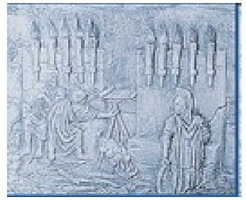
Department of Computer Engineering & Informatics

Laboratory for Signal Processing and Communications

Wireless and Mobile Communications

Key Technologies:

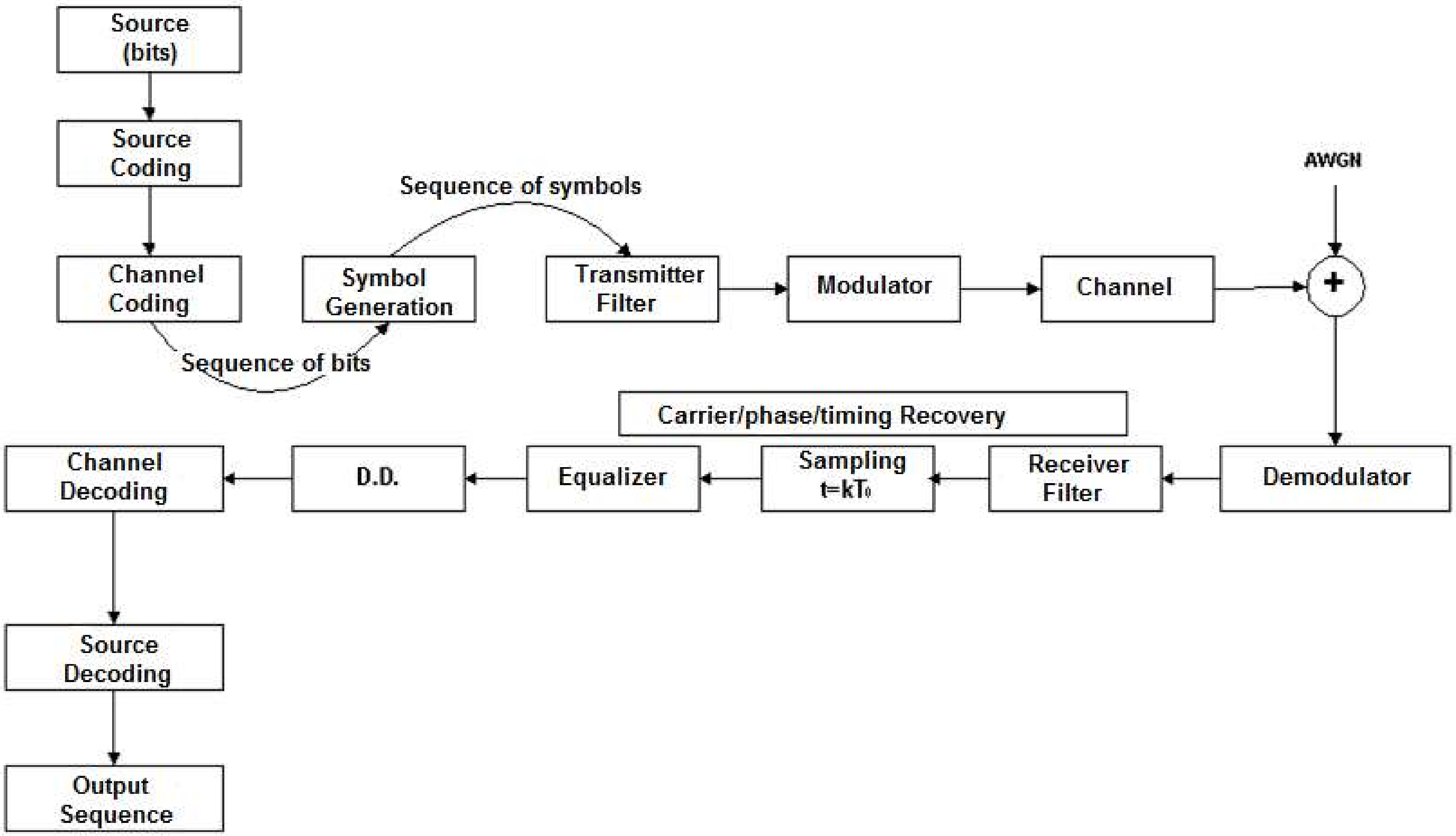
Efficient Modulation Techniques



Outline

- Modulation: Introductory concepts
- Main modulation techniques
  - Geometric representation
  - Modulation categories
  - Performance metrics
- Adaptive Modulation
- Hierarchical or layered modulation

Introductory concepts (1/5)



Introductory concepts (2/5)

■ Modulation: The process of "transforming" the information of a source so as to become suitable for transmission.

■ In the general case, it involves the transmission of information in a passband channel. The baseband signal is the "modulating" signal while the resulting passpand signal is the modulated one.

■ Demodulation: The process of extracting the baseband signal from the bandwidth signal.

■ The development of modulation techniques for mobile systems has been a subject of intensive research in the past 2-3 decades.

Introductory concepts (3/5)

- In the mobile communication environment, some important features must be taken into account, such as:
  - The multi-path phenomenon and the problems it causes (mainly due to frequency selective and/or fast fading).
  - The problem of interference from other users.
  - Non-linear distortions.
  - Complexity / Implementation cost.
  - The need for efficient use of energy (power) efficiency.
  - The urgent, very often, need for spectral efficiency.

