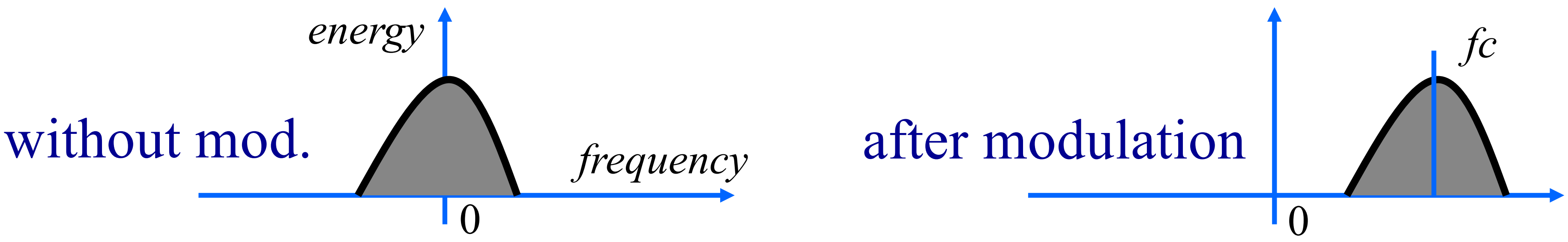
Part 2:
Wireless Communication

- Section 1: Wireless Transmission
- *Section 2: Digital modulation*
- Section 3: Multiplexing/Medium Access Control

Digital Modulation

Why Modulate?

- Modulation is the process of encoding information from a message source in a manner suitable for transmission
- In general it involves translating a baseband signal (source signal) to a modulated signal signal at a higher frequency (carrier frequency, f_c)



- Motivations:
  - Reduce antenna size: by increasing the carrier frequency, the wavelength λ decreases, as well as the antenna size (proportional to λ)
  - Allow to share the spectrum by choosing different f_c

Digital vs Analog Modulation

- Analog modulation uses mainly AM (Amplitude) and FM (Frequency Modulation)
  - characterized by a continuous variation of the parameter being modulated

- Modern mobile communication systems use digital modulation techniques
  - characterized by a discrete variation of the parameter(s) being modulated

- Offers key advantages:
  - greater noise immunity and **robustness** to channel impairments
  - more **flexibility**

