the capacity is 2 bps/Hz, corresponding SNR-dB would be 5 dB.

With the use of capacity achieving LDCP codes, there exist marginal deviation. (ie) when the capacity is 2 bps/Hz, the corresponding SNR_dB would be 6.5 dB (approx).

Why OFDM in 5G?

→ Peak data rate = (System bandwidth) * (Peak Spectral Efficiency)

Eg: Given spectral efficiency (or) Capacity } = 1.5 bps/Hz

System Bandwidth = 10 MHz

Peak data rate = 10 MHz * 1.5 bps/Hz

= 15 Mbps

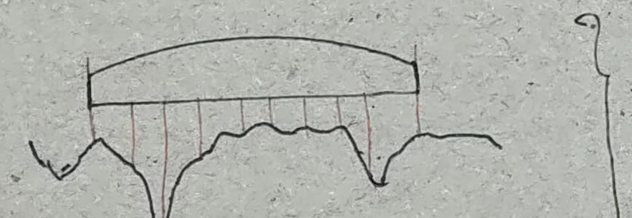
→ It is clearly visible that, increasing the system bandwidth would increase the peak data rate. But, there is a problem in doing so..

⊙ In wireless system, the data to be transmitted will get multiplied by the channel.

(i) $y = hx + n$

h — Channel

x — Transmit data

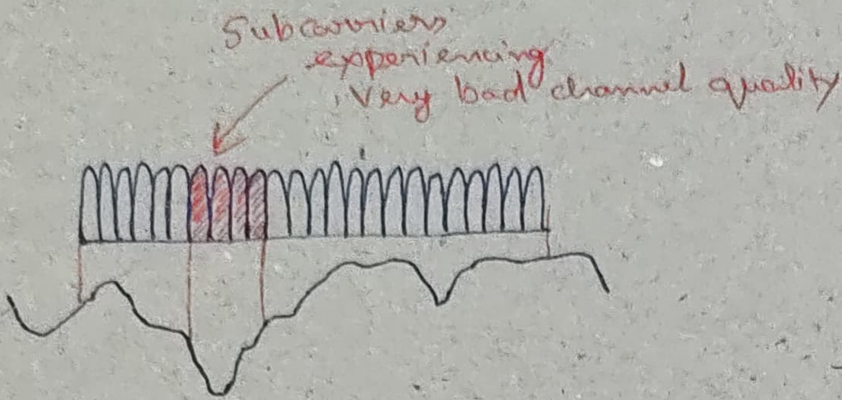


→ Single Wideband Carrier, Say 100 MHz

⊙ When the bandwidth is increased, the channel varies at rapid rate.

⊙ Estimation of the rapidly varying channel, over the wider bandwidth, at the receiver side is very difficult. (non-trivial task).

* Also, Channel equalization (removal of 'h' from x) is extremely complicated and practically it is infeasible to do.



→ OFDM signal

$y_i = h_i x_i + n_i$

- OFDM simplifies the channel estimation and equalization problem.

→ UE calculates SNR for each subcarrier

$$\gamma_i = \frac{|h_i|^2 P}{N_0}$$

→ UE averages SNR over a bunch of subcarriers to calculate a single SNR, which is Effective Exponential SNR (EESM)

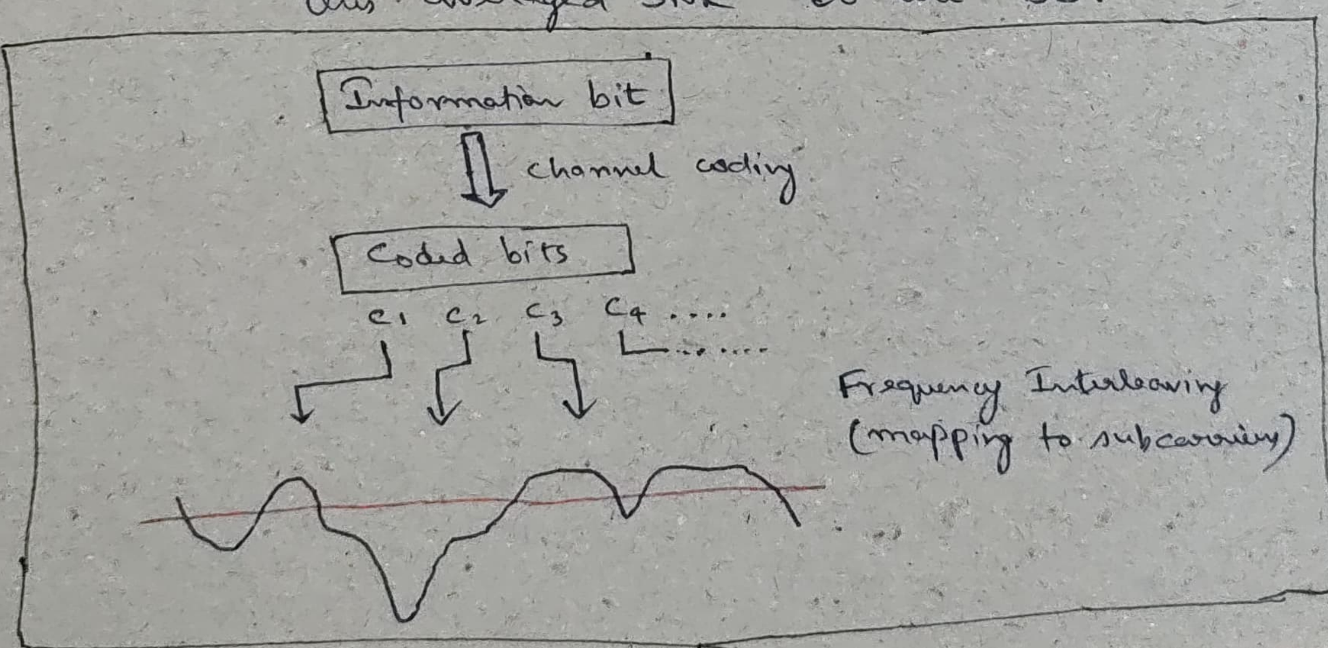
$$\boxed{\gamma_{eff} = -\lambda \ln\left(\frac{1}{N_c}\sum_{i=1}^{N_c} e^{-\frac{\gamma_i}{\lambda}}\right)}$$