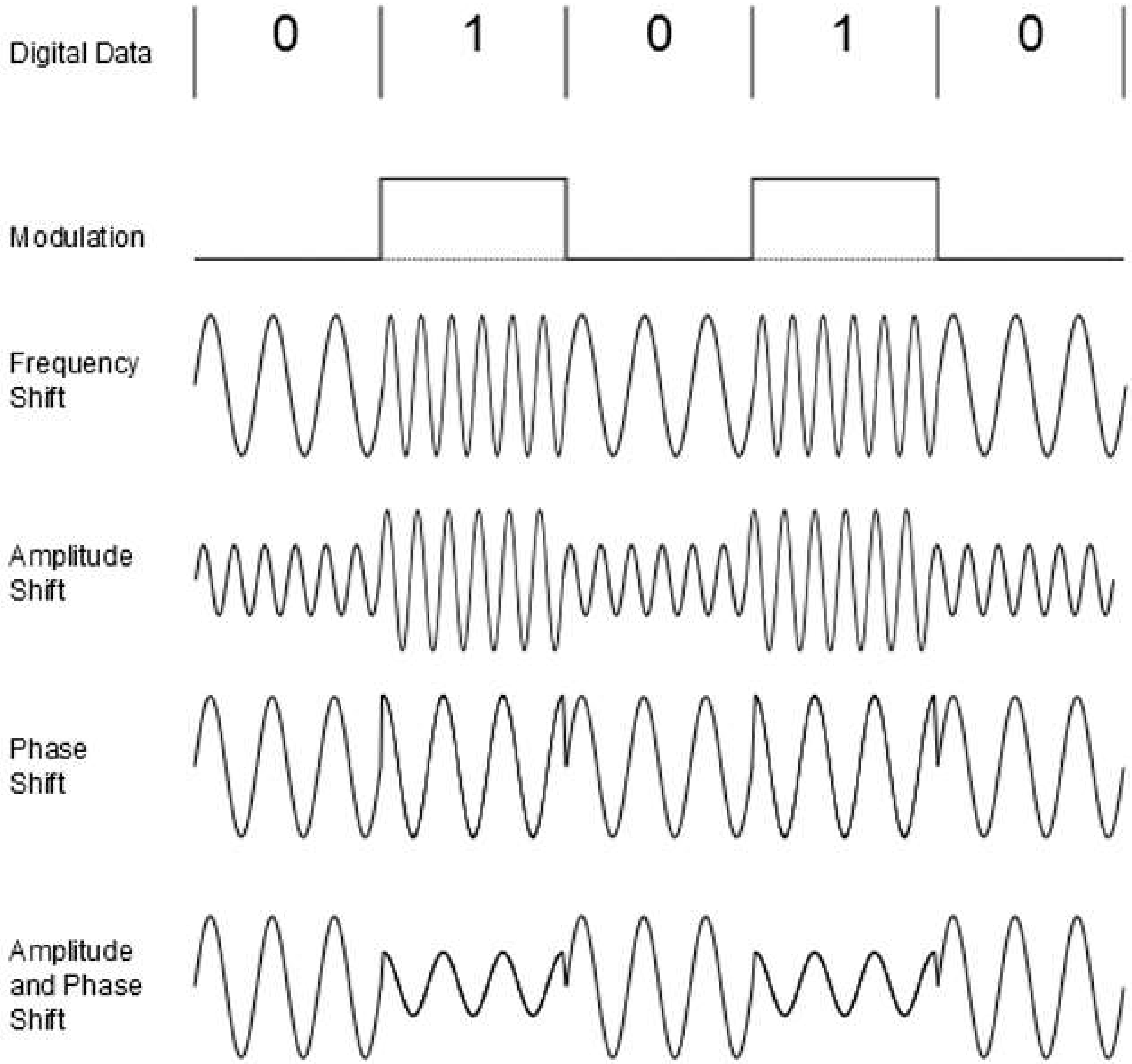
- The following criteria are **conflicting** and cannot be met at the same time
  - Power efficiency: Rate of transmitted information per Watt of power (other indicators: CNR, E_s/N_0)
  - Spectral efficiency: Rate of transmitted information per Hz of the available bandwidth (bits/sec/Hz).

Introductory concepts (4/5)

- Advantages of digital modulation and transmission:
  - Resistance to noise and channel imperfections.
  - Flexibility in multiplexing different forms of information.
  - Integration of debugging, balancing, source coding procedures.
  - Flexibility in terms of hardware and software implementation.

- Basic techniques:
  - Amplitude Shift Keying (ASK)
  - Frequency Shift Keying (FSK)
  - Phase Shift Keying (PSK)
  - Amplitude and Phase Shift (QAM)

Introductory concepts (5/5)



Modulation techniques: Space representation

Digital modulation: setting up a suitable one-to-one correspondence between symbols s_i and waveforms $s_i(t)$, where $i = 1,2,\dots,M$.