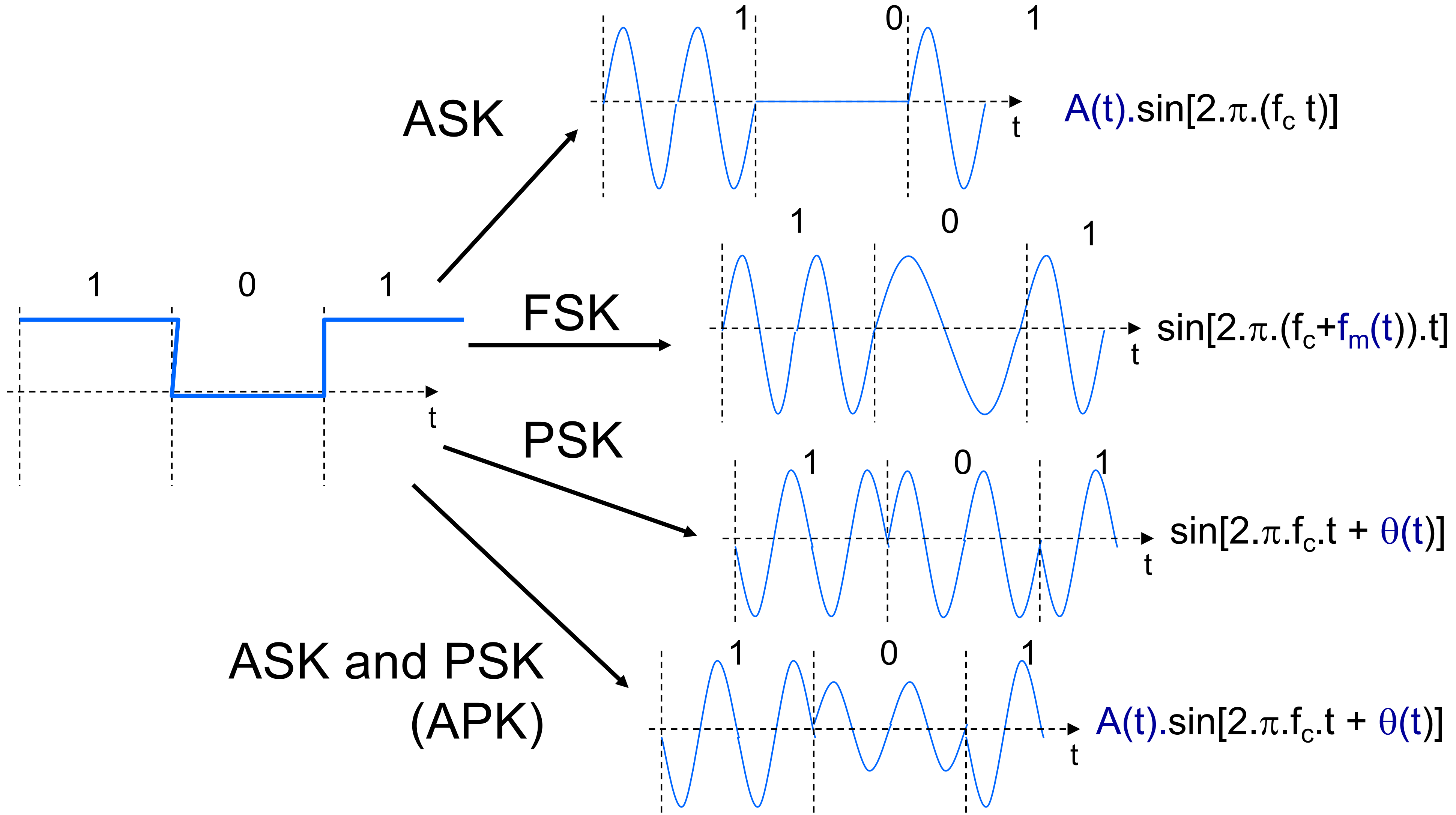
Digital Modulation techniques

- Process by which a sequence of pulses (message) of duration T is transformed into a sequence of sinusoidal waveforms, s(t) of duration T.
- The general form of the modulated signal is:

$$\boxed{s(t) = A(t).\sin[2.\pi.(f_c + f_m(t)).t + \theta(t)]}$$

- Digital modulation can then be defined as the process whereby the amplitude, frequency, phase or a combination of them is varied in accordance with the information to be transmitted
- A scheme that uses:
  - amplitude is called ASK (Amplitude Shift Keying)
  - frequency is called FSK (Frequency Shift Keying)
  - phase is called PSK (Phase Shift Keying)

Digital Modulation techniques (2)



Factors that influence the choice of Digital Modulation

The performance of a modulation scheme is often measured in terms of its **power and bandwidth efficiencies**.

- **Power efficiency:**
  - Problem: in order to increase noise immunity (i.e. maintain a certain BER, or Bit Error Rate), it is necessary to increase the signal power

    Power efficiency describes the ability to preserve the fidelity of a digital message at low power levels
  - The power efficiency expresses the "signal energy over the noise energy" ratio (**Eb/No**) required at the receiver to guaranty a certain BER

Factors that influence the choice of Digital Modulation (2)

- **Bandwidth efficiency:**
  - Problem: increasing the data rate implies decreasing the pulse width of the digital symbol, which increases the bandwidth of the signal.
  - Bandwidth efficiency describes how efficiently the allocated bandwidth is used
  - Defined as the ratio of the throughput per Hertz (bps/Hz)
  - Shannon theorem gives the fundamental upper bound:

$$C / B_w = \log_2(1+S/N)$$

    where C is the channel capacity (bps), B_w the bandwidth (Hz) and S/N the signal-to-noise ratio.

