Advanced Digital Communication

Chapter 1. Reminders

1.1.Introduction

Digital Telecommunication is based on the transmission of a digitized signal which is transformed into a binary numerical sequence that is a succession of 0 and 1. This signal can be transmitted via satellites, cable networks, terrestrial broadcasting channels and other medias as MMDS (Multipoint Microwave Distribution System) or ADSL (Asymmetric Digital Subscriber Line).

1.2.Main elements of transmission chain

The data (voice, image, text…) can be analog or digital according to the **source**. The transmission chain includes a three functional blocks at **the transmitter** and three functional blocks at **the receiver**.

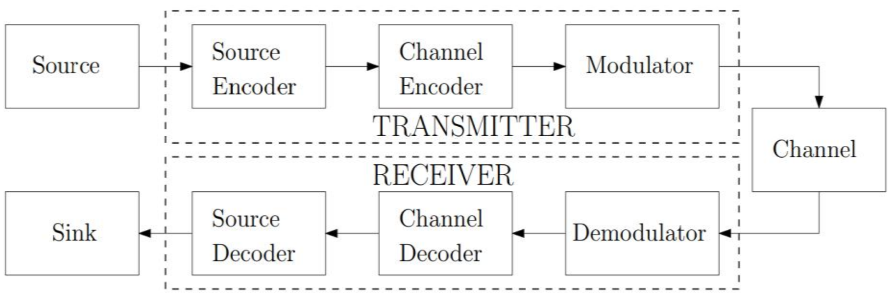


FIGURE 1 – Simplified digital communication chain

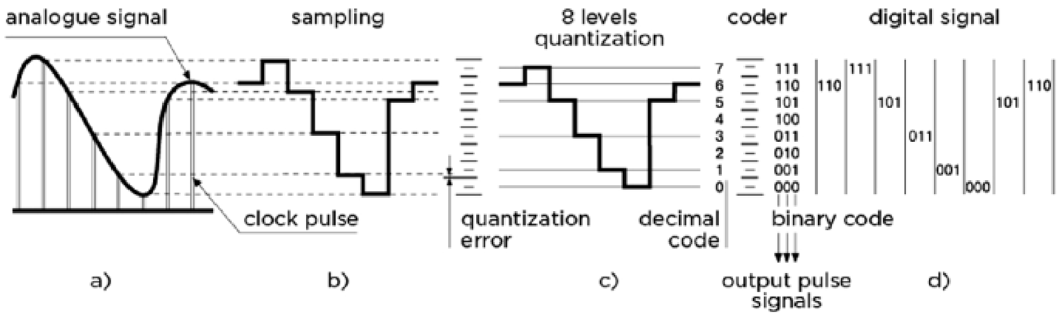
A) Transmitter

1- Source Encoder: Source encoding aims to convert information waveforms (text, audio, image, video, etc.) into binary data. The three major steps are:

a) *Sampling*: convert the continuous-time analog waveform to discrete-time sequence (but still continuous-valued).

b) *Quantization*: convert each continuous-valued symbol to discrete-valued representatives such as integers.

c) *Data compression*: remove the redundancy in the data (Huffman, Shannon-Fano...).



Signal Sampling, Quantization en encoding

2- Channel encoder

The channel encoder introduces some redundancy in the binary information sequence to prevent transmission errors due to the noise and interference encountered by the signal while in transit through the communication channel

Example:

Suppose we want to transmit 101

- Before the transmission, the bits are repeated a certain number times, example 3 times: 111 000 111
- If in the reception we detect: 011 100 111

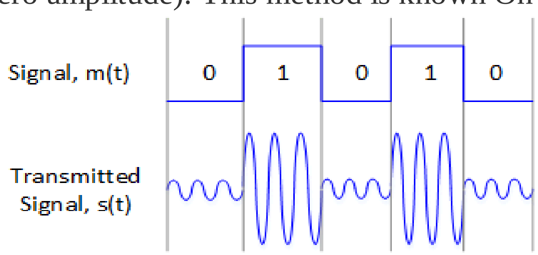
We check for each group of 3 bits, a bit is considered an error if it is different from the other two bits. 011 100 111

3- Modulator: serves as the interface to the communication channel. The encoded sequence is modulated using suitable digital modulation techniques transmitted over the communication channel. Techniques of modulation**:**

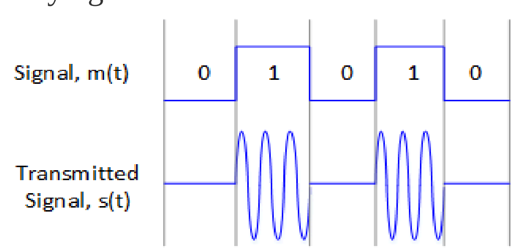
a) Amplitude Shift Keying (ASK).