- The different modulation techniques differ in the way the set of waveform signals $S = \{s_1(t), s_2(t), \dots, s_M(t)\}$ is defined.

Geometric representation:

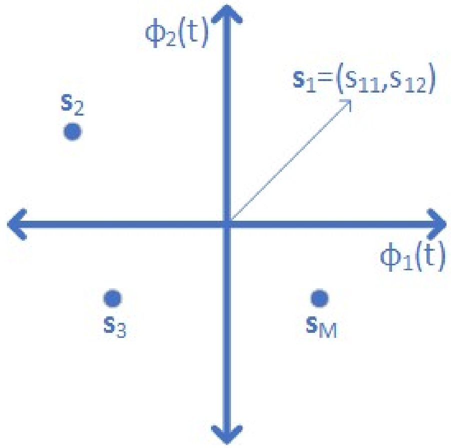
- Signals (and respective symbols) as points in a vector space.

$$s_i(t) = \sum_{m=1}^{N} s_{im}\phi_m(t)$$

- where $\phi_m(t)$, $m = 1,2,\dots,N$, the N-D space basis functions.
- s_{im}, $m = 1,2,\dots,N$, the coordinates of the signal $s_i(t)$ (i.e., the elements of the vector representing the signal $s_i(t)$)

Modulation techniques: Space representation cont.

- The constellation diagram for $N = 2$.
  - Since $s_i(t) = s_{i1}\phi_1(t) + s_{i2}\phi_2(t)$, the vector representing the $s_i(t)$ is $\mathbf{s}_\mathrm{i} = (s_{i1}, s_{i2})$.



- The constellation diagram provides useful information about the modulation system represented.
  - Frequency efficiency increases with the density of the symbols.
  - The required bandwidth increases with dimension N.
  - The minimum distance between symbols determines the error probability.
  - How energy efficiency could be improved ?

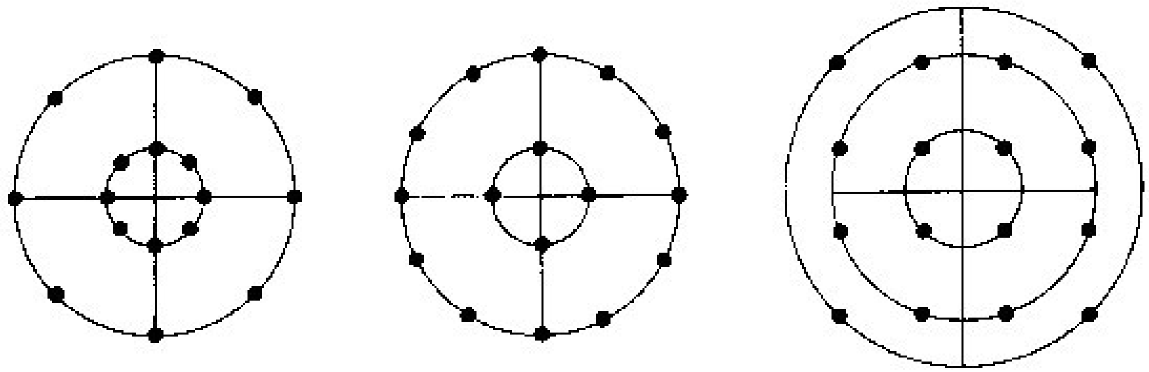
A widely used technique: Quadrature Amplitude Modulation

- M-ary Quadrature Amplitude Modulation (M-QAM)
  - The M symbols correspond to the signals

    $$s_i(t) = A_i g_T(t)\cos(2\pi f_c t + \theta_i)\,, i = 1,2,\ldots,M$$

  - An alternative form of QAM signals is the following

$$s_i(t) = A_{ic} g_T(t)\cos(2\pi f_c t) + A_{is} g_T(t)\sin(2\pi f_c t)\,, i = 1,2,\ldots,M$$