Factors that influence the choice of Digital Modulation (3)

- Very often there is a tradeoff
  - adding **error correction coding** reduces the bandwidth efficiency (redundant information is transmitted) but increases the power efficiency (fewer remaining errors at lower S/N)
  - **M-ary schemes** increase the bandwidth efficiency but require higher transmission power to keep the same BER

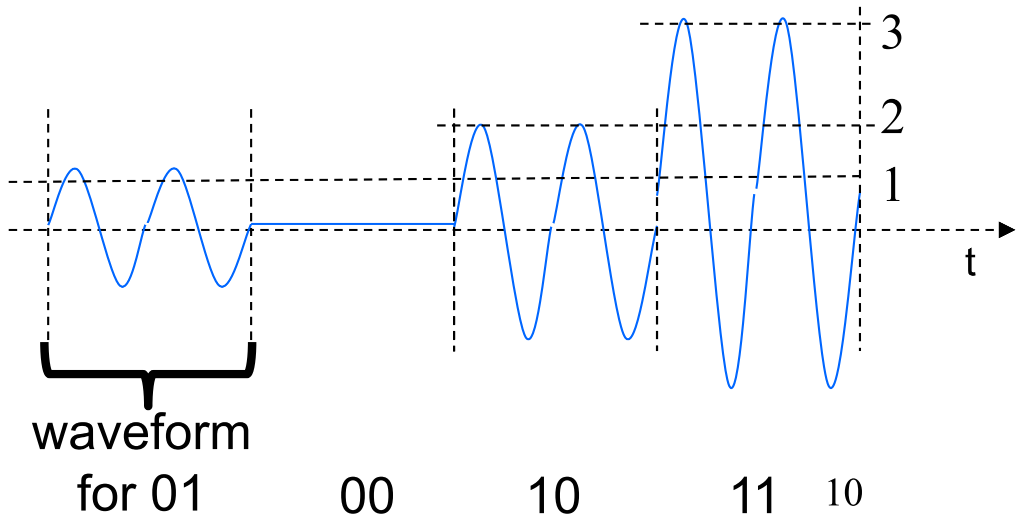
- Other factors are important
  - cost and complexity of the receiver
  - for wireless networks, the robustness under various types of channel impairments such as Rayleigh fading and multipath dispersion

Amplitude Shift Keying (ASK)

$Si(t) = A_i(t) \sin[2.\pi.f_c.t + \theta]$ $0 \leq t \leq T, i = 1.. M$

– where the amplitude has M discrete values

- If M =2, the amplitude is either 0 or 1. The scheme is called Binary ASK.
- If M > 2, each waveform carry $\log_2(M)$ bits. This scheme is therefore more bandwidth efficient. It is called M-ary ASK.
  – M = 4; $\log_2(4)$ = 2 bits/waveform
    » $A_1 = 0$ corresponds to 00
    » $A_2 = 1$ corresponds to 01
    » $A_3 = 2$ corresponds to 10
    » $A_4 = 3$ corresponds to 11

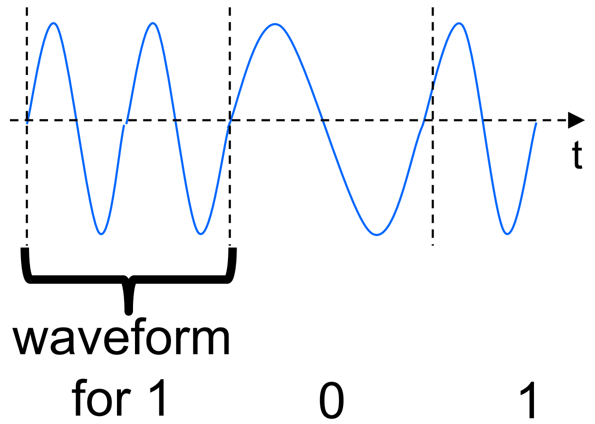


Frequency Shift Keying (FSK)

$Si(t) = (2E/T)^{1/2} \sin[2.\pi.(f_c + f_i).t + \theta]$ $\quad 0 \leq t \leq T, i = 1.. M$

