ΕΠΛ 427:
ΚΙΝΗΤΑ ΔΙΚΤΥΑ ΥΠΟΛΟΓΙΣΤΩΝ
(MOBILE NETWORKS)

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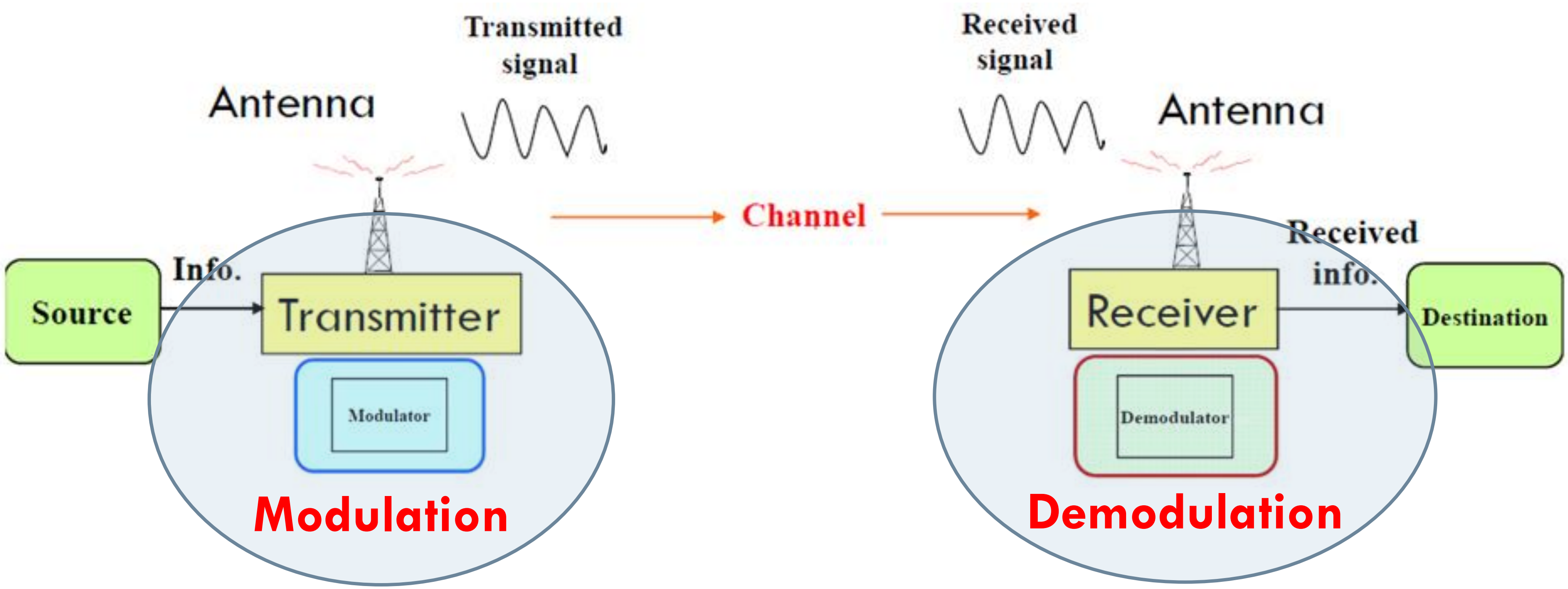
Πανεπιστήμιο Κύπρου - Τμήμα Πληροφορικής

Modulation Techniques (Τεχνικές Διαμόρφωσης)

Recall (Process and Elements of Radio Transmission)



Topics Discussed

- Digital Modulation
- Bit rate, Baud rate
- Basic Digital Modulation Techniques (ASK, FSK, PSK, QAM)
- Constellation diagrams
- Factors that influence the choice of Digital Modulation Scheme – Power Efficiency, Bandwidth Efficiency

Modulation

Message Signal
(Data to be transmitted)

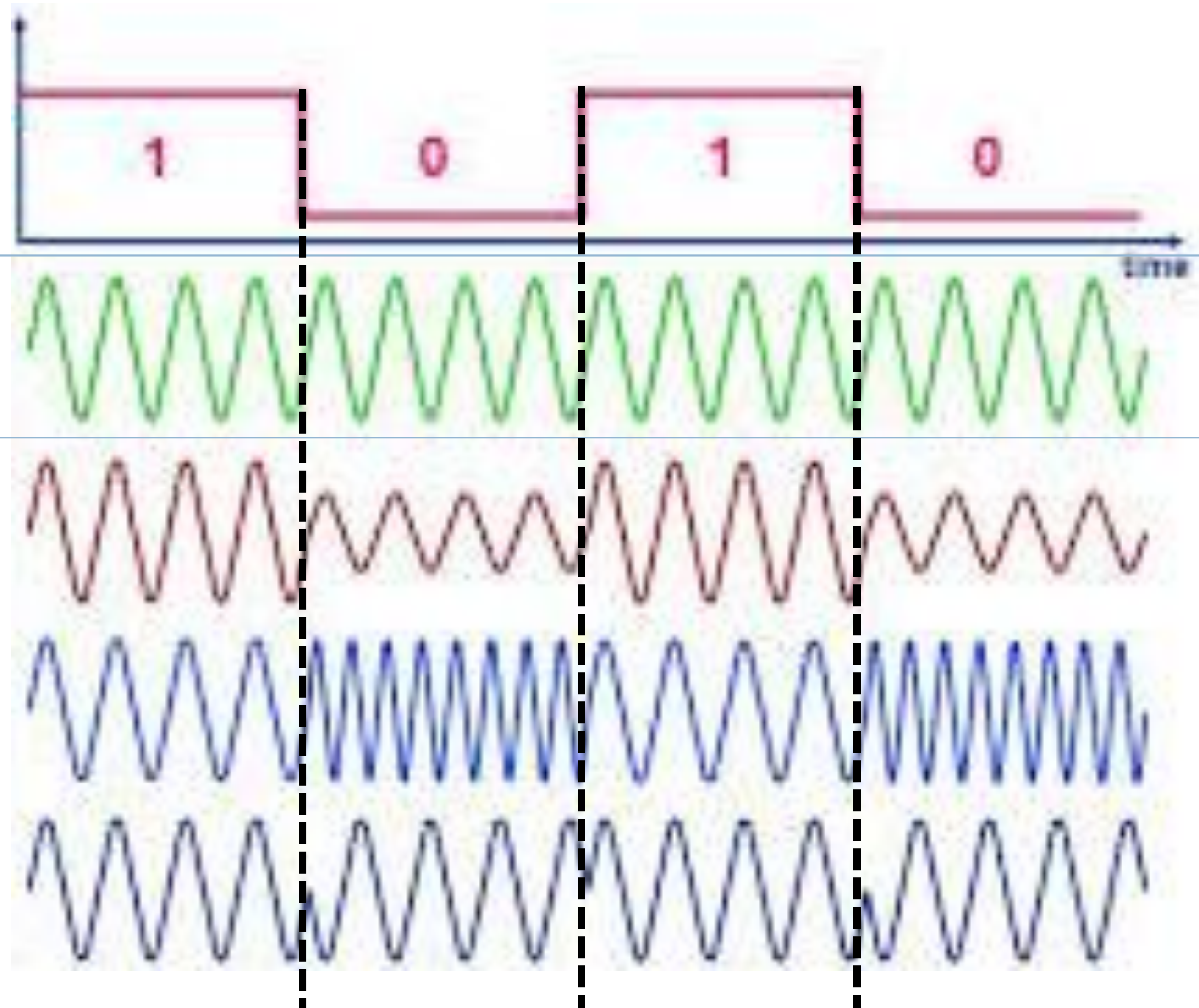
Carrier signal with frequency f_c

Modulated Signals

Controlling the Amplitude of the carrier signal (ASK)

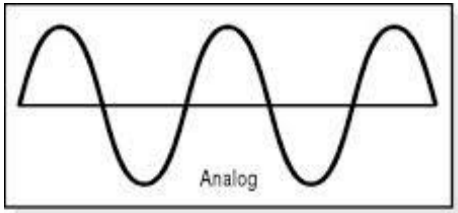
Controlling the Frequency of the carrier signal (FSK)

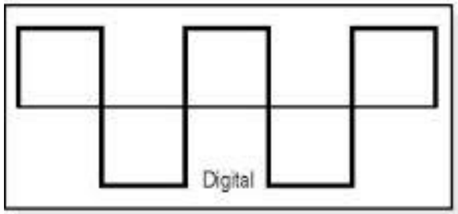
Controlling the Phase of the carrier signal (PSK)