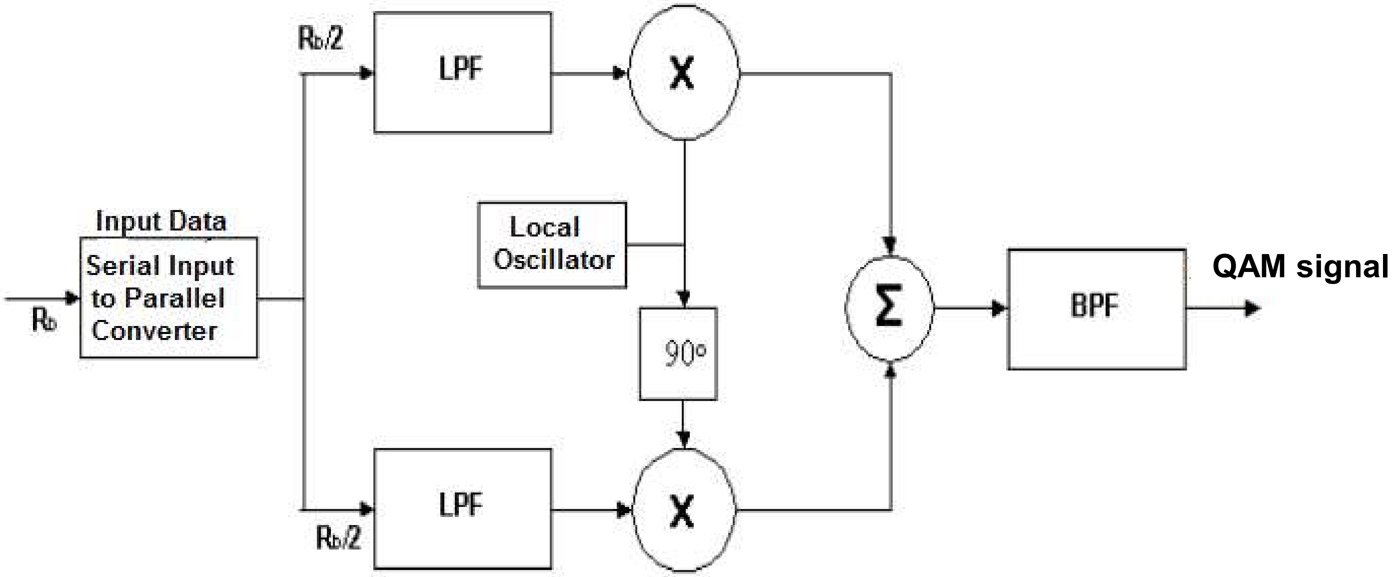
(a) 16 APK (8,8) constellation

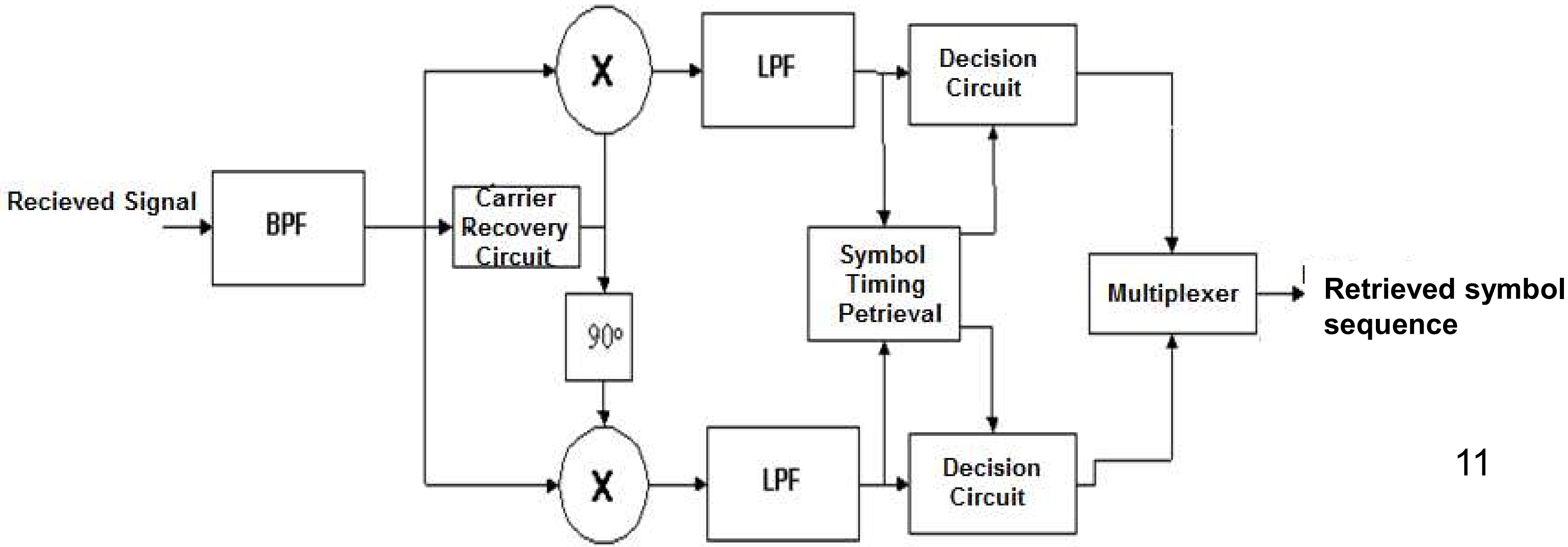
(b) 16 APK (4,12) constellation

(c) 16 APK (4,8,4) constellation (or 16 QAM)

Quadrature Amplitude Modulation (cont.)