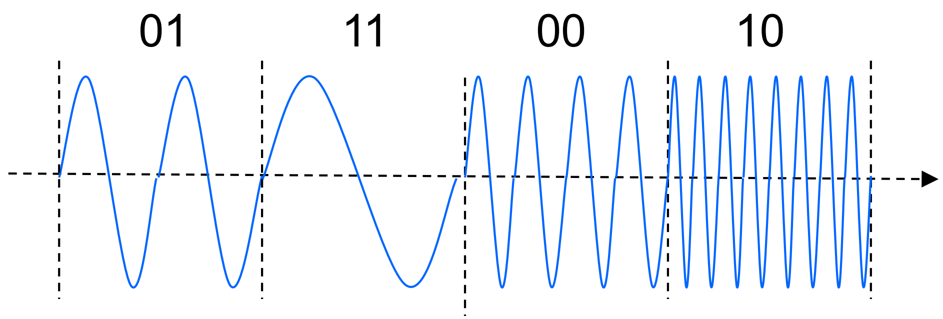
– where f_i has M discrete values, E is the symbol energy and T the symbol time duration.

- If M =2, the scheme is called Binary FSK and the carrier frequency switches between 2 values
  - » $f_1 = f_c + f_m$ *corresponds to bit 1*
  - » $f_0 = f_c - f_m$ *corresponds to bit 0*



Frequency Shift Keying (FSK) (2)

- If M > 2, each waveform carries $\log_2(M)$ bits. This scheme is therefore more bandwidth efficient. It is called M-ary FSK.
  - M = 4; $\log_2(4)$ = 2 bits/waveform
    - » $f_1 = fc + f_m$ corresponds to 00
    - » $f_2 = fc - f_m$; corresponds to 01
    - » $f_3 = fc + 2\ f_m$ corresponds to 10
    - » $f_4 = fc – 2\ f_m$ corresponds to 11

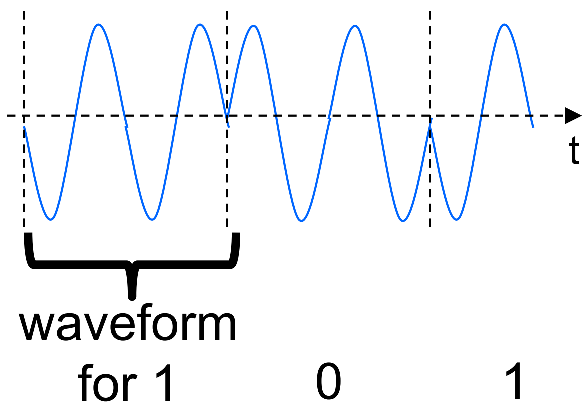


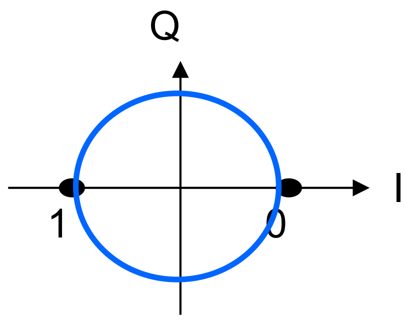
Phase Shift Keying (PSK)

$Si(t) = (2E/T)^{1/2} \sin[2.\pi.f_c .t + \theta_i(t)]$ $0 \le t \le T,\ i = 1..\ M$

- where the phase $\theta_i(t)$ *has M discrete values given by:* $\theta_i(t) = 2.\pi.i/M$
- *M-ary PSK can displayed as* ***constellation*** *diagrams*

- If M =2, the scheme is called Binary PSK and the phase switches between 2 values, *0* and π.
  - $\theta_i(t) = 0$ *corresponds to 0*
  - $\theta_i(t) = \pi$ *corresponds to 1*