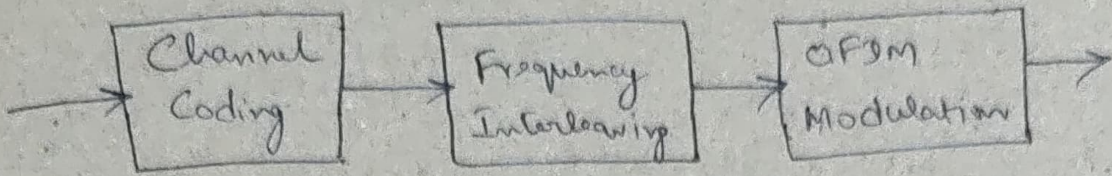
Where,

λ — Calibration parameter

N_c — No. of subcarriers.

→ UE reports the MCS index corresponding to this averaged SNR to the BS.

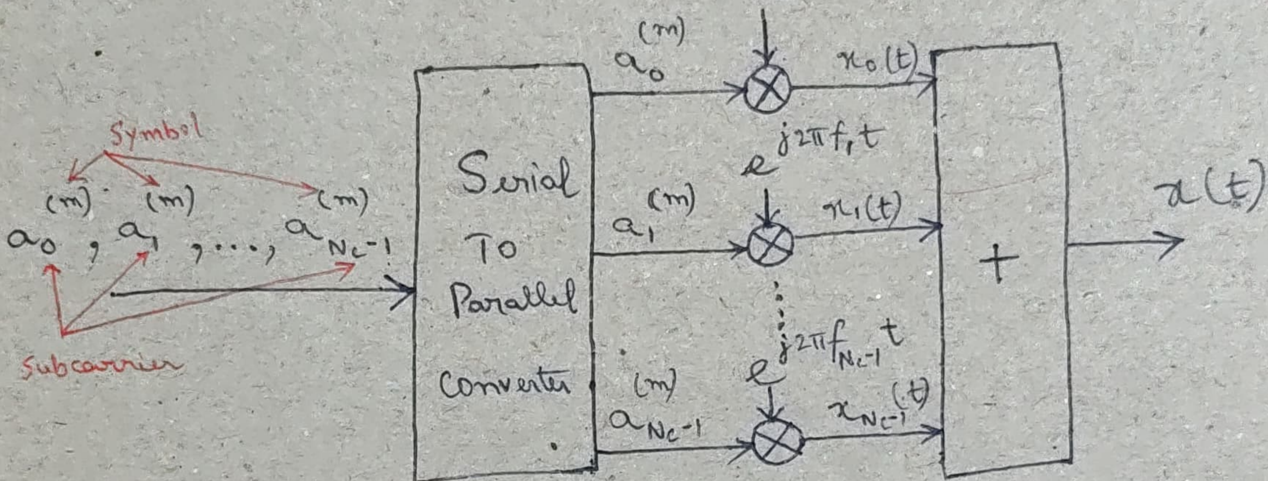




→ So, OFDM help in exploiting the frequency diversity with channel coding.

OFDM Transmitter

Consider a system with 'T_u' OFDM symbol duration and N_c subcarriers.



$$\boxed{x(t) = \sum_{k=0}^{N_c-1} a_k^{(m)} e^{j2\pi f_k t}}$$

$f_k = k\Delta f$

Figure valid for time interval

$$\underbrace{mT_u \le t < (m+1)T_u}_{\text{one Symbol duration}}$$

→ Subcarrier spacing should be $\Delta f = \frac{1}{T_u}$ for orthogonal subcarriers.