Block diagram of QAM transmitter and receiver





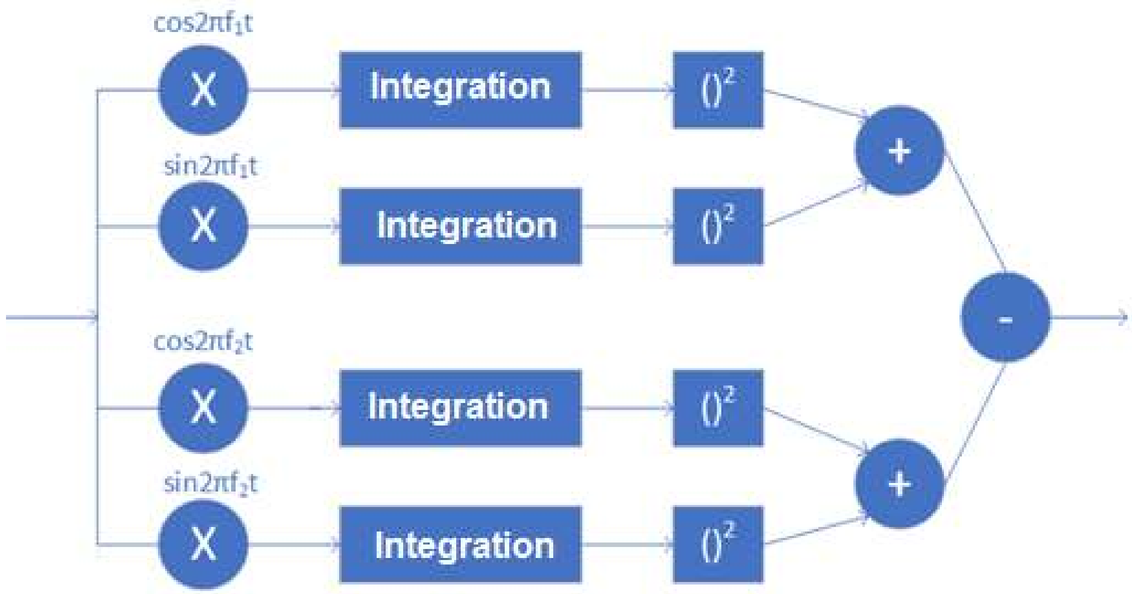
Modulation techniques: Coherent vs incoherent

- Depending on whether the modulation technique requires synchronization between transmitter and receiver. For example, the FSK has two versions that differ in the way the receiver is implemented.

  - Coherent FSK
    - Received signal: $r(t) = f(\cos(2\pi f_c t + 2\pi i \Delta \mathrm{f} t + \phi_i))$
    - Requires knowledge of the ϕ_i

  - Incoherent FSK
    - Received signal:
      $r(t) = f(\cos(\phi_i)\cos(2\pi f_i t) + \sin(\phi_i)\sin(2\pi f_i t))$

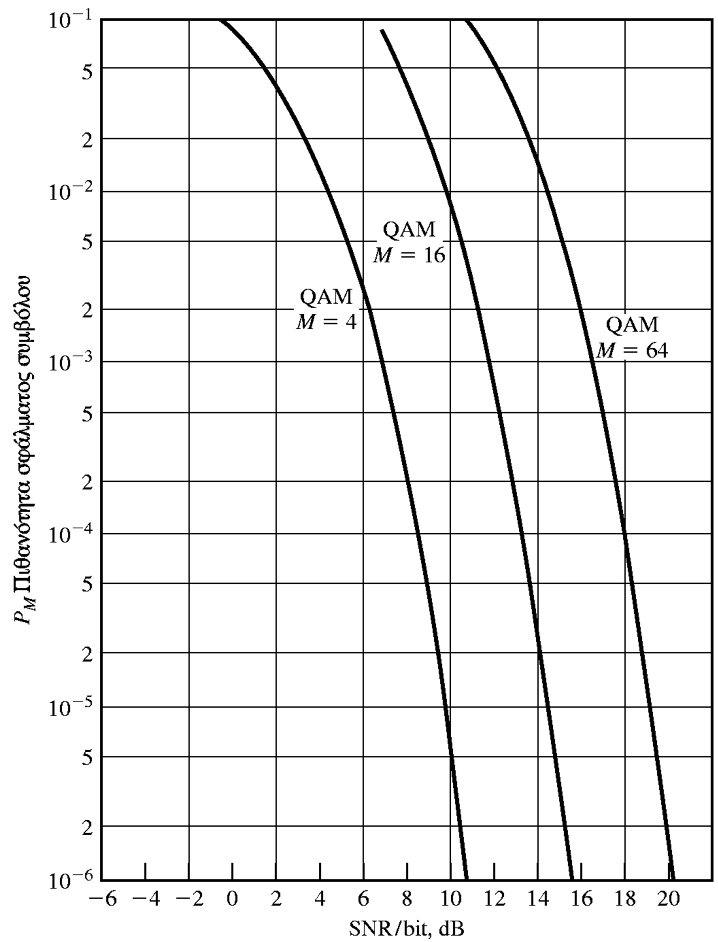
Block diagram of 2-FSK receiver in the incoherent case