Analog and Digital Signals
Αναλογικά και Ψηφιακά Σήματα

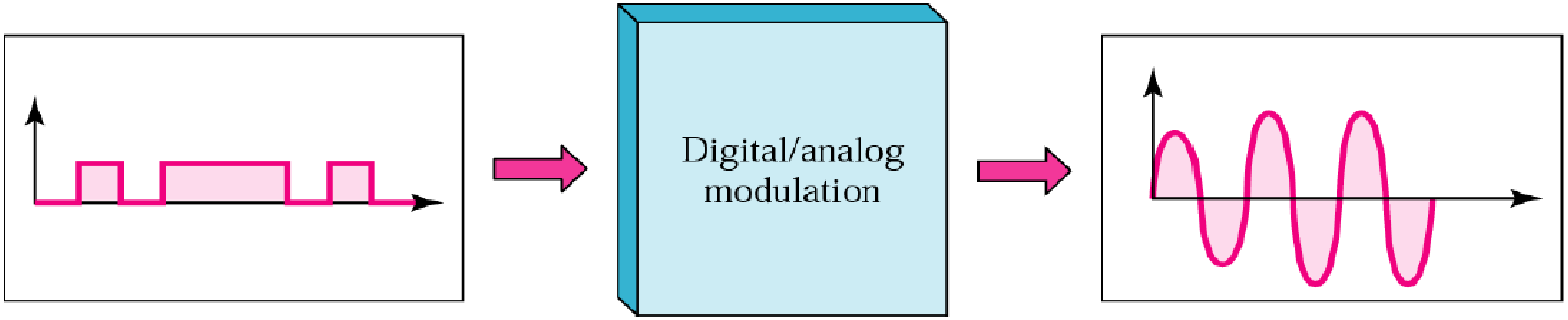
- **Means** by which data are propagated over a medium (Οι τρόποι με τους οποίους τα δεδομένα διαδίδονται μέσω κάποιου μέσου).
- ***An Analog Signal is a continuously varying electromagnetic wave (ένα συνεχόμενο εναλλασσόμενο ηλεκτρομαγνητικό κύμα) that may be propagated over a variety of media:***
  - ***Wire, fiber optic, coaxial, space (wireless)***
- A **digital signal** is a sequence of discrete voltage pulses (είναι μια αλληλουχία **διακριτών** παλμών τάσης) that can be transmitted over a **wire medium**:
  - E.g., a **constant positive level** of **voltage** to represent **bit 1** and a constant **negative level** to represent **bit 0**.





Modulation for Wireless
Digital Modulation

- **Digital modulation** is the process by which an **analog carrier wave** is **modulated to include a discrete (digital) signal**. (Ψηφιακή διαμόρφωση είναι η διαδικασία κατά την οποία ένας μεταφορέας αναλογικού σήματος διαμορφώνεται έτσι ώστε να συμπεριλάβει ένα διακριτό (ψηφιακό) σήμα (π.χ., 1 or 0))
- **Digital modulation methods** can be considered as **Digital-to-Analog conversion**, and the corresponding Demodulation (e.g., at the Receiver) as **Analog-to-Digital conversion**.



Modulation for Wireless
Digital Modulation

- The **modulation** that will be applied on the (analog) **carrier signal to include the data that will be carried (e.g., 1 or 0, etc.)** are **chosen** from a **finite number** of **M alternative symbols (or signal units** or **signal elements) based on the Digital Modulation Technique** and the ***Modulation Alphabet*** **that will be used**. (Η διαμόρφωση που θα γίνει στον (αναλογικό) μεταφορέα σήματος για να συμπεριλάβουν την πληροφορία που θα μεταφερθεί (π.χ., 1 ή 0) επιλέγονται από ένα πεπερασμένο αριθμό από εναλλακτικά σύμβολα (σήματα) ανάλογα με την **Τεχνική διαμόρφωσης και** το ***Αλφάβητο Διαμόρφωσης*** που θα χρησιμοποιηθεί.
  - Symbol Pattern 1 → 0
  - Symbol Pattern 2 → 1
- This **same Modulation Alphabet** have to be **used both** from the **Transmitter** (for modulating the signal) **and the Receiver** (for demodulating the signal)

Digital Modulation

- The general form (pattern) of the modulated signal is (Η γενική μορφή ενός διαμορφωμένου σήματος):

$$s(t) = A(t) \sin(2\pi \times (f_c + f_m(t))\, t + \phi(t)$$

Modulation for Wireless
Digital Modulation

- **The three essential parameters that can be modulated (**Οι τρείς βασικές παράμετροι που μπορούμε να διαμορφώσουμε**)**

$$s(t) = A \sin(2\pi f t + \phi)$$

  - Amplitude value (**A**) — **ASK** (Amplitude Shift Keying)
  - Frequency value (**f**) — **FSK** (Frequency Shift Keying)
  - Phase value (**ϕ**) — **PSK** (Phase Shift Keying)

- **Digital modulation**: Amplitude (***A***), frequency (***f***) and Phase (ϕ) are used to represent a **digital state**. (Στην Ψηφιακή διαμόρφωση το **πλάτος**, η **συχνότητα**, και η **φάση** του σήματος χρησιμοποιούνται για να αναπαραστήσουν μία **ψηφιακή κατάσταση ή τιμή**)

Basic Digital Modulation Techniques

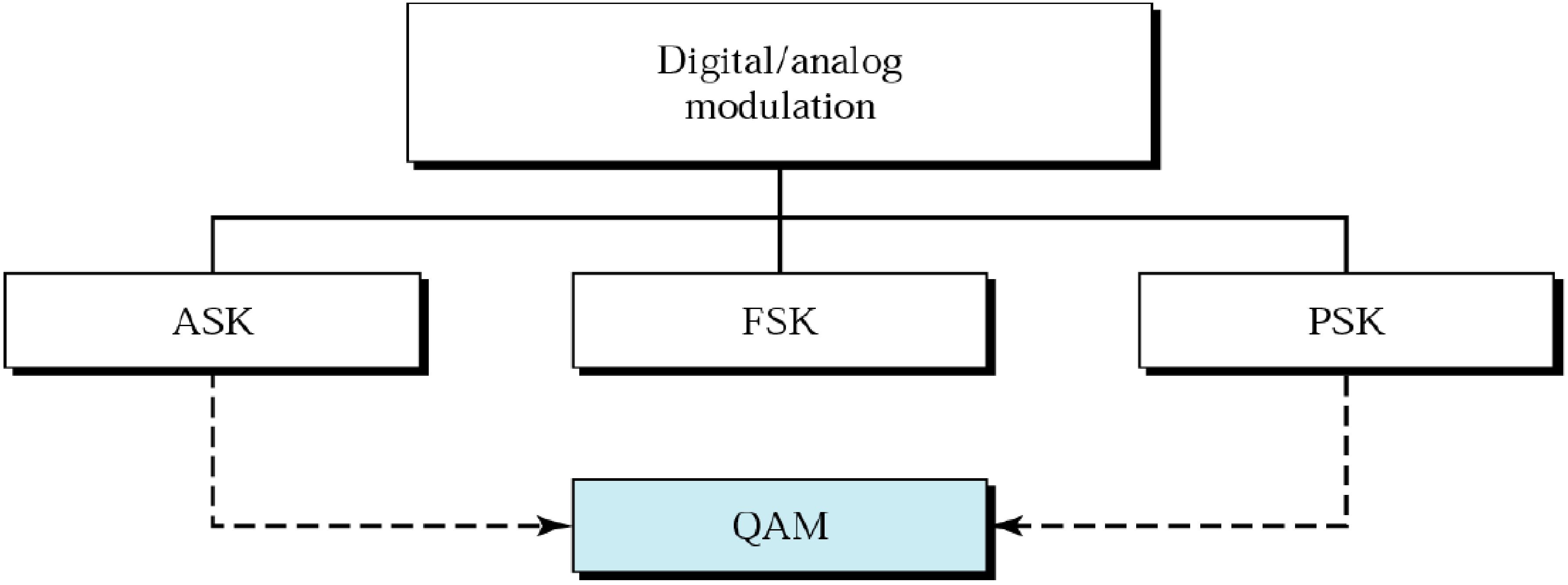
- **Basic Digital Modulation Techniques** work by **varying** the **Amplitude**, **Frequency** or **Phase** (**or a combination of them**) of **a sinusoidal carrier wave** depending on the **information (data)** that will be transmitted and the **Modulation Alphabet** that will be used.

  - **ASK**: Amplitude Shift Keying $\quad s(t) = A \sin(2\pi f t + \phi)$
  - **FSK:** Frequency Shift Keying $\quad s(t) = A \sin(2\pi f t + \phi)$
  - **PSK:** Phase Shift Keying $\quad s(t) = A \sin(2\pi f t + \phi)$
  - **Quadrature Amplitude Modulation (QAM)** or **Amplitude Phase Shift Keying (APSK)**