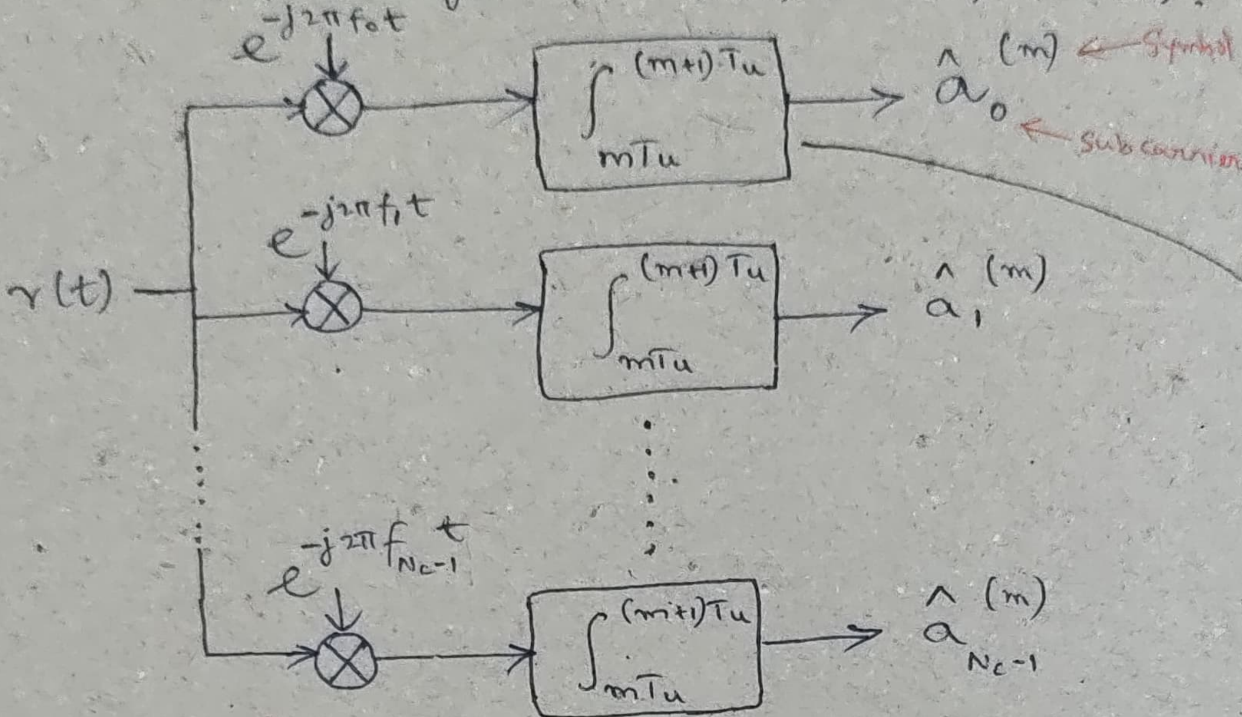
→ For two subcarriers, $f_{k1} = k_1 \Delta f$ and $f_{k2} = k_2 \Delta f$, orthogonality implies

$$\int_{mT_u}^{(m+1)T_u} e^{j2\pi k_1 \Delta f t} \cdot e^{-j2\pi k_2 \Delta f t} \, dt = 0$$

where $k_1 \neq k_2$

OFDM receiver

OFDM receive signal is $r(t) = x(t) + n(t)$.