Modulation techniques: Spectral vs Power Efficiency

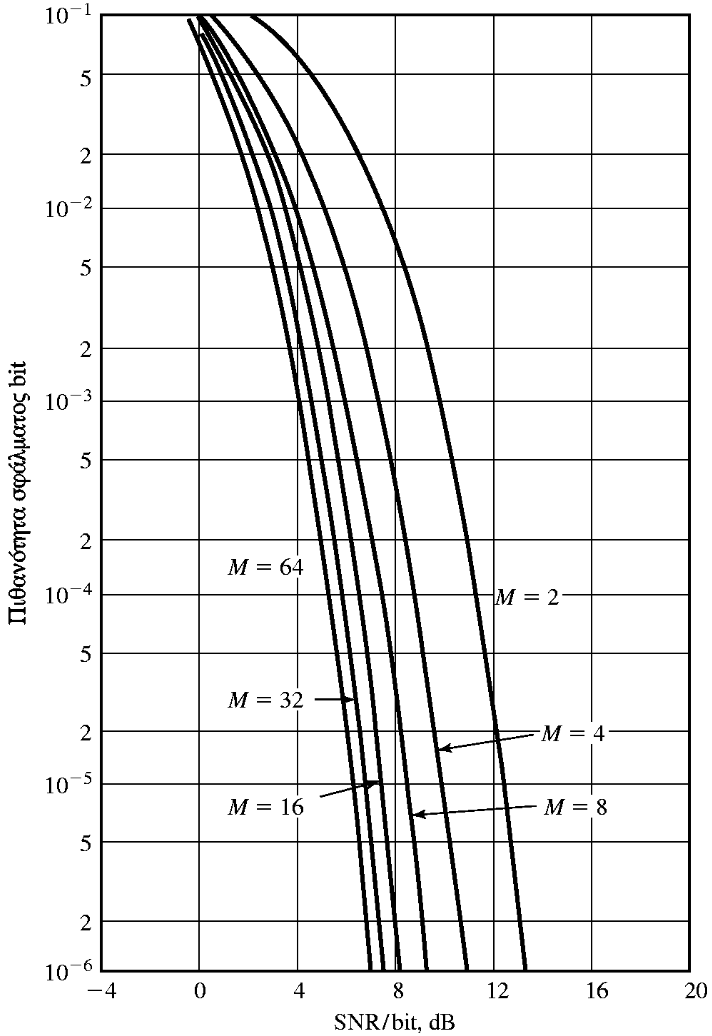
■ Spectral efficient techniques:

■ Performance of the so-called antipode techniques, such as M-PAM, M-QAM, M-PSK



Modulation techniques: Spectral vs Power Efficiency cont.

- Power efficient techniques:
  - Performance of the so-called orthogonal techniques, such as M-PPM and M-FSK

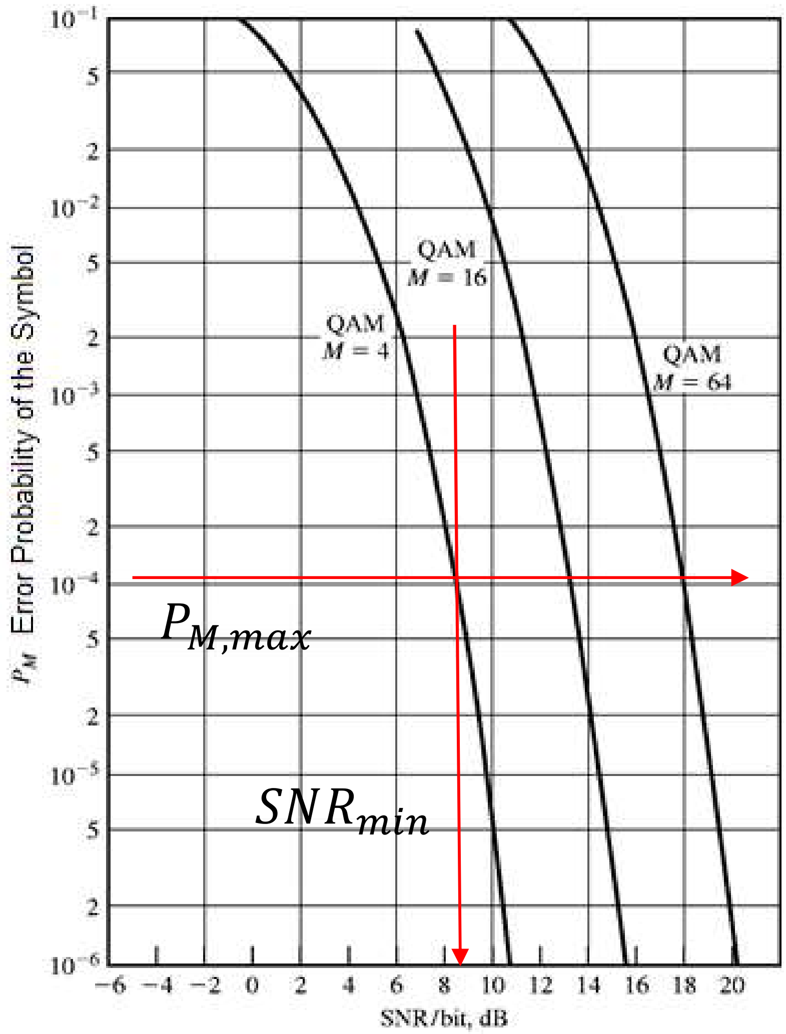


Adaptive modulation (1/3)

■ The aforementioned modulation systems do not take into account the current state of the channel.

■ Example of a non-adaptive modulation technique:

- ■ M-QAM, $M = 4, 16, 64$.
- ■ Suppose we want $P_M \leq 10^{-4}$.
- ■ How can we achieve this?
- ■ If we additionally want to improve spectral efficiency?
- ■ If at the same time we wanted to maximize coverage?
- ■ What problems might arise?