In the ASK the radio wave carrier with changes in amplitude corresponding to the "HIGH (1)" and "LOW (0)" level in our signal.

For the LOW level representation, the radio wave carrier could just be switched OFF (i.e zero amplitude). This method is known On-Off keying or **OOK**



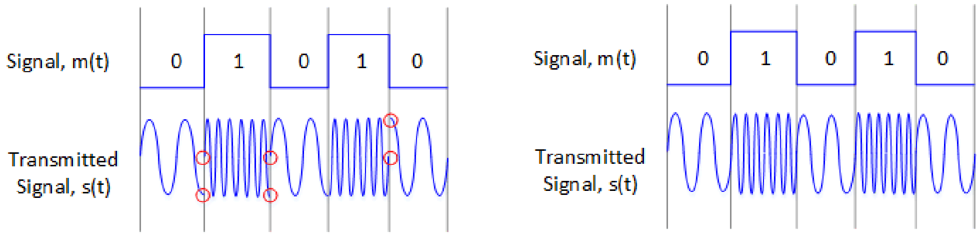
ASK modulation



ON-OFF Keying (OOK)

b) Frequency Shift Keying or FSK

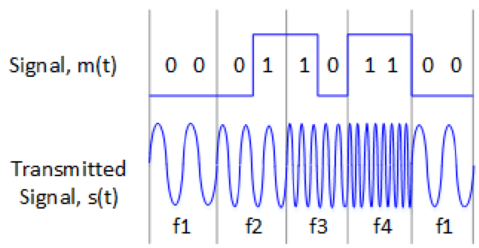
The radio wave carrier with shifts in frequency corresponding to the "HIGH(1)" and "LOW(0)" level in our signal. SK can be implemented by switching 2 oscillators of different frequency in response to our digital signal.



FSK modulation with phase discontinuity (left): coherence FSK and phase continuity (right): non coherence FSK

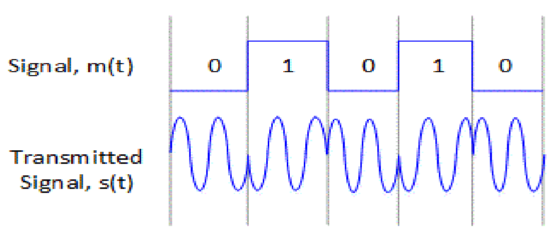
FSK variants

By grouping 2 bits together forming 4 symbols (00,01,10,11) and each symbol can be mapped to a frequency value



c) Phase Shift Keying (PSK)

The radio wave carrier with shifts in phase corresponding to the "HIGH (1)" and "LOW (0)" level in our signal. This is known as **Phase Shift Keying or PSK.** The simplest PSK is **BPSK (Binary Phase Shift Keying)** where a single bit is mapped to one phase shift. For example, bit 0 can be 0 degrees and bit 1 can be 180 degrees phase shift.



BPSK modulation

d) QAM

QAM (Quadrature Amplitude Modulation) is a modulation scheme used in wireless communication systems, including Wi-Fi. Different types of QAM modulation are characterized by the number of amplitude and phase levels they use, which directly affects the number of bits per symbol that can be transmitted.

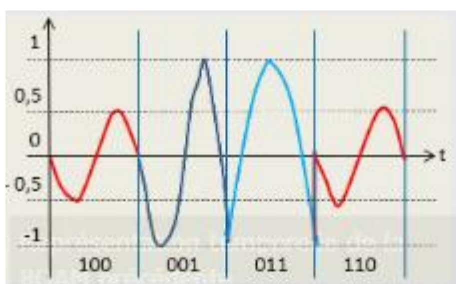
Example

1- QPSK (Quadrature Phase Shift Keying): QPSK uses 4 different phase shifts to encode 2 bits per symbol. Each symbol represents 2 bits of data.