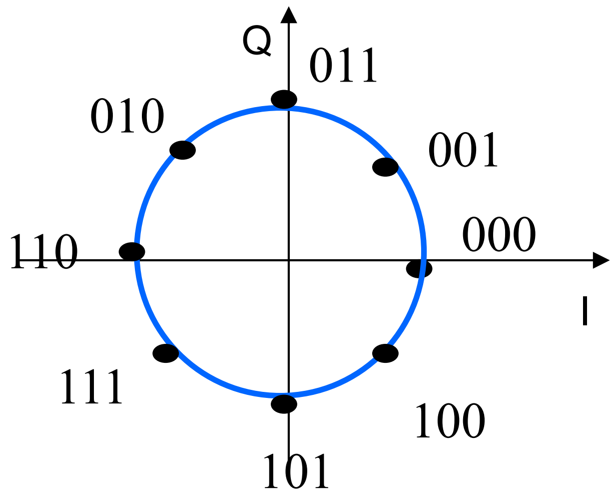




constellation diagram

Phase Shift Keying (PSK) (2)

- If M > 2, the scheme is called M-ary PSK and carries $\log_2(M)$ bits/waveform
  - *If M=8, 3 bits/waveform*
    - » $s0(t) = (2E/T)^{1/2} \sin[2.\pi.f_c.t]$
    - » $s1(t) = (2E/T)^{1/2} \sin[2.\pi.f_c.t + \pi/4]$
    - » $s2(t) = (2E/T)^{1/2} \sin[2.\pi.f_c.t + \pi/2]$
    - » ...
    - » $s7(t) = (2E/T)^{1/2} \sin[2.\pi.f_c.t + 7.\pi/4]$



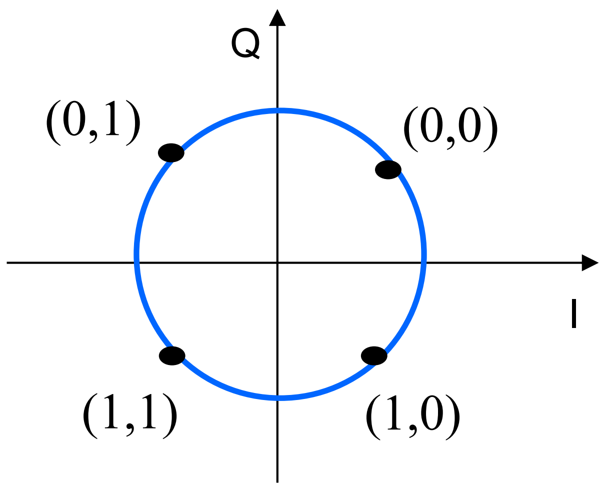
constellation diagram

- Question : how to assign bits to waveforms? Are all solutions equivalent? In practice Gray Codes are used to limit bit errors for adjacent waveforms…

A particular case: Quadrature PSK (QPSK)

- If M=4 then the scheme is called Quadrature PSK

$$Si(t) = (2E/T)^{1/2} \cos[2.\pi.f_c.t + \iota.\pi/2] \quad i = 1,..4$$



constellation diagram

Phase Shift Keying (PSK) (3)

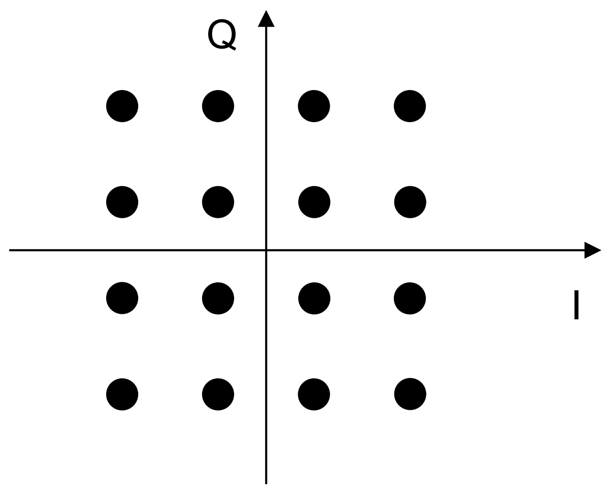
- the bandwidth efficiency of an M-ary PSK scheme increases as M increases (more bits per waveform)
- ...however the distance between 2 points in the constellation is reduced, so the error rate increases too
- As M increases, the transmission power must be increased to keep the BER (Bit Error Rate) at a target (e.g., 10^{-6}) and the power efficiency decreases