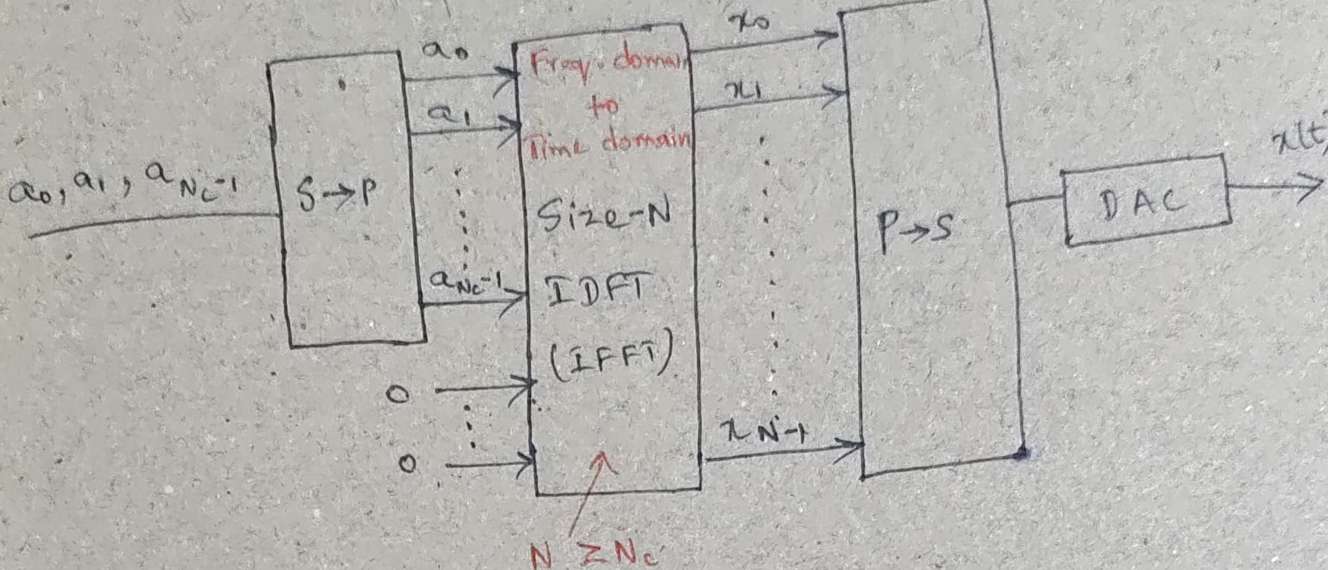
$f_k = k\Delta f$

$$r(t) = x(t) + n(t) = \left(\sum_{k=0}^{N_c-1} a_k^{(m)} e^{j2\pi f_k t} \right) + n(t)$$

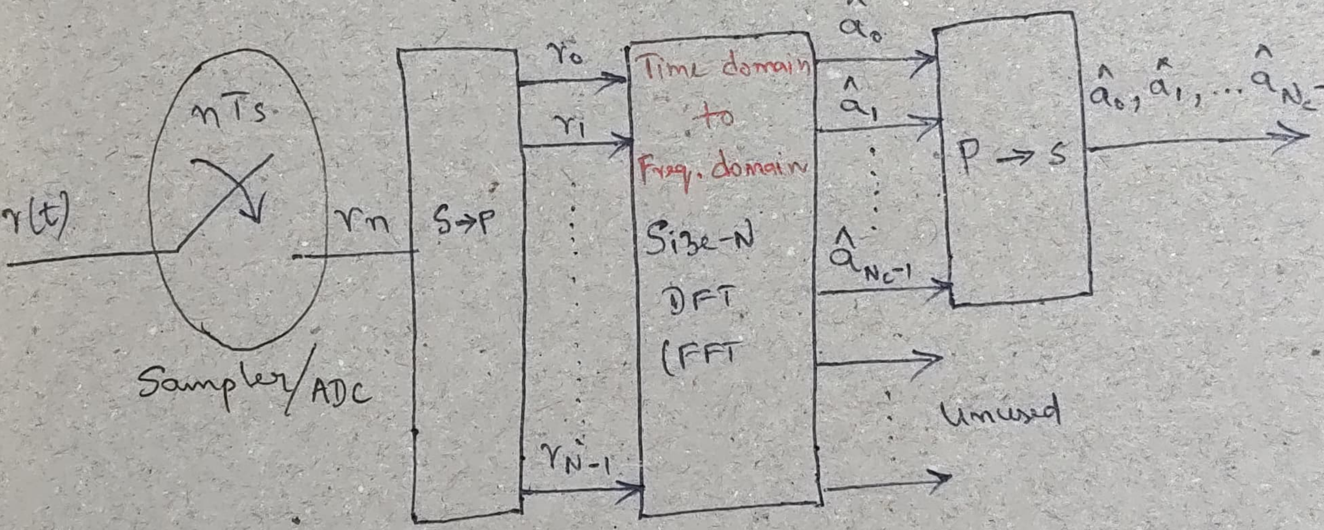
$$\int_{mT_u}^{(m+1)T_u} \left(\sum_{k=0}^{N_c-1} a_k^{(m)} \cdot \underbrace{e^{j2\pi f_k t} \Big) \cdot e^{-j2\pi f_0 t}}_{= \begin{cases} 0, & \text{if } k_1 \neq k_2 \\ 1, & \text{if } k_1 = k_2 \end{cases}} dt$$

$$= a_0^{(m)}.$$

5G-NR baseband OFDM transmitter with IFFT



5G-NR baseband OFDM receiver with FFT



System dimensioning for 5G NR (Example 1)

(Most typically used in 5G NR system)

→ NR baseband bandwidth = 100 MHz (99 MHz usable)
(1 MHz guard band)

→ Subcarrier spacing, $\Delta f = 30$ KHz

→ Total Subcarriers required, $N_c = \dfrac{\text{usable baseband bandwidth}}{\text{Subcarrier spacing}}$

$$= \frac{99 \text{ MHz}}{30 \text{ KHz}} = 3.3 \times \frac{10^6}{10^3}$$

$$= 3300$$

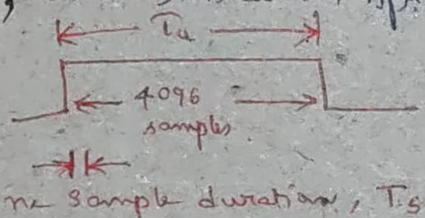
→ FFT/IFFT size, $N = 4096$ (2^{12})

Reason : FFT size in terms of 2^k is easy to implement.