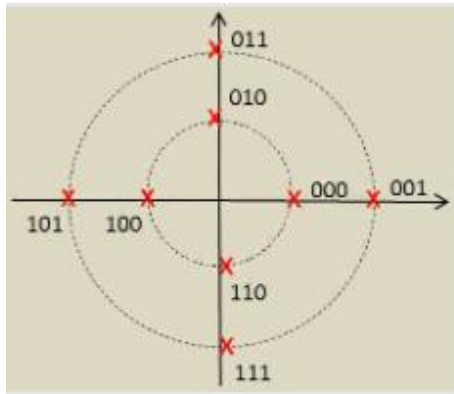
2- 8QAM : in this case 3 bits per symbol is transmitted, counting 2^8 combinations, we use 2 different amplitudes whish give us codes:

Groupe bits	Amplitude	Déphasage
000	0.5	0
001	1	0
010	0.5	$\pi/2$
011	1	$\pi/2$
100	0.5	π
101	1	π
110	0.5	$3\pi/2$
111	1.	$3\pi/2$

The temporal representation of 8 QAM



The constellation representation of 8 QAM



Remark: there are many versions of QAM (16-QAM, 64-QAM, 256-QAM,…):

16-QAM : uses 16 different amplitude and phase combinations to encode 4 bits per symbol.

64-QAM uses 64 different amplitude and phase combinations to encode 6 bits per symbol.

….

Channel: support of transmission (cable, optical fiber, WIFI,..) that allows transfer of data from point to point or point to multi-points.

4- Receiver: composed of three blocks

a) Demodulator : demodulates the received data to obtain a sequence of channel encoded data in digital format

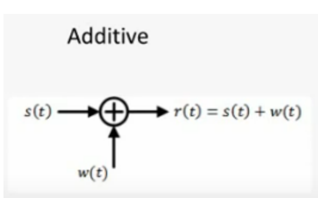
b) **Chanel decoder:** Decode dada using redundant data inserted in the encoder block.

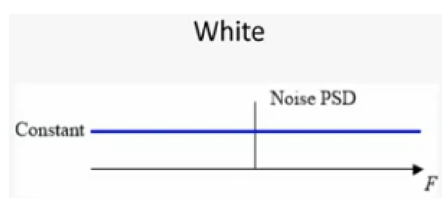
c) Source decoder: Decompress and reconstructs the original information message.

1.3.Noise

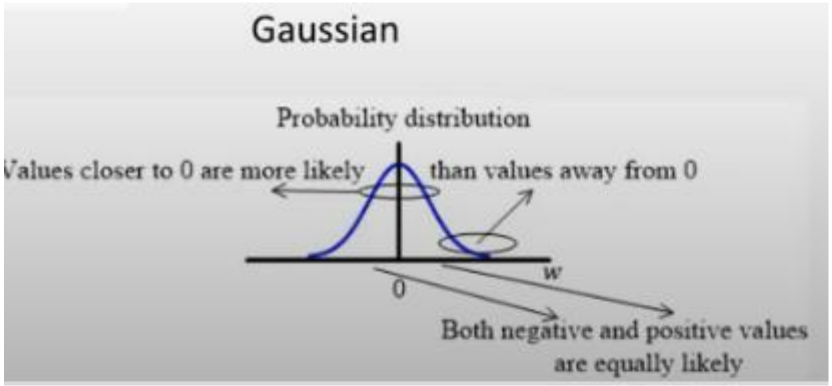
a) Additive white Gaussian noise (AWGN) model

Noise power is a measure of the average power of the noise signal. For AWGN, noise power is related to the noise variance.





- Noise is typically modeled as a Gaussian random variable N(t) with a mean of zero and variance σ_n^2.



- The power of the noise Pn is equal to the variance σ_n^2.

Formula for Noise Power

$$Pn=\sigma_n^2$$

This equation tells us that the noise power is simply the variance of the noise.

b) Thermal Noise (Johnson-Nyquist noise**)**

- It originates from the random motion of electrons in any conductor due to thermal agitation. In many practical systems, noise power is often described in terms of thermal noise. The thermal noise power Pn over a bandwidth B is given by:

$$P_n = kTB$$

Where:

  - k is Boltzmann's constant (1.38×10^{-23} J/K).
  - T is the absolute temperature in Kelvin.
  - B is the bandwidth in Hertz.

Example

Lets a communication receiver operating over a bandwidth of 10 MHz at temperature 290K. The thermal noise power can be calculated as:

$$P_n = kTB = (1.38 \times 10^{-23}\,\mathrm{J/K})(290\,\mathrm{K})(10 \times 10^{6}\,\mathrm{Hz})$$

$$P_n = 4.002 \times 10^{-15}\,\mathrm{W} = -144\,\mathrm{dBm}$$

This means that any signal weaker than -144 dBm (decibels per milliwatt) would be covered under thermal noise, making reliable detection extremely difficult.