M	2	4	8	16	32	64
R/B_w in bits/Hz (**bandwith efficiency**)	0.5	1	1.5	2	2.5	3
required S/N (**power efficiency**)	10.5	10.5	14	18.5	23.4	28.5

Amplitude and Phase modulation

- M-ary QAM modulates both the amplitude and phase of the carrier
  - called Quadrature Amplitude Modulation (QAM) because waveforms can be produced as the sum of two carriers that are out of phase by 90°, each of them being subject to an ASK

- If M=16, it is called 16-QAM
  - M = 16; $\log_2(16)$ = 4 bits/waveform
  - NB: energy per waverform isn't constant
    $\Rightarrow$ some waveforms are more prone to errors than others

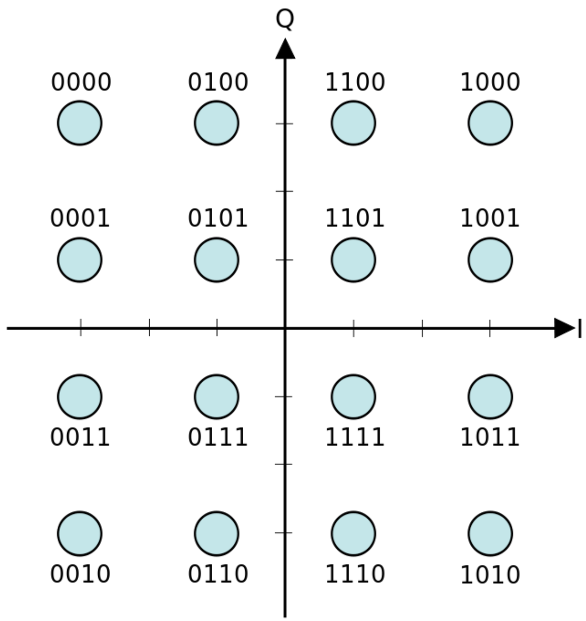


constellation diagram

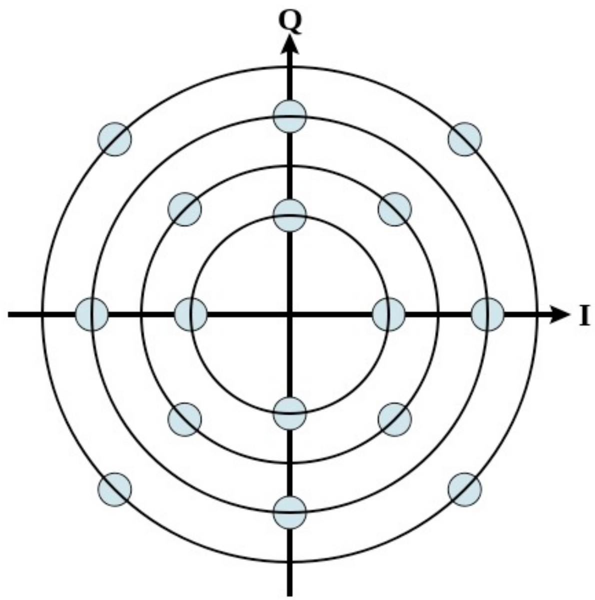
see https://en.wikipedia.org/wiki/Quadrature_amplitude_modulation