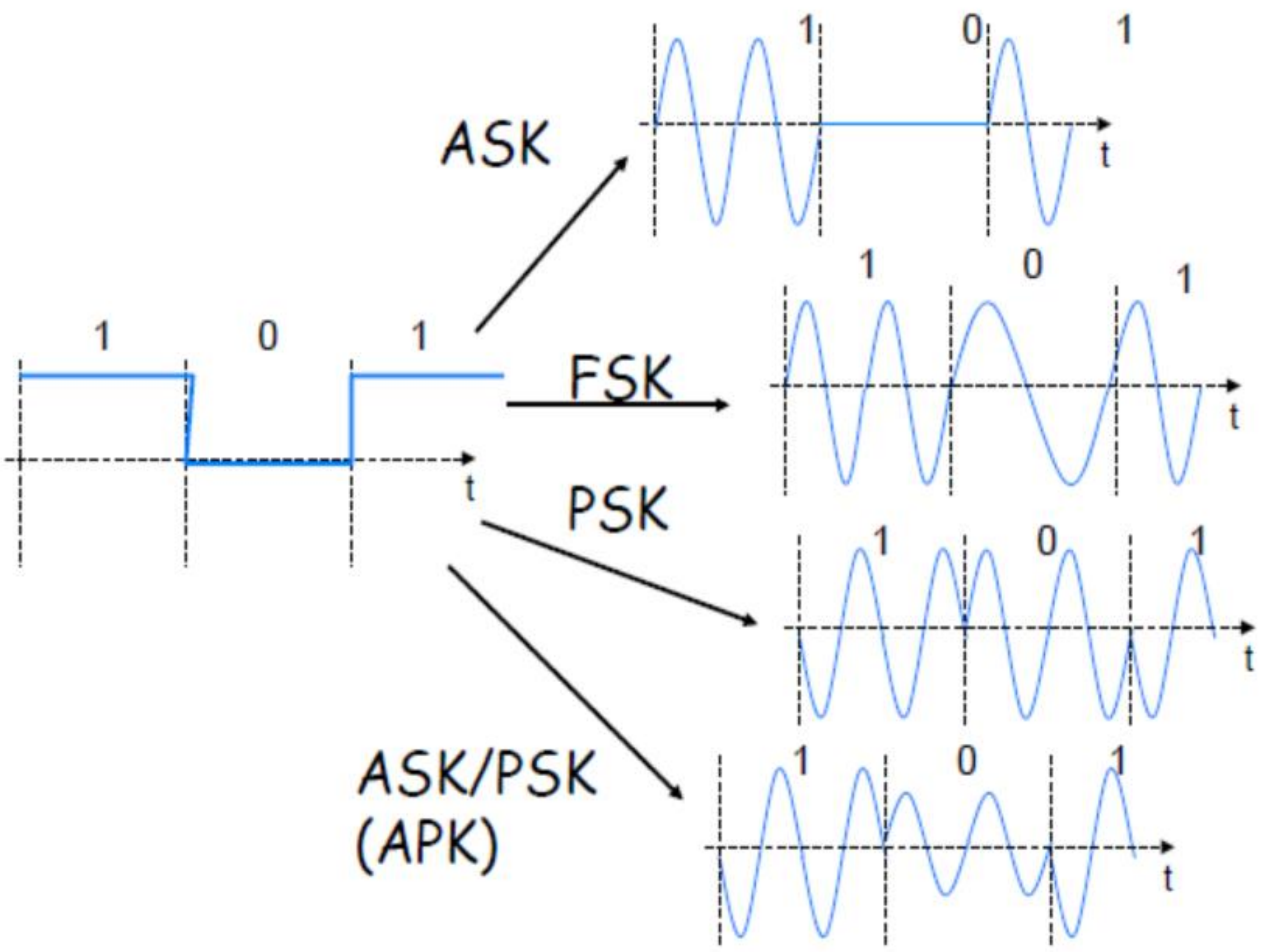
$$s(t) = A \sin(2\pi f t + \phi)$$

Basic Digital Modulation Techniques

- Types of Digital to Analog Modulation



Basic Digital Modulation Techniques Illustration



$A(t).\sin[2.\pi.f_c.t]$

$\sin[2.\pi.(f_c+f_m(t)).t]$

$\sin[2.\pi.f_c.t + \theta(t)]$

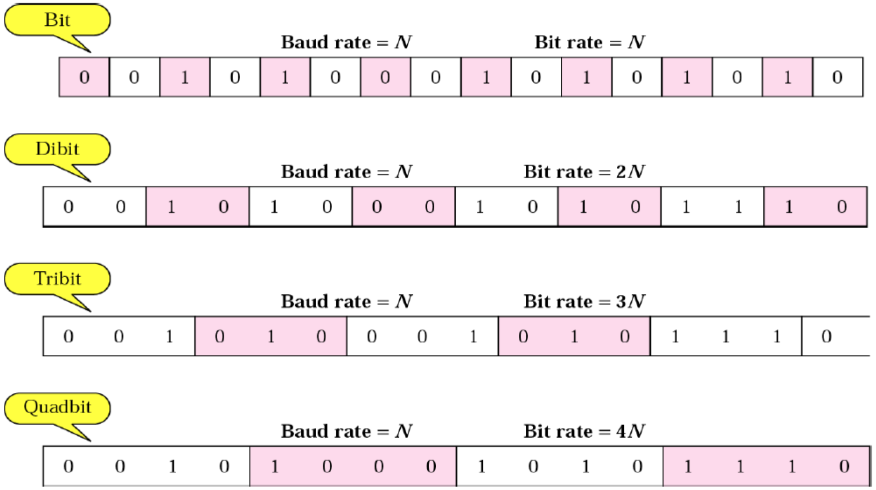
$A(t).\sin[2.\pi.f_c.t + \theta(t)]$

Bit Rate and Baud Rate

- **Bit Rate** is the **number of bits (data) that can be carried per second**.
- **Baud Rate** is the **number** of **signal units (or symbols) per second used for carrying the bits (and achieve the Bit Rate).**
  - **Baud Rate** can be **less than** or **equal** to the **bit rate** → Note that **each symbol can carry one or more bits!**
  - **Baud Rate** is important in **Bandwidth efficiency**.
    - Baud rate **determines the bandwidth required** to send the **message signal (**Καθορίζει το εύρος ζώνης που απαιτείται για να σταλεί μήνυμα**)**
    - **Baud Rate = Bit Rate / Number of Bits per Symbol**
    - Thus, the **lower the Baud Rate (symbols/second)** the **less the bandwidth required**
  - **The number of bits that can be carried by one Symbol**, depends on the **Modulation Technique used**.
    - The **Baud Rate** depends on the **type of Modulation** used.

Bit Rate and Baud Rate Examples

- **Example 1**: A modulated signal **carries 4 bits** in **each signal unit (i.e., symbol)**. If **1000 signal units (symbols)** are sent per second, find the Baud Rate and the Bit Rate
  - **Baud Rate = 1000 baud/s**
  - **Bit Rate** = 1000 x 4 = **4000 bps**
- **Example 2:** The **bit rate** of a modulated signal is **3000 bps**. If each **signal unit** carries **6 bits**, what is the baud rate?
  - **Baud Rate =** 3000/6 = **500 (baud/s)**
- **Example 3**: A modulated signal has a **bit rate of 8000 bps** and a baud rate of **1000 baud**. How many bits are carried by each signal element?
  - **Bits/Baud** = **8000/1000 = 8**



Amplitude Shift Keying (ASK)

- The **strength of the carrier signal (Amplitude)** is varied to represent digital data (1 and 0) - **Binary ASK.**
- **Frequency** and **Phase remains the same while the amplitude changes**.

$$s(t) = \begin{cases} A_1 \sin(2\pi f t + \phi) & 1 \\ A_2 \sin(2\pi f t + \phi) & 0 \end{cases}$$

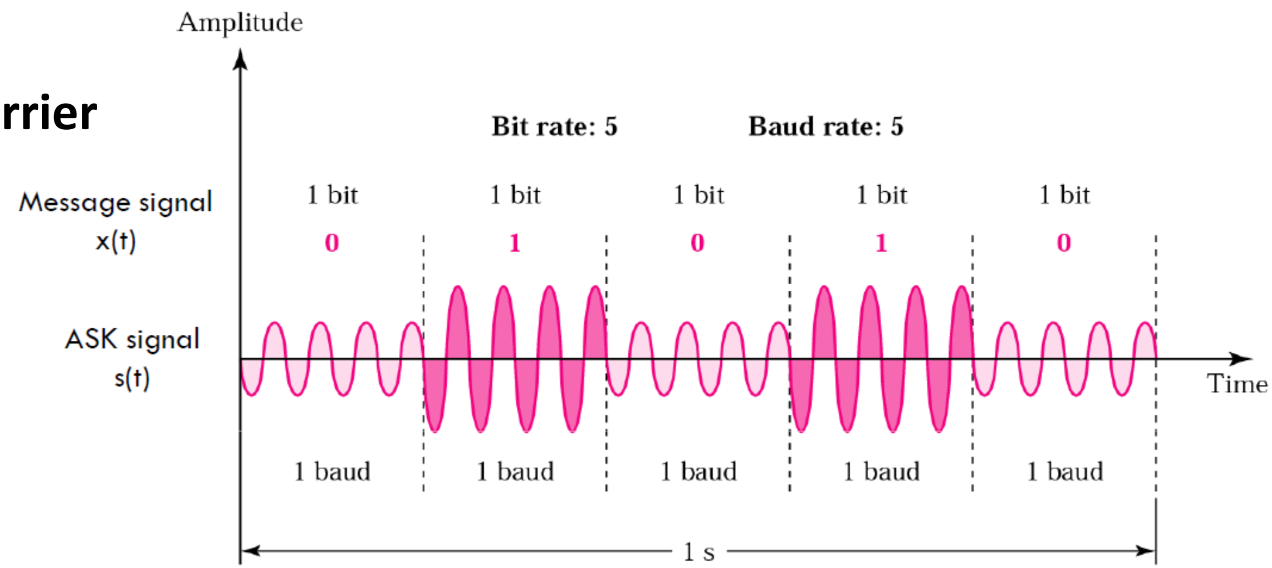
Carrier

Modulated Signal

Two states used

One bit per symbol!