- **Mitigation Techniques:**

While thermal noise cannot be eliminated, its effects can be managed through techniques such as:

1. **Increasing Signal Power**: Boosting the signal power can improve the SNR, making the signal more distinguishable from noise.
2. **Reducing Bandwidth**: By limiting the bandwidth, the noise power can be reduced (since $Pn \propto B$).
3. **Cooling Components**: Reducing the temperature of components (e.g., in deep-space receivers) can lower Pn.

1.4. Metrics of transmission chain assessment

Numerous metrics are used to assess the reliability

a) Signal to noise ratio (SNR)

It is an indicator used to evaluate the quality of a communication link. It means a communication link is in good condition when the SNR is higher (Arokia & Maran 2016). The SNR is computed as ratio of the signal power to the noise power in decibel (dB).

$$SNR = 10log_{10}\left(\frac{P\_signal}{P\_noise}\right)$$

P_signal: signal power

P_noise: noise power

- The maximum data rate in presence of the noise is given by the Shannon-Harley theorem that states:

$$C=R=B.\log_2(1+SNR)$$

C is the capacity (data rate).
B is the bandwidth.
$\frac{S}{N}$ is the SNR (linear).

b) A Bit Error Rate (BER)

The noise can alter Bits (0/1) in binary sequence. The Bit Error Rate (BER) is a measure of how many Bits are received in error compared to those transmitted.

$$BER = \frac{number\ of\ bits\ received\ in\ error}{total\ number\ of\ bits\ transmitted}$$

c) Spectral efficiency

Spectral efficiency is a measure of the performance of channel coding methods. It refers to the ability of a given **channel encoding method** to **utilize bandwidth efficiently**.

Spectral efficiency is defined as the data rate (or throughput) transmitted per unit bandwidth. Mathematically, it is expressed as

$$\boldsymbol{\eta = \frac{R}{B}}\ \textbf{(bits/s/Hz)}$$

where:

η: is the spectral efficiency in bits per second per Hertz (bits/s/Hz).
R: is the data rate (bits/s).
R=(Symbol rate) x (number of Bits per symbol)
B: is the bandwidth (Hz).

In the **wireless networks** where we consider spatial dimensions along with the traffic load, bandwidth, and area the spectral efficiency is computed as:

$$\boldsymbol{\eta = \frac{Total\ carried\ traffic\ intensity}{Total\ BW\ \times Total\ Area}}$$

- Total Carried Traffic Intensity: This usually refers to the aggregate data throughput (or total traffic) over a given region. In mobile or cellular networks, this can be expressed as the sum of the data rates (in bps) handled by the network in a given area.
- Total Bandwidth: This is the sum of the frequency bandwidth (in Hz) used by the network in that area.
- Total Area: This term represents the geographic area (e.g., in square kilometers) over which the network is operating.

Factors Affecting Spectral Efficiency: Several factors influence spectral efficiency, including:

- **Modulation Scheme**: More advanced modulation schemes (like QAM) can increase spectral efficiency.
- **Coding Techniques**: Efficient error-correcting codes can improve data rates without increasing bandwidth.
- **Signal-to-Noise Ratio (SNR)**: Higher SNR can lead to higher spectral efficiency as it allows for more complex modulation schemes.
- **Multiple Access Techniques**: Techniques like OFDM, CDMA, and MIMO can significantly impact spectral efficiency.

Examples

Suppose a communication system has a symbol rate 10Msymbol/s, each symbol is 1bit and uses a bandwidth of 5 MHz.

Data rate R:

R= symbol rate X Bits per symbol
R=10Msymbol/s x 1bite/symbol =10Mbps

The spectral efficiency would be:

$$\eta = \frac{10Mbps}{5MHz} = 2bps/Hz$$

Let’s assume the system still uses 16-QAM modulation (4 bits per symbol) with the same symbol rate of 10Msymbol/s. However, now we keep the bandwidth fixed at 5MHz, just like in the first example.

- **Data rate R**:

R=10Msymbole/s x 4bits/symbol
R=40Mbps

- η **with the same 5MHz bandwidth**
  η =40Mbps/5MHz
  η = 8bps/Hz

Interpretation

After upgrading to 16-QAM, the **spectral efficiency increases by a factor of 4** (from 2 bit/s/Hz to 8 bits/s/Hz). This means that, without increasing the bandwidth, the system can now transmit **4 times more data** over the same frequency band, demonstrating a more efficient use of the available spectrum.