Adaptive modulation (2/3)

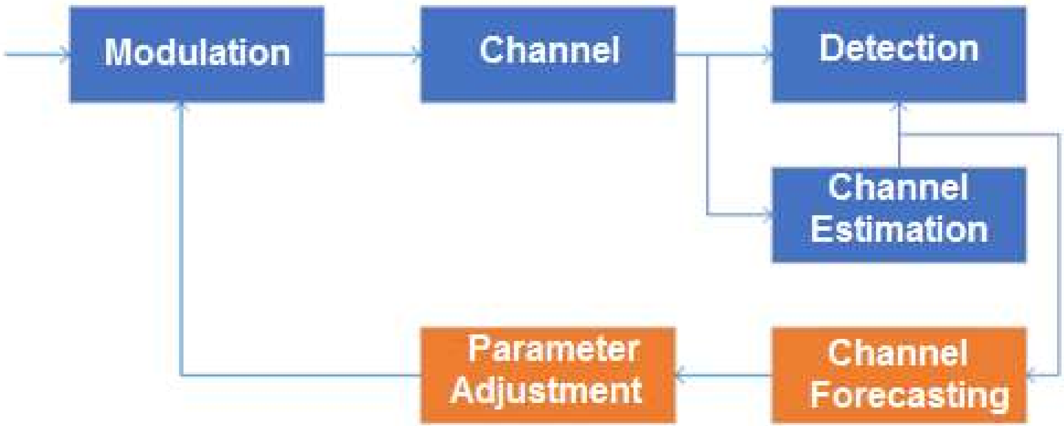
- Drawbacks of non-adaptive modulation techniques:
  - The wireless channels are time varying, which implies that the instantaneous SNR is also varying, as well as the resulting probability of error
  - The instantaneous SNR is a function of the transmission conditions:

$$y(t) = a(t)s(t) + w(t)$$

    - The channel gain $a(t)$ depends on transmitter-receiver distance, multipath, weather conditions, etc.
  - If the selection of a (non-adaptive) modulation technique was simply based on the expected values of SNR, then we could not ensure a specified maximum probability of error.
  - For example, a minimum instantaneous SNR might also be required in addition to setting a maximum distance.
  - In the above cases, the choice of the modulation technique would be made so as to satisfy "worst case" conditions, regardless of how often these cases occur.

Adaptive modulation (3/3)

- In adaptive modulation, the system is able to continuously adapt to the varying channel condition.
- Adaptive techniques have been adopted by various standards such as IEEE 802.11 (Wi-Fi), IEEE 802.16 (Wi-Max), LTE advanced and 5G.
- In order to apply adaptive techniques, we need to have a mechanism that estimates in real-time the channel parameters (e.g., the current value of SNR)
  - This information is fed back to the transmitter, which, in turn, makes the necessary parameter changes of the adopted modulation technique.



- In what cases is "channel forecasting" needed?

Hierarchical or layered modulation

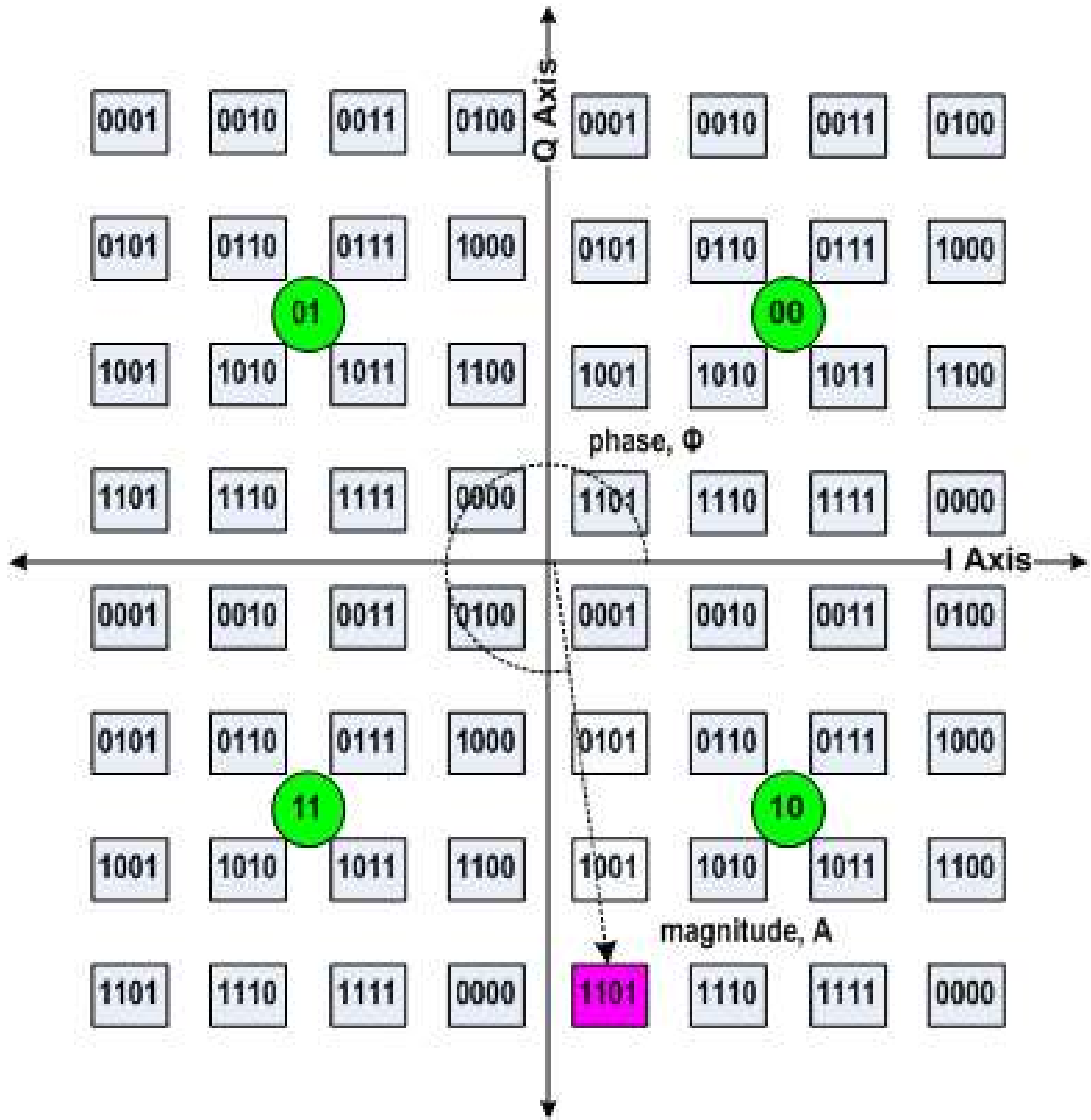
- In hierarchical (or layered) modulation, information is modulated at two levels:
  - 1º High Priority Level (HP) where a robust but low-rate flow is generated (e.g., QPSK, why?).
  - 2º Low Priority Level (LP) where a less robust but high-rate flow is generated (e.g., 64-QAM).
- The two levels are formed into a common signal which is transmitted to the receiver.
- This type of modulation is used, for example, in digital terrestrial video transmission (DVB-T).
- A receiver with poor reception conditions is limited to decoding the information present at the first level,
- If the channel condition allow the second level is also decoded.
- It can also support easy system upgrades while maintaining "backwards" compatibility.