Baud Rate = Bit Rate

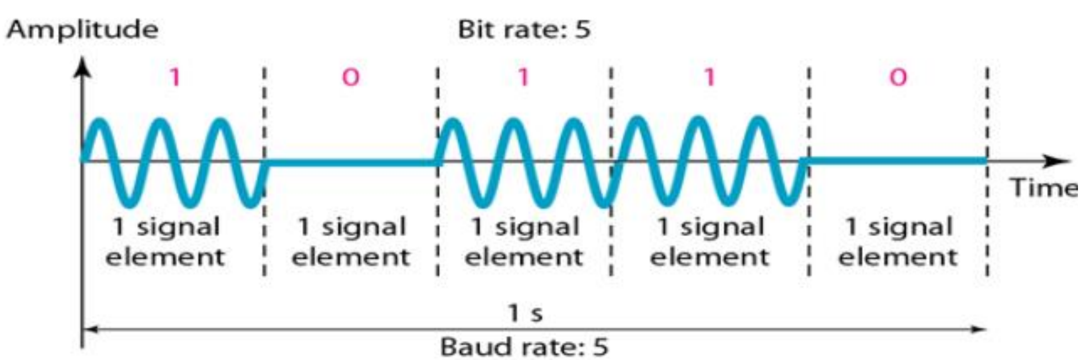


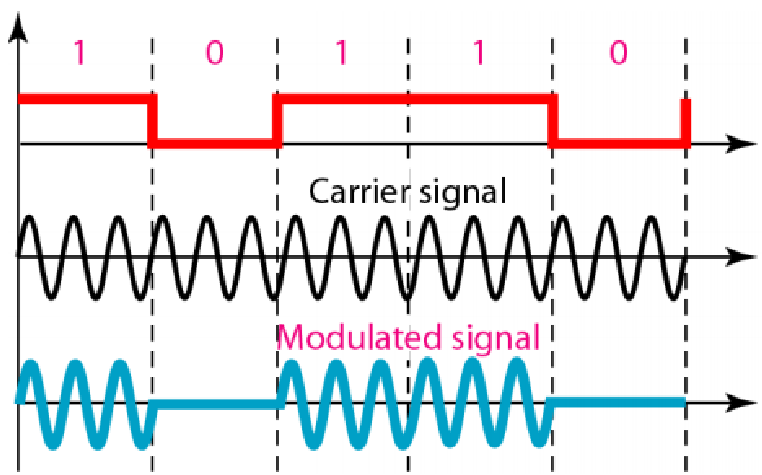
Amplitude Shift Keying (ASK)

- ASK is **susceptible to noise and interference (ευάλωτο στο θόρυβο) as noise can change the amplitude of a signal.** This can cause errors on the Receiver during demodulation.
  - *Noise refers to unintentional voltages introduced onto a line by various phenomena such as heat or electromagnetic induction created by other sources.*

On/Off Keying

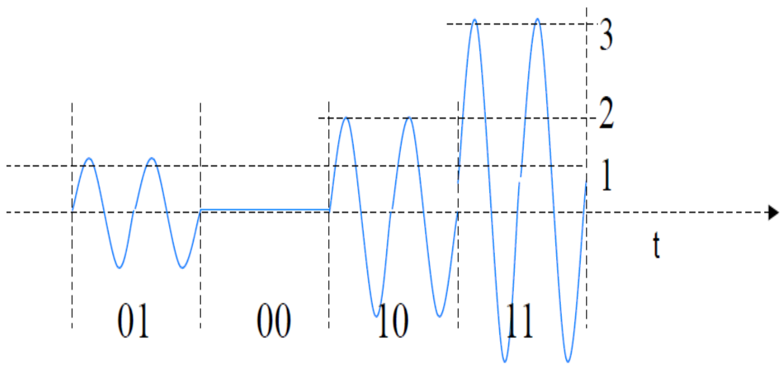
$$s(t) = \begin{cases} A \sin(2\pi f t + \phi) & 1 \\ 0 & 0 \end{cases}$$





Amplitude Shift Keying (ASK)
M-ary ASK

- **Binary ASK** has **only two possible states** representing only **0** and **1**
- **M-ary ASK** has **more than 2 possible states**.
- For example, if M = 4, the ASK refers to **four different Amplitudes** in which the **carrier is send**.
  - As **4 states** are possible, **two bits** can be encoded per symbol.
  - **In general if number of possible states M > 2, each symbol can carry log2(M) bits**. This scheme is therefore more bandwidth efficient.



Modulation Alphabet

with 4 possible states

$$s(t) = \begin{cases} A_1 \sin(2\pi f t + \phi) \\ A_2 \sin(2\pi f t + \phi) \\ A_3 \sin(2\pi f t + \phi) \\ A_4 \sin(2\pi f t + \phi) \end{cases} \quad \begin{cases} A_1 = 0: \ 00 \\ A_2 = 1: \ 01 \\ A_3 = 2: \ 10 \\ A_4 = 3: \ 11 \end{cases}$$

Example: M = 4 (4 different states)

$\log_2(4) = 2 \rightarrow$ 2 bits/symbol

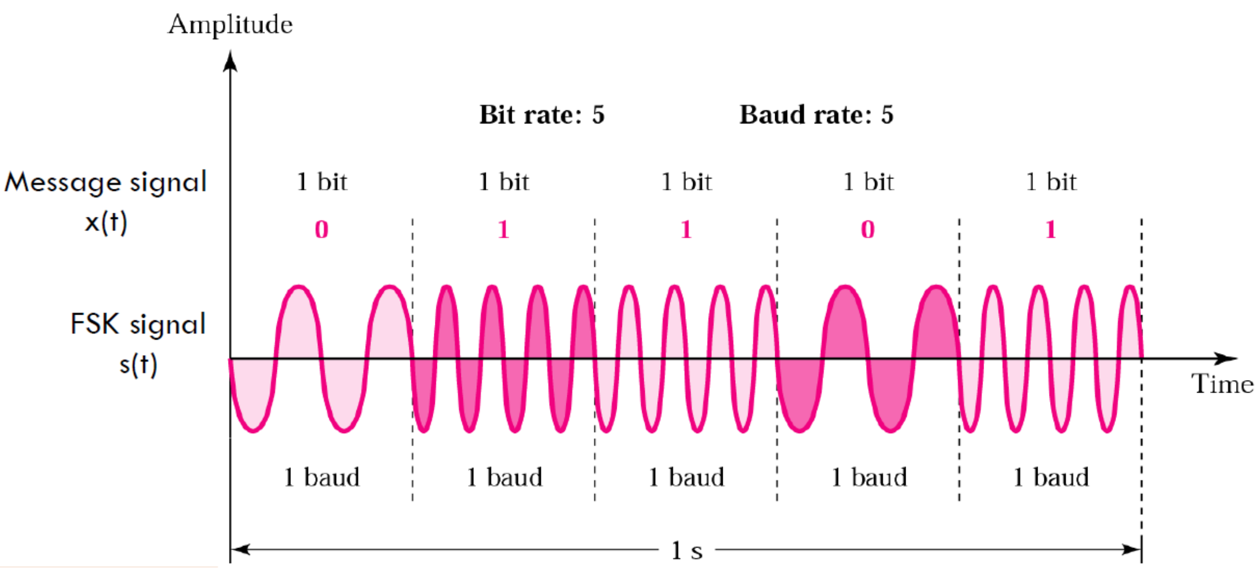
→ Baud Rate= N, Bid Rate= 2N

Frequency Shift Keying (FSK)

- The **frequency of the carrier signal (f_c)** is varied to represent digital data (1 and 0) - **Binary FSK (2 frequencies: f_1 and f_2)**
- Both **peak amplitude** and **phase** remain **constant.**

In this case the carrier switches between 2 values (two states; M = 2):

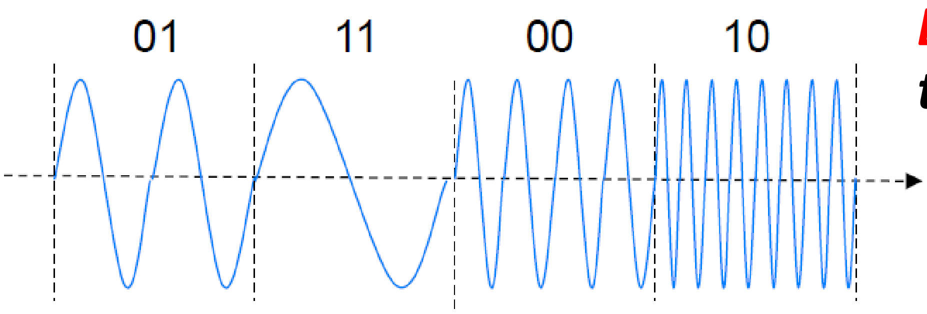
$$s(t) = \begin{cases} A \sin(2\pi (f_1)\, t + \phi) & \rightarrow 0 \\ A \sin(2\pi (f_2)\, t + \phi) & \rightarrow 1 \end{cases}$$



Baud Rate = Bit Rate

Frequency Shift Keying (FSK)

- **Binary FSK** has only two possible states representing only 0 and 1
- **M-ary FSK** has **more than 2 possible states**.
- For example, if **M = 4**, the FSK refers to **four different frequencies** in which the carrier is modulated and send.
  - As **4 states are possible**, **two bits** can be encoded **per symbol**.