→ OFDM symbol duration, $T_u = \dfrac{1}{\Delta f}$

(OFDM symbol duration is fixed, once Subcarrier spacing is fixed)

→ Sampling time, $T_s = \dfrac{T_u}{4096}$



→ Sampling rate / Sampling frequency,

$$F_s = \frac{1}{T_s} = \frac{4096}{T_u} = \frac{4096}{1/\Delta f} = 4096 \times \Delta f$$

$$= 4096 \times 30 \text{ KHz}$$

$$= 122880 \text{ KHz}$$

$$= 122.88 \text{ MHz}$$

Sampling rate according to Nyquist Criteria } = 99 MHz (By considering usable bandwidth)

System dimensioning for 5G NR (Example 2)

→ NR base band bandwidth = 50 MHz (49.5 MHz usable)
(0.5 MHz guard band)

→ Subcarrier spacing, $\Delta f = 15$ KHz

→ Total subcarriers required, $N_c = \dfrac{\text{usable baseband bandwidth}}{\text{Subcarrier spacing}}$

$$= \frac{49.5 \text{ MHz}}{15 \text{ KHz}} = 3.3 \times \frac{10^6}{10^3}$$

$$= 3300$$

→ FFT/IFFT size, $N = 4096$ (2^{12}).

→ OFDM symbol duration, $T_u = \dfrac{1}{\Delta f}$

→ Sampling time, $T_s = \dfrac{T_u}{4096}$

→ Sampling rate / Sampling frequency,

$$F_s = \frac{1}{T_s} = \frac{4096}{T_u} = \frac{4096}{1/\Delta f} = 4096 \times \Delta f$$

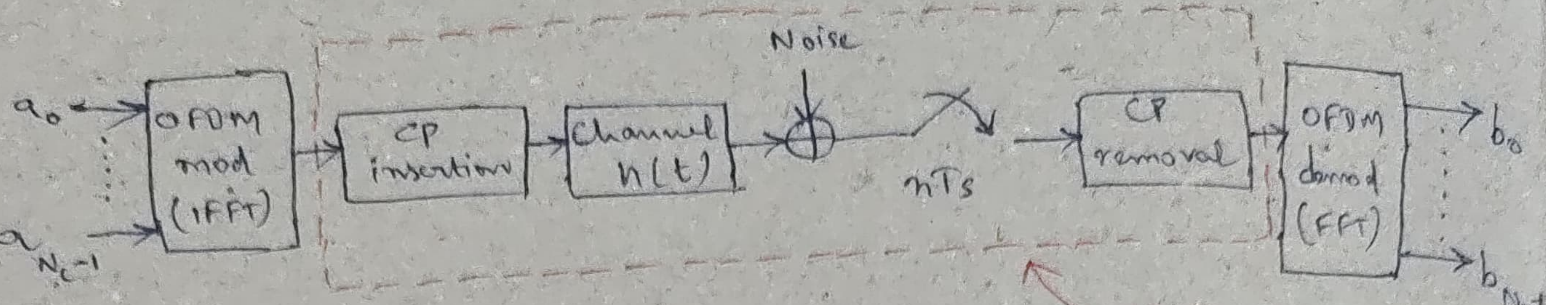
$$= 4096 \times 15 \text{ KHz}$$

$$= 61440 \text{ KHz}$$

$$= 61.44 \text{ MHz}$$

Sampling rate according to Nyquist Criteria } = 49.5 MHz (Considering only usable bandwidth)

Equivalent OFDM system WITH CHANNEL



Helps in handling the Channel

→ System model for data on subcarriers

$$b_0 = h_0 a_0 + n_0$$
$$\vdots$$
$$b_{N_c-1} = h_{N_c-1} a_{N_c-1} + n_{N_c-1}$$

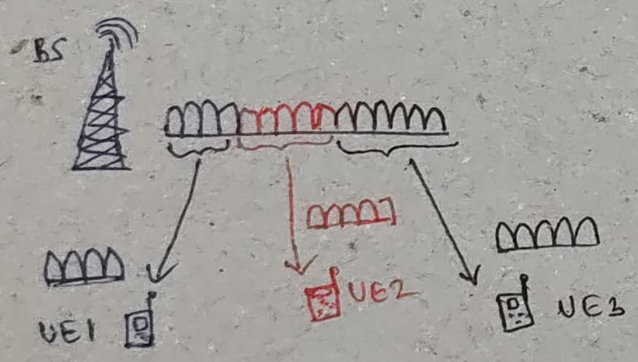
→ Noise is independent across subcarriers.