Hierarchical or layered modulation (cont.)

Example: 64-QAM (by design each symbol corresponds to 6 bits)

First layer: 2 bits (QPSK)

Second layer: 4 bits



Error probability in wireless channels (1/4) (OXI)

- We will focus on the case of a frequently flat channel that changes slowly.
- The signal received at the receiver can be written as

$$r(t) = a(t)e^{-\theta(t)}s(t) + n(t), 0 \leq t \leq T$$

  - $\alpha(t), \theta(t)$ denote the effect of the channel on the amplitude and phase of the signal $s(t)$, T the symbol period and $n(t)$ is white Gaussian noise.

- To calculate the error probability of a modulation technique we rely on the corresponding error probability when the channel is AWGN.

$$r(t) = s(t) + n(t), 0 \leq t \leq T$$

- Let this error probability be

$$P_{AWGN} = f(X)$$

  - Where X is the signal-to-noise ratio (usually E_b/N_0).

- In case the wireless channel X is a function of $a(t)$.

Error probability in wireless channels (2/4) (OXI)

- To calculate the error probability $P_e = g(X)$ in the case of wireless channels, it is assumed, in principle, that the channel gain is constant.
  - For a given channel gain α, the probability of error is

$$P_e(X(a)) = P_{AWGN}(a^2 E_b/N_0)$$

- The error probability P_e is calculated as

$$P_e = \int_0^{+\infty} P_e\big(X(a)\big)p\big(X(a)\big)dX(a)$$

- The probability density function (pdf) $p\big(X(a)\big)$ is derived from the pdf of the channel gain α.
  - For example, if the gain α is described by Rayleigh pdf, then

$$p\big(X(a)\big) = \frac{1}{\Gamma} e^{-\frac{X(a)}{\Gamma}}, \text{όπου } \Gamma = \frac{E_b}{N_0}\overline{a^2}$$

Error probability in wireless channels (3/4) (OXI)

- The GMSK as an example.
  - When the channel is AWGN

$$P_{AWGN} = Q\left\{\sqrt{\frac{2\gamma E_b}{N_0}}\right\},$$

    - $\gamma = 0{,}68$ and $\gamma = 0{,}85$ when $B_0 T_b = 0{,}25$ and $B_0 T_b = \infty$, respectively.
  - When the channel is wireless (with the previous views) then

$$P_e = \frac{1}{2}\left(1 - \sqrt{\frac{\gamma\Gamma}{\gamma\Gamma + 1}}\right)$$

- The case of BPSK.
  - AWGN: $P_{AWGN} = Q\{\sqrt{2E_b/N_o}\}$
  - Wireless channel: $P_e = \frac{1}{2}\left[1 - \sqrt{\Gamma/(1+\Gamma)}\right]$

Error probability in wireless channels (4/4) (OXI)

■ Comparison of BPSK when the transmission is done through the two different channel models considering $\overline{a^2} = 1$.