Baud Rate = Bit Rate/2 → Reduces the Required Bandwidth to half

Modulation Alphabet

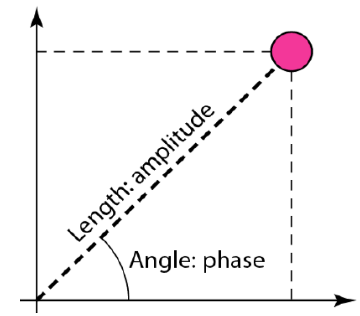
$$s(t) = \begin{cases} A \sin(2\pi (f_1)\, t + \phi) & \rightarrow 00 \\ A \sin(2\pi (f_2)\, t + \phi) & \rightarrow 01 \\ A \sin(2\pi (f_3)\, t + \phi) & \rightarrow 10 \\ A \sin(2\pi (f_4)\, t + \phi) & \rightarrow 11 \end{cases}$$

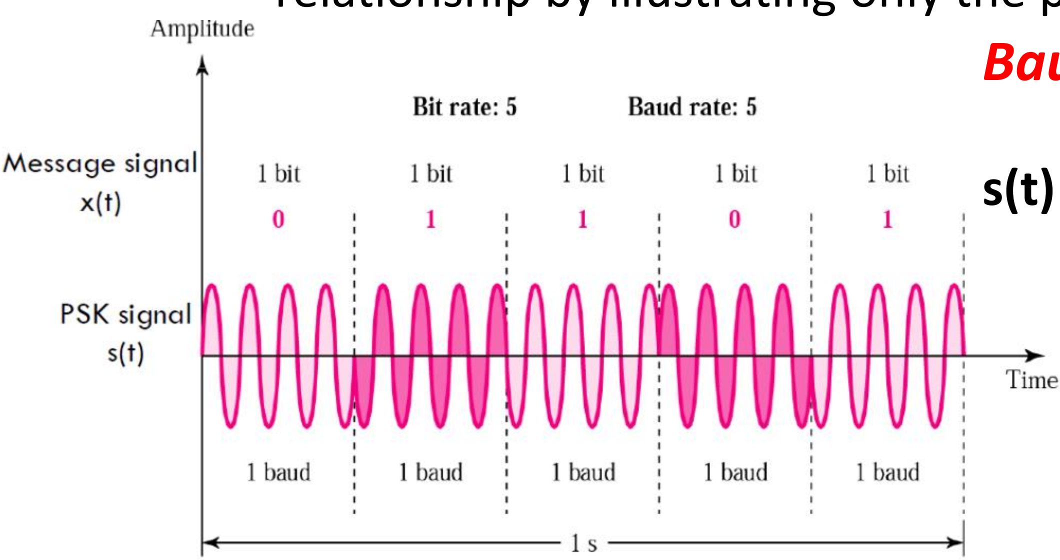
Frequency Shift Keying (FSK)

- **FSK is not susceptible to noise interference as it avoids noise interference** by **looking at frequencies** (change of a signal) and **ignoring amplitudes**.
  - Because the **Receiving device** is **looking for specific frequency changes** over a **given number of periods**, it **can ignore voltage spikes**. (Ο Receiver κοιτάζει μόνο για συγκεκριμένες αλλαγές στη συχνότητα του μεταφορέα σήματος σε συγκεκριμένες περιόδους (περίοδος ενός signal unit)) και αγνοεί αλλαγές στην τάση (πλάτος) του σήματος.)

Phase Shift Keying (PSK)

- The **phase of the carrier signal** is varied to represent digital data (binary 0 or 1), i.e., **Binary PSK (BPSK)**
- Both **peak amplitude** and **frequency remain constant** as the phase changes.
- **Phases are separated by 180 degrees.**
  - If we start with a **phase of 0º** to represent **bit 0**, then we can change the **phase to 180º** to send **bit 1** (or inversely).
  - The **Constellation** or **phase-state Diagram** shows the relationship by illustrating only the phases.



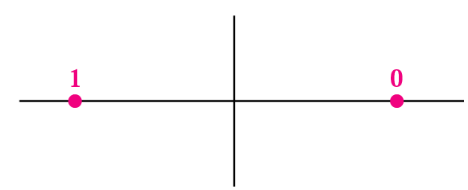


Baud Rate = Bit Rate

$$s(t) = \begin{cases} A\sin(2\pi f t + 0^{\circ}) & 0 \\ A\sin(2\pi f t + 180^{\circ}) & 1 \end{cases}$$

Bit	Phase
0	0
1	180

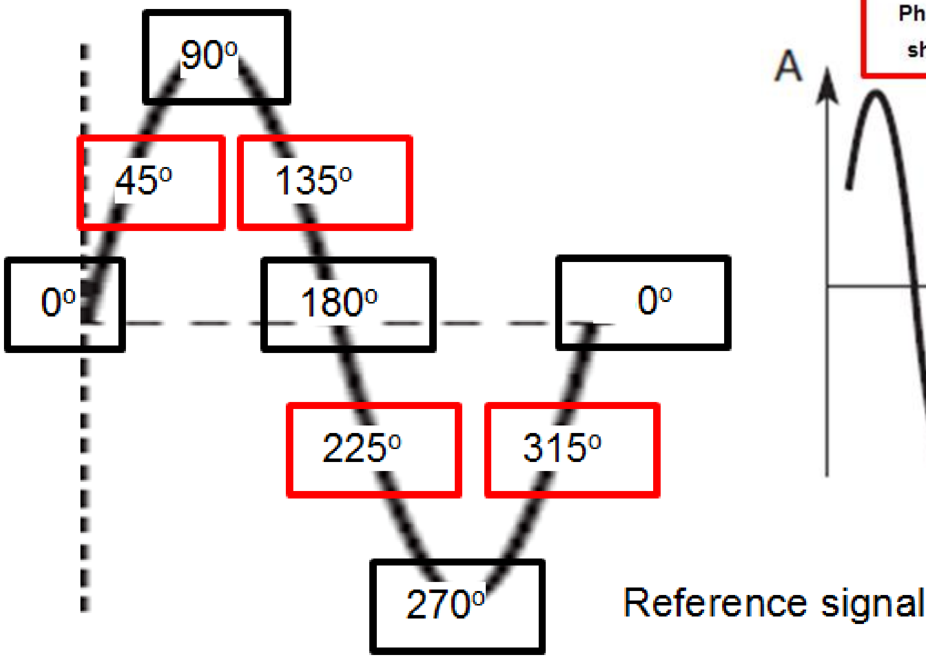
Bits

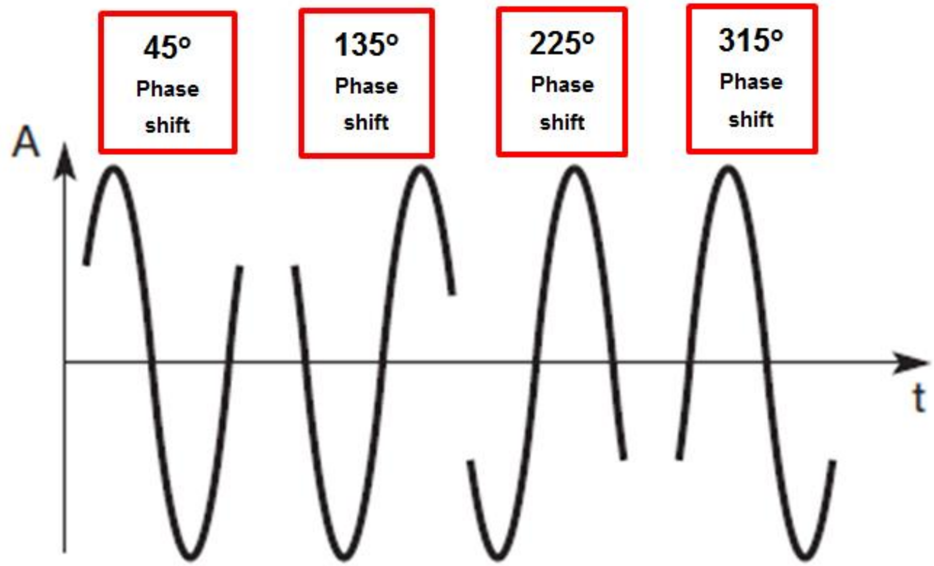


Constellation diagram

Phase Shift Keying (PSK)
Phase Shifts Examples

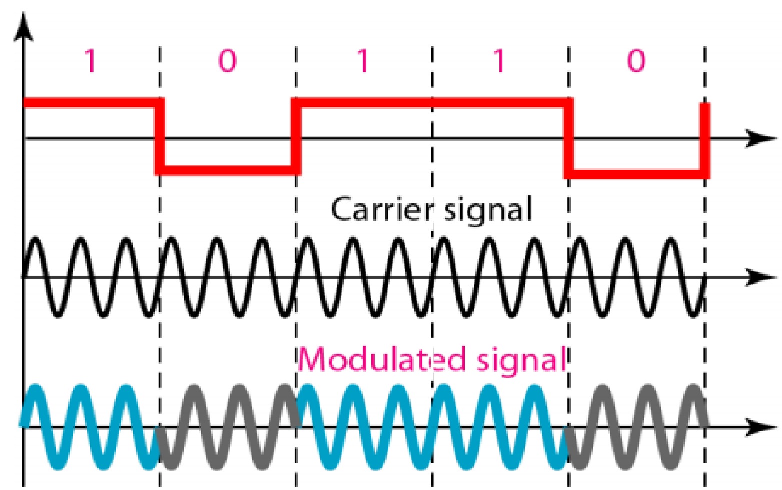
- **Phase Shifts Example**





Phase Shift Keying (PSK)

- PSK is **not susceptible to noise degradation** that affects **ASK, neither has the limitation of FSK that needs to repeatedly tune at different frequencies (i.e., no need for filtering the signal of different frequencies → simpler demodulator needed).**
- **Simple to implement**, and is used extensively in wireless communication.