Amplitude and Phase modulation

- 16-QAM, 64-QAM and 256-QAM are common
  - no M-ary ASK, FSK or PSK can reach such a high bandwidth efficiency with a good power efficiency
- for a given M value, several constellations are possible
  - differ by the easiness to produce the waveforms
  - differ by their noise immunity (distance between contiguous waveforms)



constellation diagram for rectangular 16-QAM



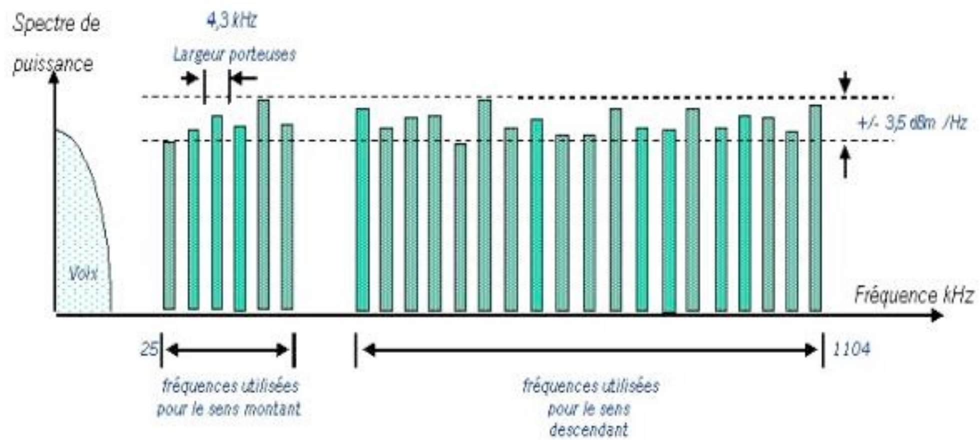
constellation diagram for circular 16-QAM

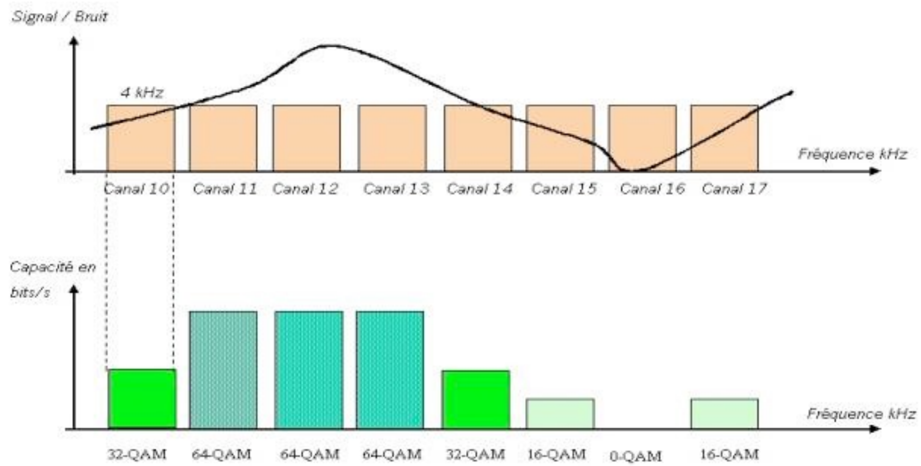
multi-carrier modulation with OFDM

- idea: it is more efficient to split the available bandwidth into sub-carriers than modulating a single carrier
  - more **flexible**
  - **adaptable to varying noise conditions** at certain frequencies
- Orthogonal Frequency Division Multiplexing (OFDM) uses
  - multiple narrow-band sub-carriers
  - sub-carriers are orthogonal, i.e., do not overlap with one another
  - use the most appropriate QAM modulation on each sub-carrier
  - spread information on the sub-carriers
    - » e.g., those with higher M-ary QAM transmit more bits
- now used almost everywhere
    - » ADSL
    - » Wifi (IEEE 802.11g and above)
    - » DVB-T (French TNT)
    - » 4G/LTE (variant of OFDM)

multi-carrier modulation with OFDM (2)

- Example: ADSL (i.e., a **wired** technology!)
  - 256 channels, each of bandwidth 4.4 KHz
  - channel 1: analogic voice
  - channel 2 to 6: signaling
  - 250 remaining channels [25 kHz, 1.1 MHz]: upstream/downstream data
  - measure S/N of each channel and adjust the M-ary QAM accordingly





multi-carrier modulation with OFDM (3)