OFDM as multiple access scheme in 5G - downlink

→ OFDMA - Orthogonal Frequency Division Multiple Access

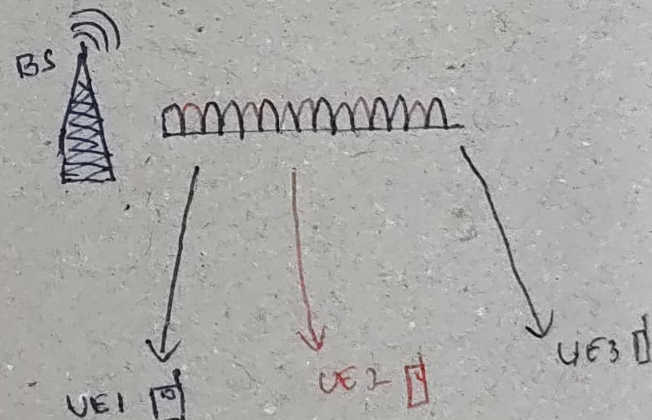
→ Two types of subcarrier allocation

⊙ Localized



⊙ Applicable for pedestrians (or) slow moving users

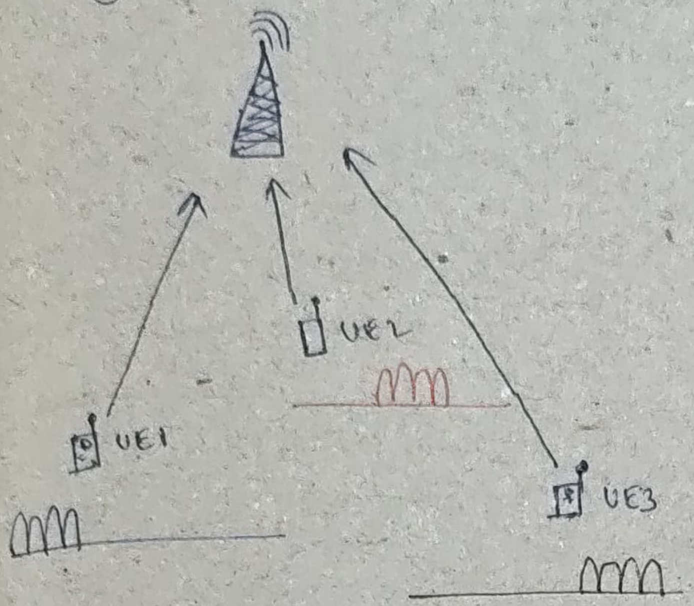
⊙ Distributed



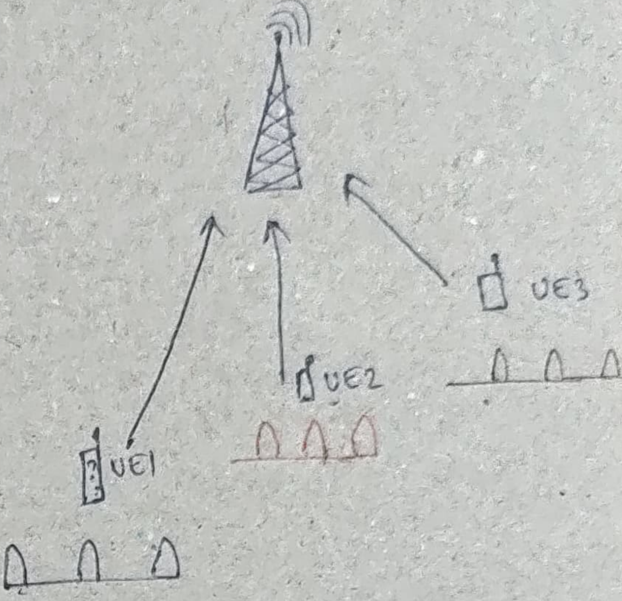
⊛ Applicable for fast moving users

OFDM as multiple access scheme in 5G - Uplink

(i) Localized



(ii) Distributed



Automatic Repeat Request (ARQ) protocol

→ Receiver uses an Error detection code, to check whether a received data block is in error.

→ Error detection code is typically
- Cyclic Redundancy Check (CRC)

→ If no error is detected in the received data block,
- the received data is declared error free
- the transmitter is notified by sending a positive acknowledgement (ACK)

→ If an error is detected,
- the receiver discards the received data
- the receiver notifies the transmitter via a return channel, by sending a negative acknowledgement (NAK)
- In response to an NAK, the transmitter retransmits the same information

Note:

Error Correction Code (FEC)
- LDPC - 5G
- Turbo - 4G

Hybrid - ARQ (HARQ) protocol

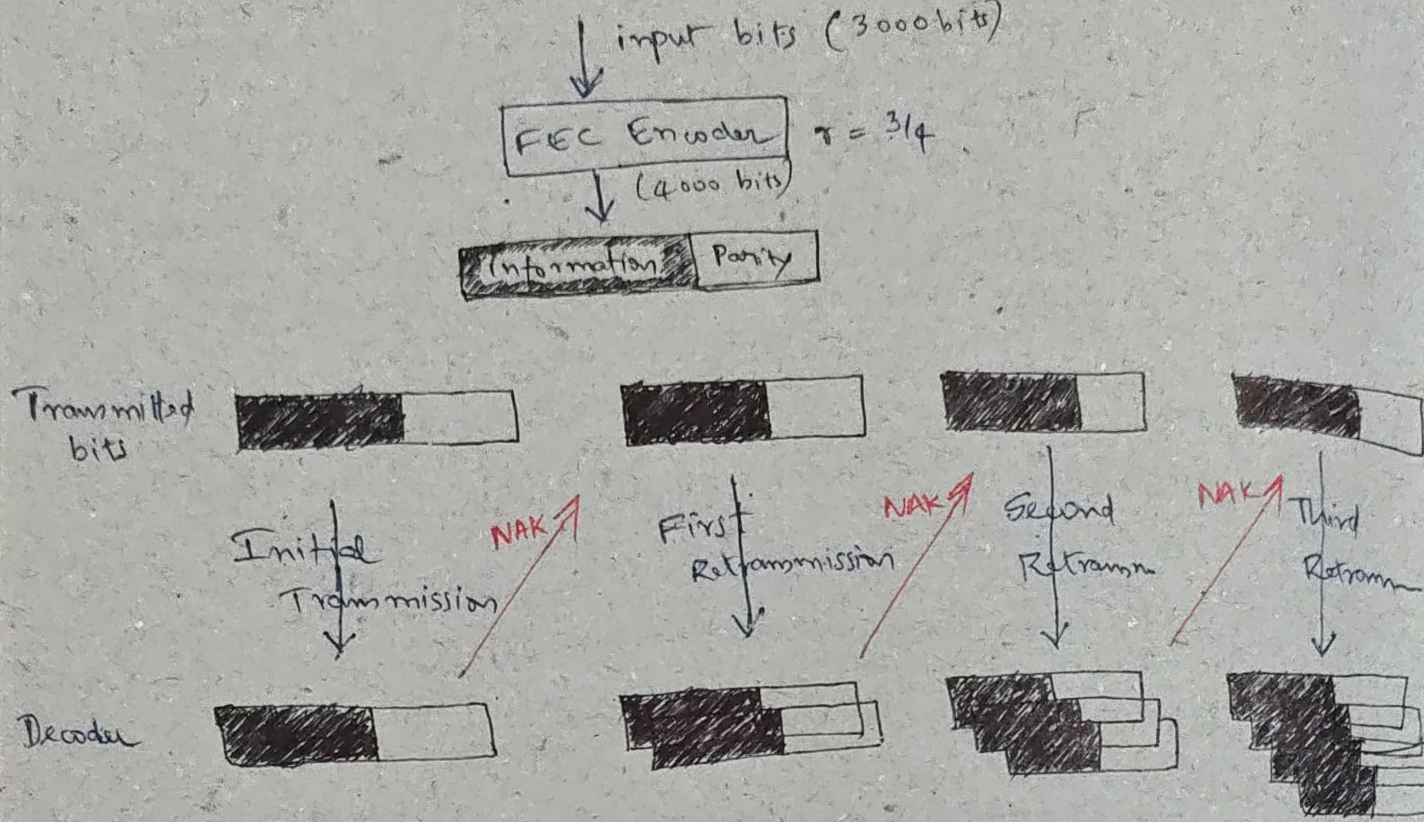
→ All modern communication systems, including 5G NR, employ a combination of FEC and ARQ, which is known as Hybrid ARQ (HARQ)

→ HARQ uses FEC codes, to correct a subset of all errors, and relies on error detection, to detect uncorrectable errors.

→ Erroneously received blocks are retained and receiver requests retransmissions of corrupted packets.

→ Two flavors of HARQ are used
- ⓘ Chase combining
- ⓘⓘ Incremental redundancy.

Hybrid ARQ — Chase Combining



- Consider, code rate $= 3/4$
- Retransmission consist of same set of coded bits as original transmission

(*) Received signal during initial transmission $\Big\}$ $r_1(t) = x_1(t) + n_1(t)$

$$SNR = \frac{E[x^2(t)]}{E[(n(t))^2]} = \frac{P}{\sigma^2}$$

(*) Received signal during first retransmission $\Big\}$ $r_1'(t) = x_1(t) + n_2(t)$