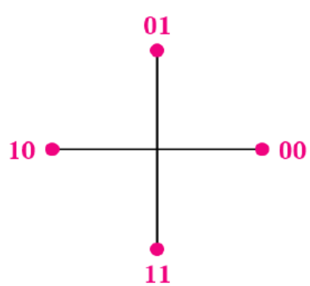
Quadrature Phase Shift Keying (QPSK)

- **QPSK** refers to **PSK with 4 states**.
- The "Q - *Quadrature*" in QPSK refers to **four phases** in which **a carrier is modulated and send in QPSK**. Also, called **4-PSK**.
- Because QPSK has **4 possible states**, QPSK can encode **two bits per symbol**.
  - Because **2 bits** are **allocated to each symbol**, QPSK can achieve **twice the Data Rate** of a **comparable BPSK** scheme **for a given bandwidth.**

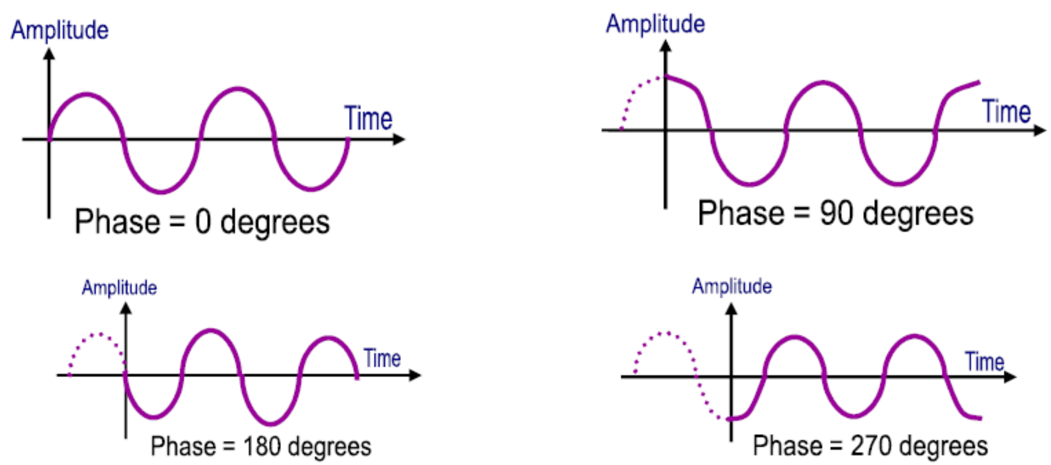
Example: Relationship between different phases:

Dibit	Phase
00	0
01	90
10	180
11	270

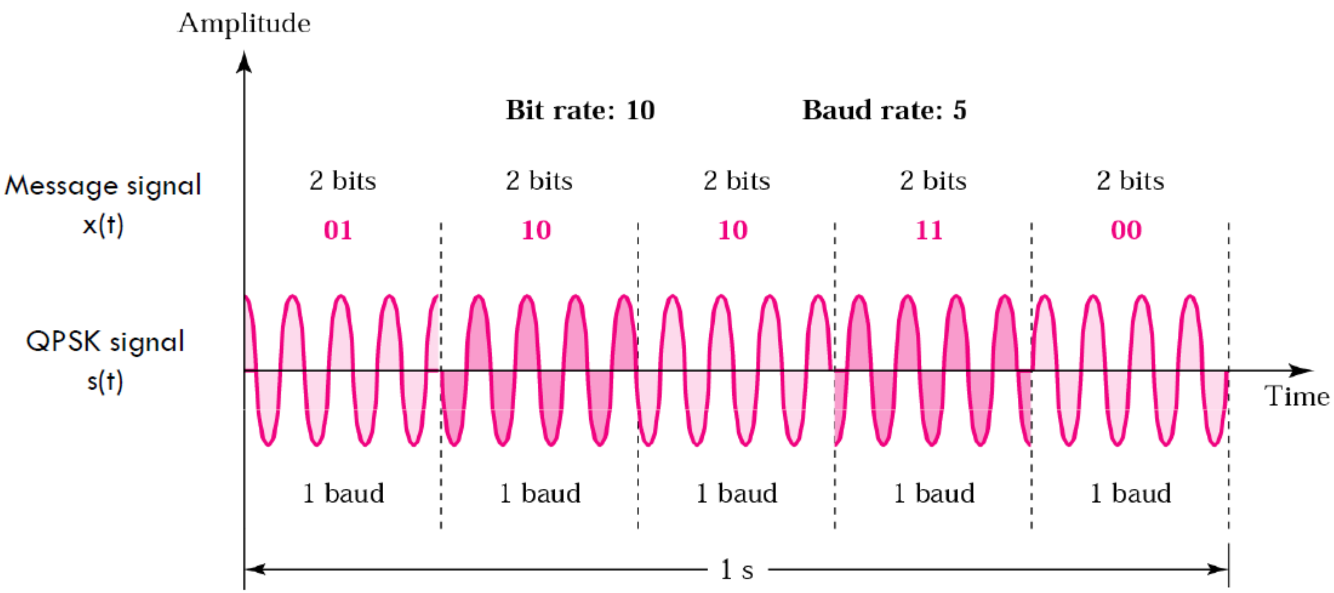
Dibit
(2 bits)



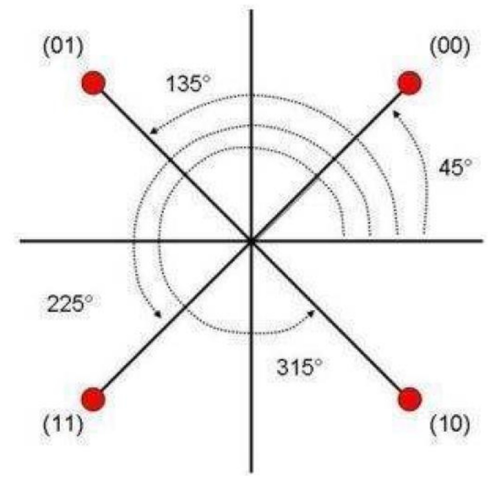
Constellation diagram



Quadrature Phase Shift Keying (QPSK)



Phase	Data
45	00
135	01
225	11
315	10

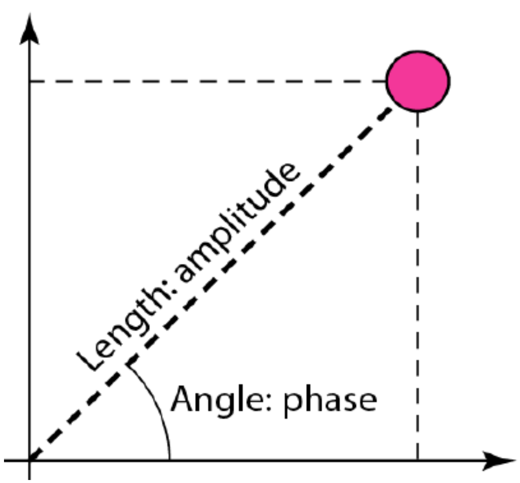


Two Modulation Alphabets

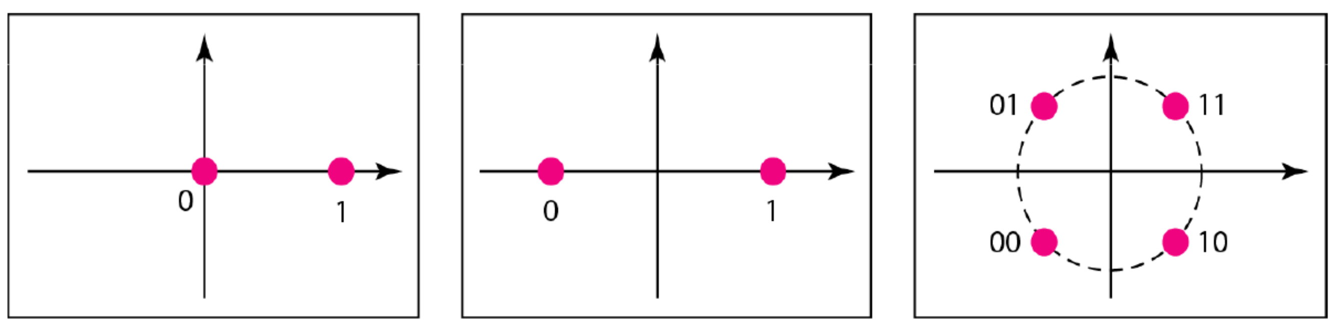
$$s(t) = \begin{cases} A\sin(2\pi f t + \phi_1) \\ A\sin(2\pi f t + \phi_2) \\ A\sin(2\pi f t + \phi_3) \\ A\sin(2\pi f t + \phi_4) \end{cases} \quad \begin{cases} \phi_1 = 0^o \\ \phi_2 = 90^o \\ \phi_3 = 180^o \\ \phi_4 = 270^o \end{cases} \quad \text{OR} \quad \begin{cases} \phi_1 = 45^o & 00 \\ \phi_2 = 135^o & 01 \\ \phi_3 = 225^o & 10 \\ \phi_4 = 315^o & 11 \end{cases}$$