- Example: 4G/LTE

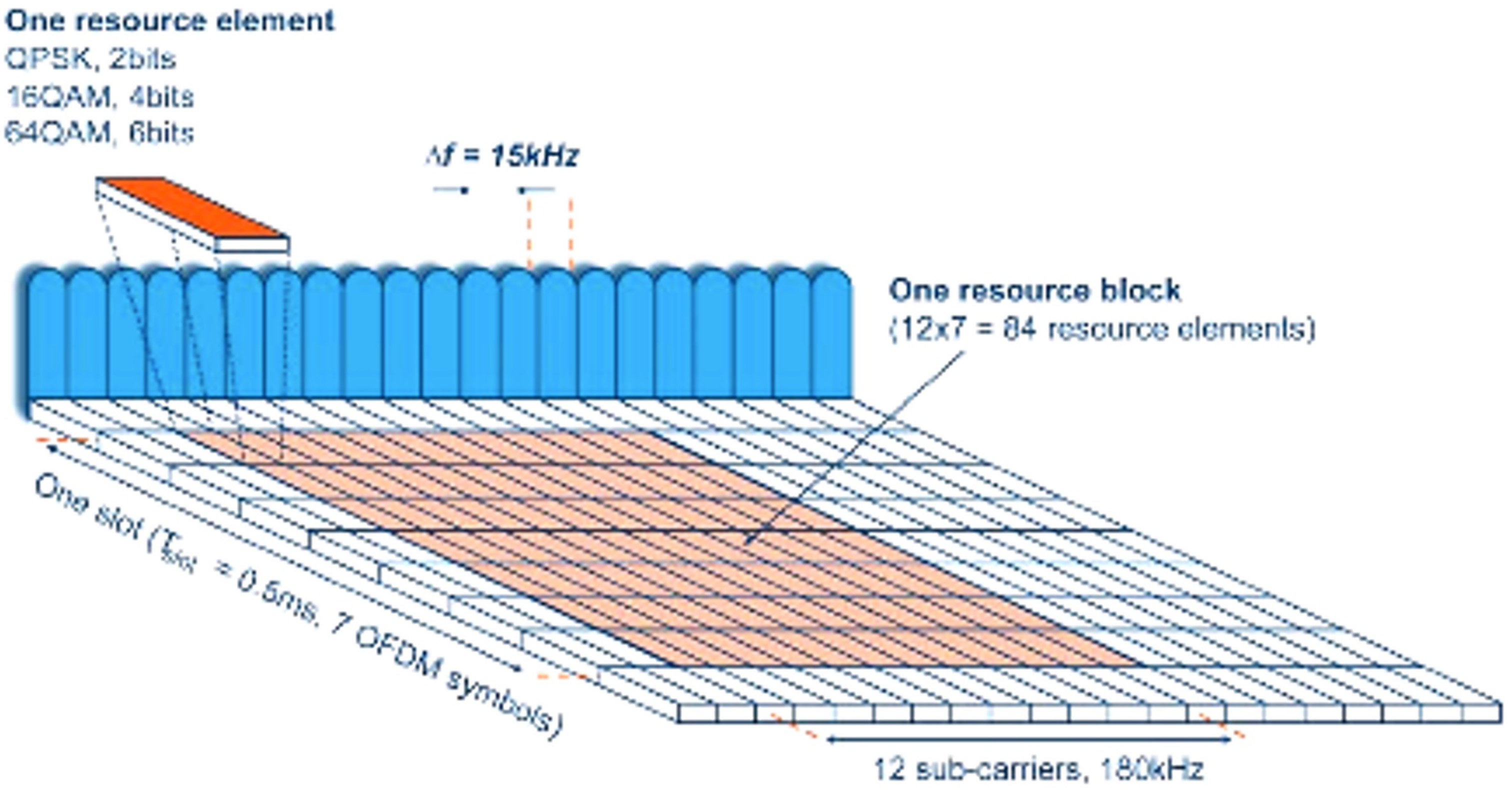


Figure 4: The LTE downlink physical resource based on OFDM