(*) combining $\Rightarrow r_1(t) + r_1'(t)$

$$= 2x_1(t) + n_1(t) + n_2(t)$$

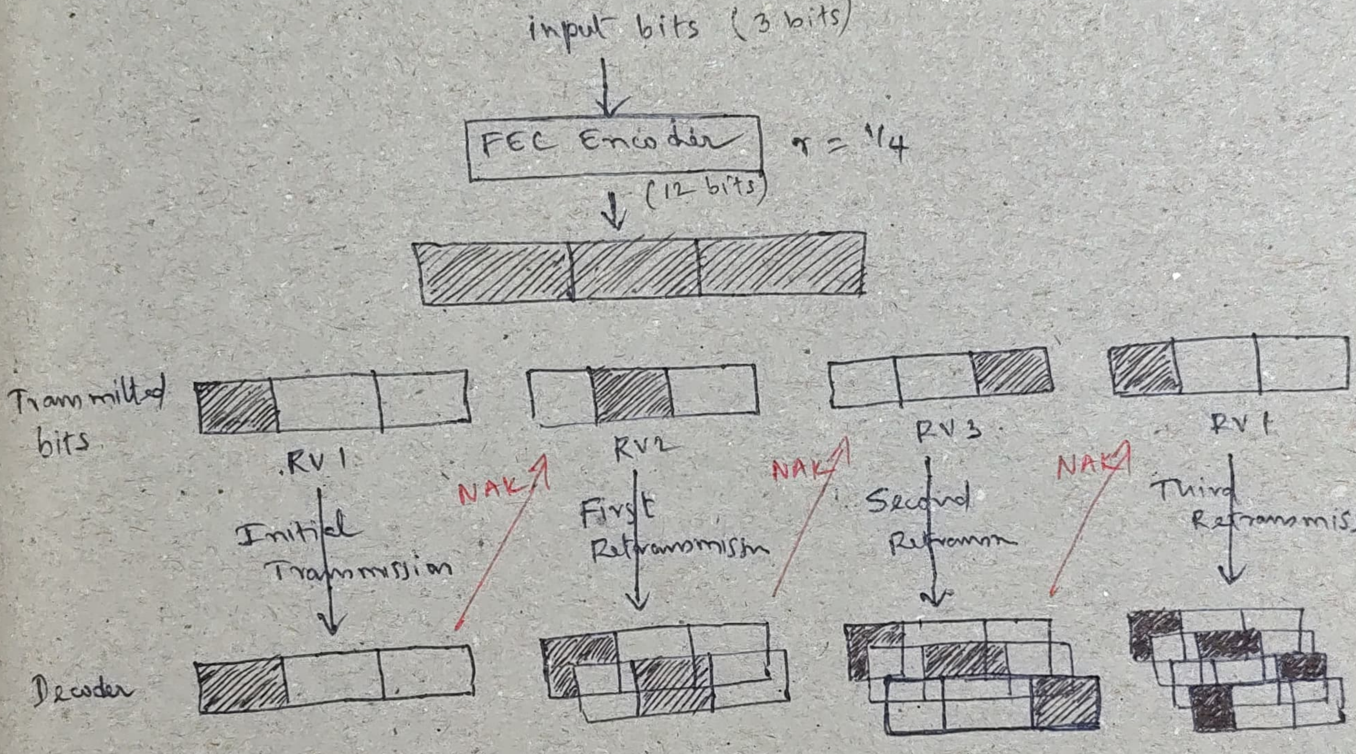
$$SNR_c = \frac{E[(2x_1(t))^2]}{E[(n_1(t)+n_2(t))^2]}$$

$$= \frac{4P}{E[n_1^2(t) + n_2^2(t) + \underbrace{2n_1(t)n_2(t)}_{0}]} = \frac{4P}{2\sigma^2} = \frac{2P}{\sigma^2}$$

- For every retransmission, the receiver combines each received channel bit with the previous transmissions of the same bit.
- combined signal is fed to the FEC decoder
- The Effective code rate remains same.

Note: For every retransmission, the SNR doubles up. Hence, there is better chance of recovering the signals.

Hybrid ARQ – Incremental redundancy (IR)



- Assume a basic rate – 1/4 code.
  Eg.. For 3 message bits, No. of output bits = 12
- For initial transmission, every one third coded bit is only transmitted.
  No. of transmit bits = 4
  Effective code rate = 3/4.

- For first retransmission, 4 additional bits are transmitted.

  Effective code rate $= 3/(4+4) = 3/8$

- For second retransmission, 4 additional bits are transmitted.

  Effective code rate $= 3/(4+4+4) = 3/12 = 1/4$

- For third retransmission, 4 old bits are transmitted.

  Effective code rate $= 3/(4+4+4) = 1/4$.

Chase Combining Vs Incremental Redundancy HARQ.

→ Chase combining framework is easier to implement than IR, but 5G NR provides a generic framework.

→ If all RVs provide the same amount of information about the data packet, Order of the RVs is not critical. However, for some code structures, not all RVs are of equal importance.

Eg. LDPC codes, where the systematic (message) bits are of higher importance than parity bits. Initial transmission should at least include all the systematic bits and some parity bits.

→ In the retransmission(s), parity bits not in the initial transmission can be included. If the initial transmission was received with poor quality or not at all,

- A retransmission with only parity bits is not appropriate
- As a retransmission of (some of) the systematic bits provides better performance.
- Better to use chase combining.