Constellation Diagrams
Διαγράμματα Αστερισμού

- It is a **convenient way** to **represent the symbols (define the amplitude and phase)** of the **Modulation Alphabet** that will be used for **modulating signal carrier** and **transmitting the signal**. (Είναι ένας εύκολος τρόπος για να αναπαραστήσουμε **τα σύμβολα του Αλφαβήτου Διαμόρφωσης** που θα χρησιμοποιηθούν για τη διαμόρφωση του μεταφορέα σήματος για την αποστολή του σήματος)



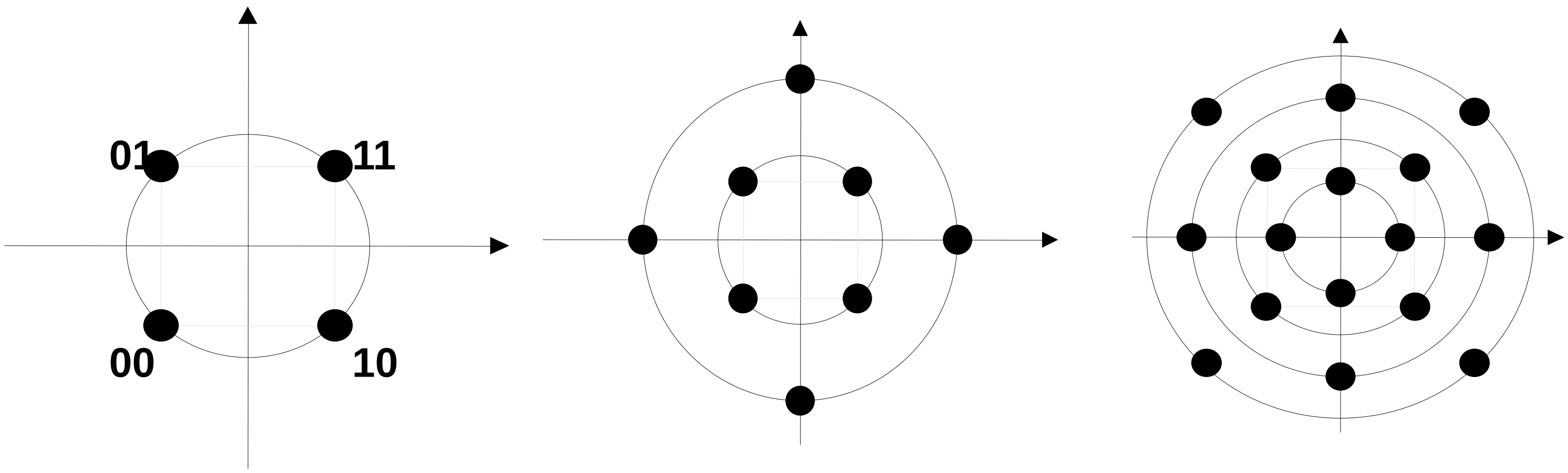
Examples:



a. ASK (OOK) b. BPSK c. QPSK

Constellation Diagrams
Circular Constellation Diagrams

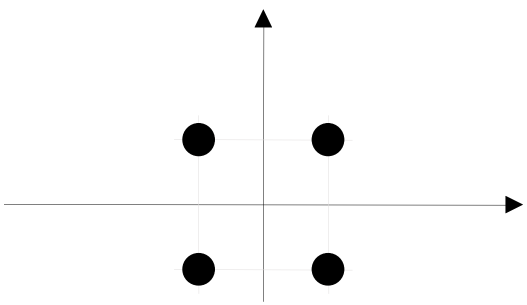
Examples:



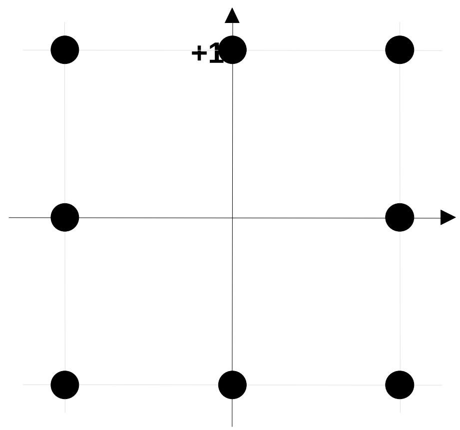
(a) Circular 4-QAM **(b) Circular 8-QAM** **(c) Circular 16-QAM**

Constellation Diagrams
Rectangular Constellation Diagrams

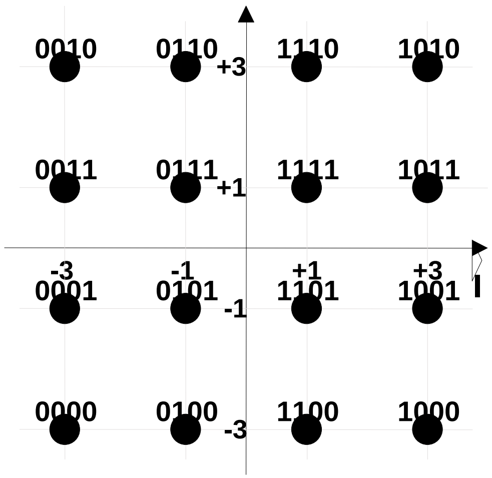
Examples:



Rectangular 4-QAM



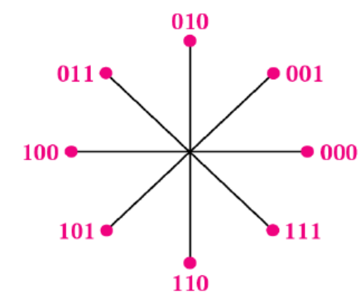
Rectangular 8-QAM



Rectangular 16-QAM:

Higher Order Modulation: 8-PSK

- We **can extend the Modulation Alphabet**, by varying the **signal by shifts of 45°** (instead of 90° in QPSK). (Μπορούμε να επεκτείνουμε το Αλφάβητο Διαμόρφωσης με το μεταβάλλουμε το σήμα με μετατοπίσεις 45° παρά 90° όπως το QPSK)
- With 8 (2^3) different phases, each phase (i.e., signal unit or symbol) can represent **3 bits.**



Constellation diagram

Baud Rate = Bit Rate/3 → Reduces the Required Bandwidth to one third

$$s(t) = \begin{cases} A\sin(2\pi f t + \phi_1) & 000 \\ A\sin(2\pi f t + \phi_2) & 001 \\ A\sin(2\pi f t + \phi_3) & 010 \\ A\sin(2\pi f t + \phi_4) & 011 \\ A\sin(2\pi f t + \phi_5) & 100 \\ A\sin(2\pi f t + \phi_6) & 101 \\ A\sin(2\pi f t + \phi_7) & 110 \\ A\sin(2\pi f t + \phi_8) & 111 \end{cases}$$

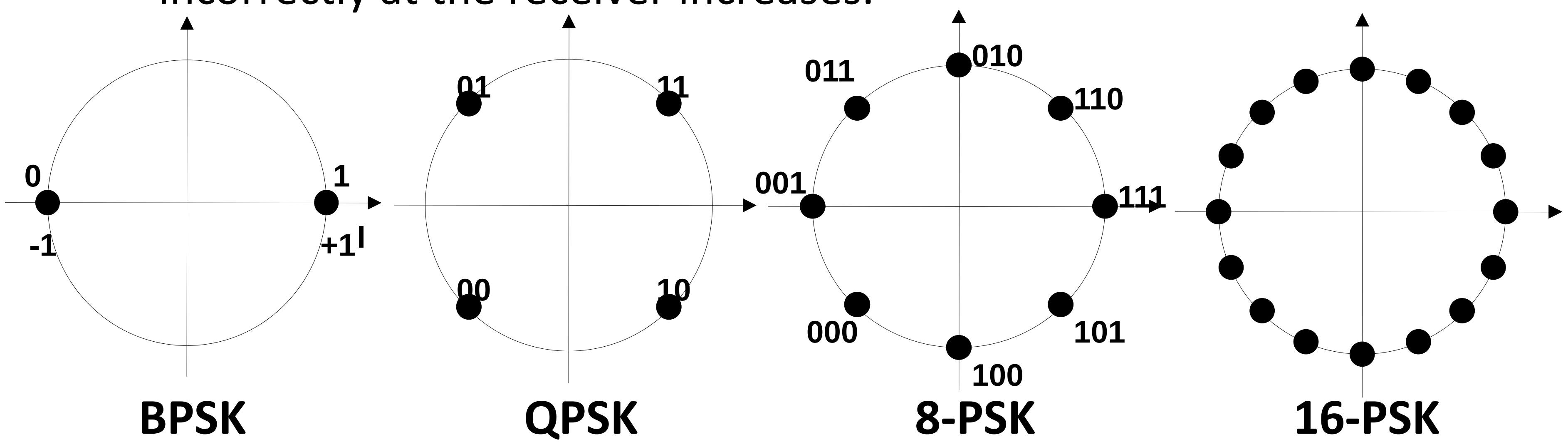
$$\begin{cases} \phi_1 = 0^o \\ \phi_2 = 45^o \\ \phi_3 = 90^o \\ \phi_4 = 135^o \\ \phi_5 = 180^o \\ \phi_6 = 225^o \\ \phi_7 = 270^o \\ \phi_8 = 315^o \end{cases}$$