Practical Considerations

In real-world scenarios, achieving high spectral efficiency requires addressing issues like interference, propagation conditions, and regulatory constraints. Techniques like adaptive modulation and coding, power control, and advanced signal processing are often employed to optimize spectral efficiency.

By improving spectral efficiency, communication systems can accommodate more users and higher data rates without needing additional spectrum, which is a valuable and often limited resource.

1.5.Relationship between BER, SQR and mQAM

How are BER and SNR related for PSK and QAM

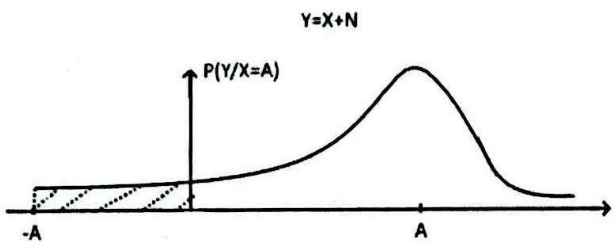
Lets Y the received signal and X the transmitted signal that affected by noise N (AWGN)

So: Y=X+N

N: Gaussian noise

A conditional probability of y given X: P(Y/X=A)

- **BPSK**



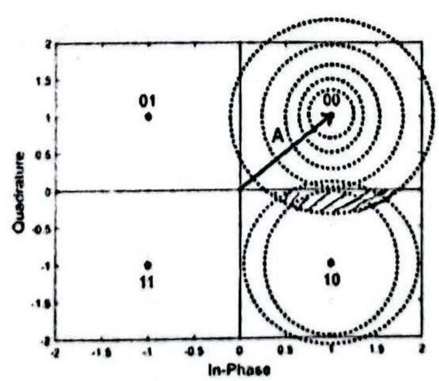
The hashed surface means a probability to receive an error (negative phase on BPSK)

$$BER=1-\int_0^{\infty}\frac{1}{\sqrt{2\pi\sigma^2}}e^{-\frac{(Y-A)^2}{2\sigma^2}}dy$$

And, $SNR=\frac{A^2}{N_0}$

- **QAM**

Now let have a advanced modulation (QAM), 2 bit per symbol, so we talk about SER rather tha BER



a) mQAM

In mQAM, the number of constellation points (m) indicates the modulation order. Each point represents a different combination of amplitude and phase of the carrier signal.

- **Higher m** (e.g., 64-QAM) allows for more bits per symbol (**increased data rate**) but **requires a higher SNR** for reliable transmission.
- **Lower m** (e.g., 4-QAM or QPSK) is **more robust to noise** but offers **lower data rates.**

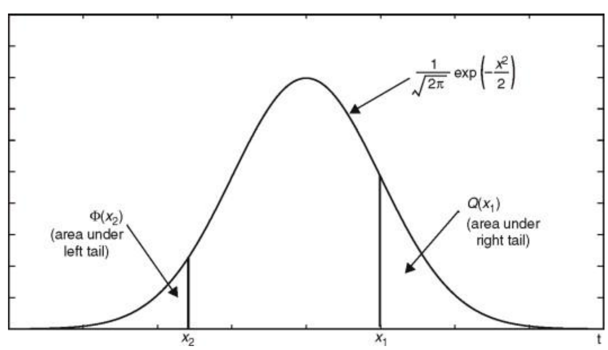
b) Bit Error Rate (BER):

BER measures the fraction of bits received incorrectly over the total transmitted bits. In mQAM, BER depends on both the modulation order m and the SNR.

For **mQAM** in an **AWGN** channel, an approximate expression for BER can be derived using the **Q-function**:

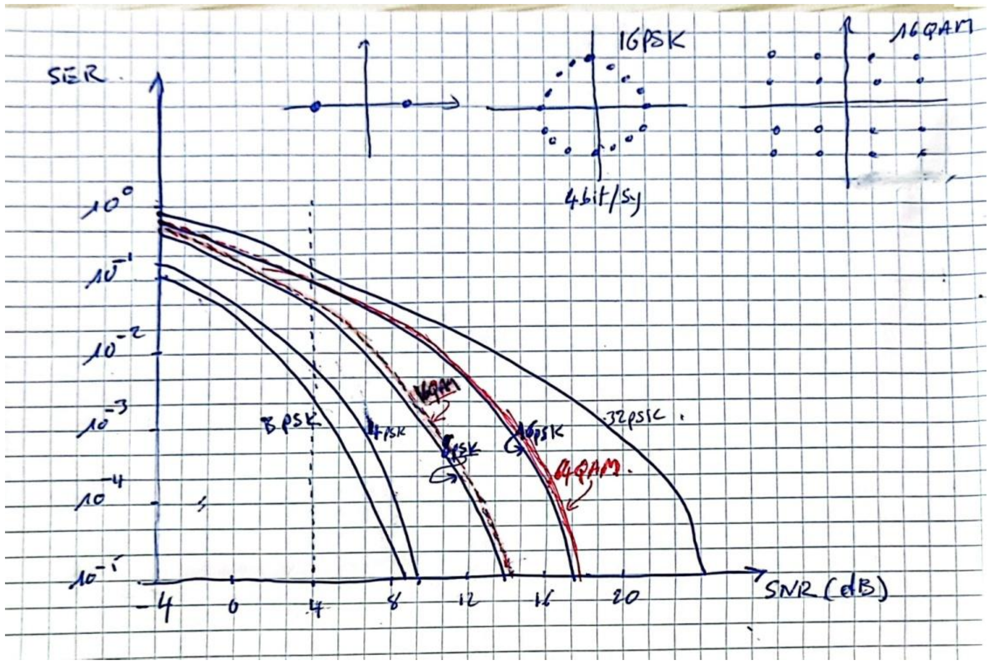
$$BER \approx \frac{4}{n}(1-\frac{1}{\sqrt{m}})Q(\sqrt{\frac{3n \cdot SNR}{m-1}})$$

- Where the **Q function** is the tail probability of a Gaussian distribution



$$Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^{\infty} e^{-\frac{t^2}{2}}\, dt$$

- $n = \log_2(m)$
  Exp: for 16QAM ➔ $n = \log_2(16) = 4$



SER in $\log_2$

10^{-1} ➔ 1 error every 10 symbols

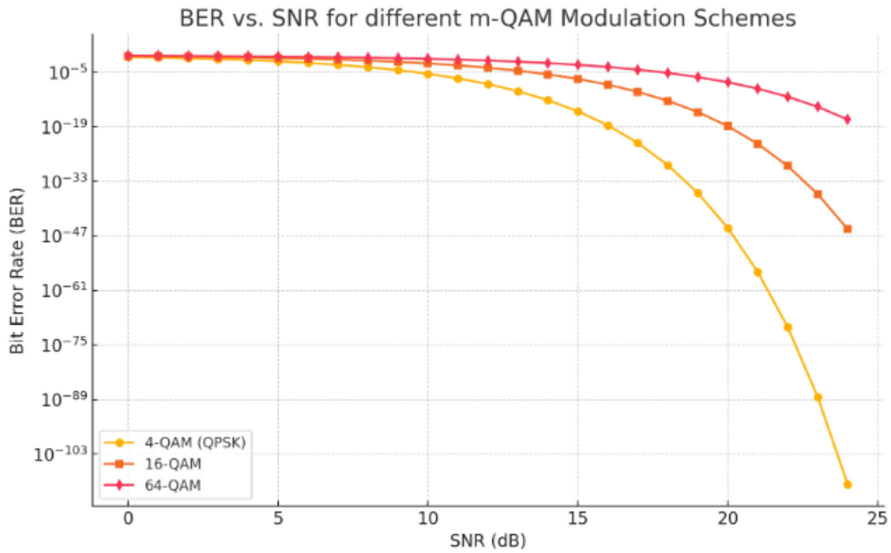
10^{-2} ➔ 1 error every 100 symbols

For a fixed SNR,

- BPSK (data rate 1bit/sym) ➔ 1 err each 1000 sym
- 4PSK (data rate 2bit/sym) ➔ 1 err each 100 sym
- 16PSK (data rate 4bit/sym) ➔ 1 err each 10 sym

Remarque:

- When we increase the data rate the probability of making error rises, and we need powerful signal (SNR).
- For a fixed SNR, we making the lower amount of error using whether 16QAM then using 32psk. The advantage of QAM is that the rata rate is more important but we need the amplify the signal because QAM depends on amplitude and phase unlike the PSK that depends only on phase



Here is the BER vs. SNR plot for different mQAM schemes (4-QAM, 16-QAM, and 64-QAM).

As seen in the plot:

4-QAM (QPSK) has the lowest BER for a given SNR, making it more robust to noise.

16-QAM requires a higher SNR to achieve the same BER compared to 4-QAM.

64-QAM demands an even higher SNR for the same BER, reflecting its greater sensitivity to noise due to the closer spacing of constellation points.