Using the Constellation Diagram we can easily produce the Modulation Alphabet

Tribit	Phase
000	0
001	45
010	90
011	135
100	180
101	225
110	270
111	315

Higher Order Modulation: M-PSK

- Obviously **the bandwidth efficiency** of a M-ary PSK scheme increases as **M (the number of possible states) increases** because **more bits per symbol can be sent**
- ...however **the distance between 2 points** in the **constellation** is **reduced** and therefore the possibility for decoding the symbol incorrectly at the receiver increases.



- As M increases, **the bandwidth efficiency increases** but the **waveform energy (i.e., the transmission power used to send the symbol)** must **be increased to keep the BER at a certain level**.

Quadrature Amplitude Modulation (QAM) – Phase and Amplitude Modulation

- **PSK is limited** by the ability of the equipment to **distinguish between small differences in phases**.
  - Limits the potential data rate. (Περιορίζει το πιθανό data rate)
- The principle of **Quadrature Amplitude Modulation** (QAM) or **Amplitude Phase Shift Keying** (APSK) is to have **X possible variations** in **Phase** (X πιθανές διαφορετικές φάσεις) and **Y possible variations** of **Amplitude** (Y πιθανά διαφορετικά πλάτη) .
  - Up to **X • Y** possible variations → **More different states** that the **carrier signal can be modulated**, therefore **more bits can be carried per symbol** → Therefore greater Data Rates and Throughput.
  - **QAM (or APSK) is an application of ASK to PSK (**Εφαρμογή του ASK πάνω στο PSK**)**

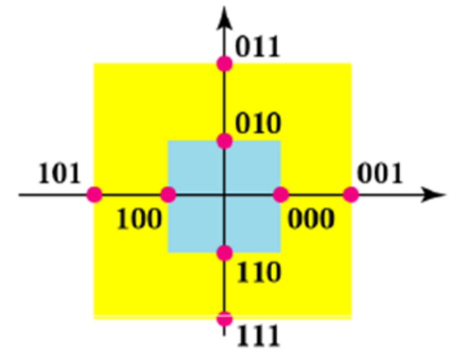
Quadrature Amplitude Modulation (QAM) – Phase and Amplitude Modulation

Example: **8-QAM example**

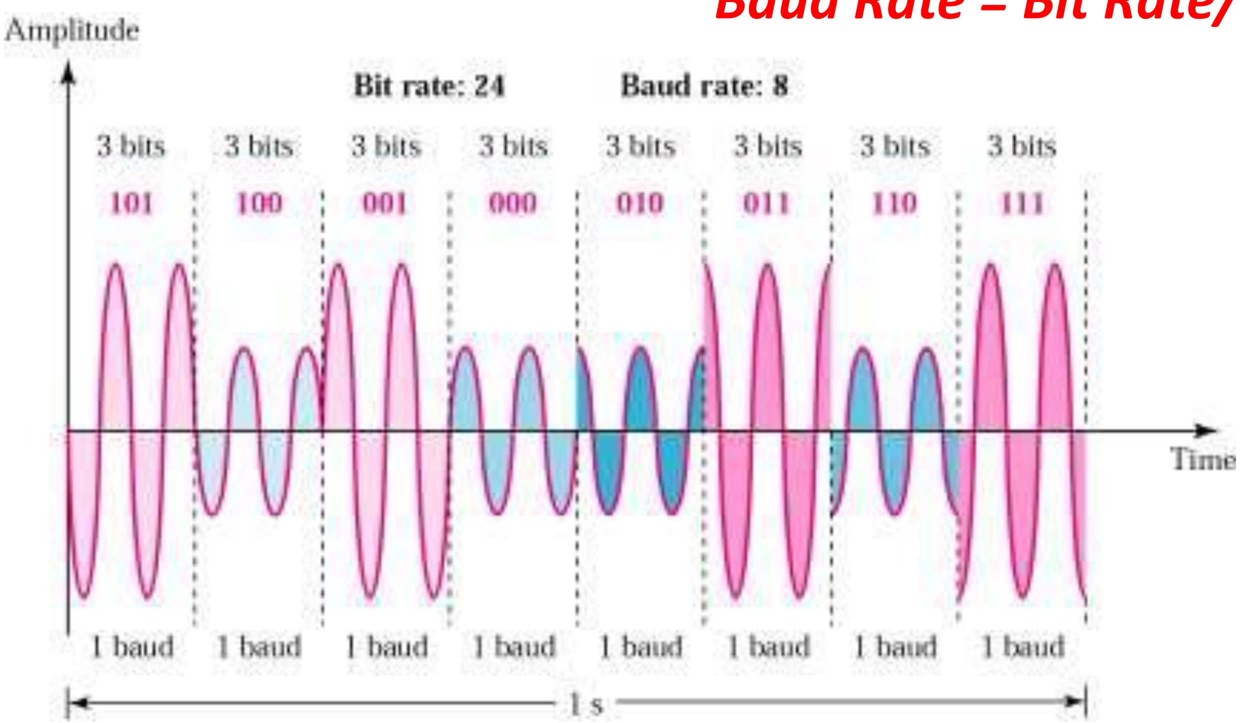
Two (2) possible *different* ***Amplitudes*** *(A1 = 1; A2 = 2)*

Four (4) possible *different* ***Phases*** *(0º, 90º, 180º, 270º)*

Total *of* ***8*** **QAM symbols →** ***3 bits per symbol***



Baud Rate = Bit Rate/3

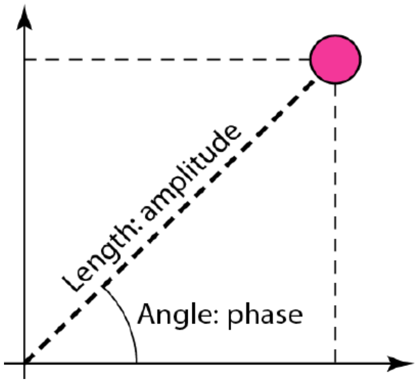


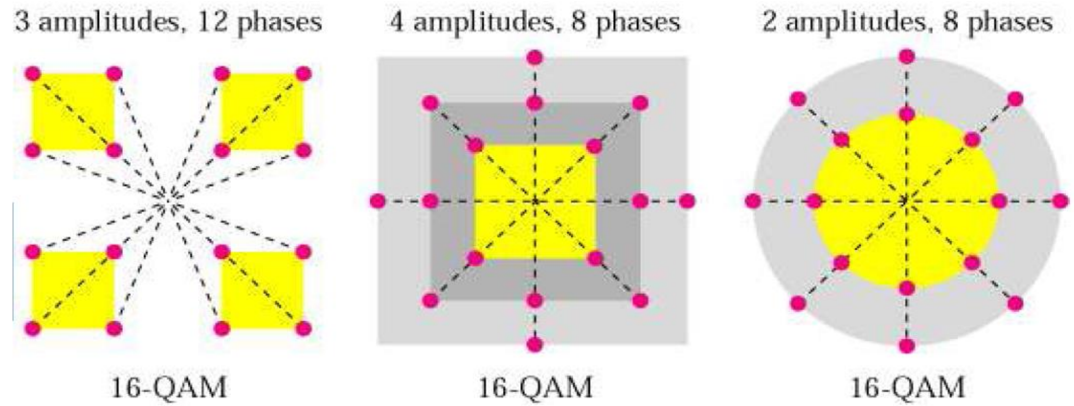
Modulation Alphabet

A = 1, Phase = 0º:	**000**
A = 2, Phase = 0º:	**001**
A = 1, Phase = 90º:	**010**
A = 2, Phase = 90º:	**011**
A = 1, Phase = 180º:	**100**
A = 2, Phase = 180º:	**101**
A = 1, Phase = 270º:	**110**
A = 2, Phase = 270º:	**111**

Quadrature Amplitude Modulation (QAM) or APSK

- We can have **numerous possible variations** (Διάφορες πιθανές παραλλαγές) of **Phase Shifts** and **Amplitude shifts**
  - However the **Number of Phase Shifts** should selected to be **GREATER** than **Number of Amplitude shifts**. (Why??)





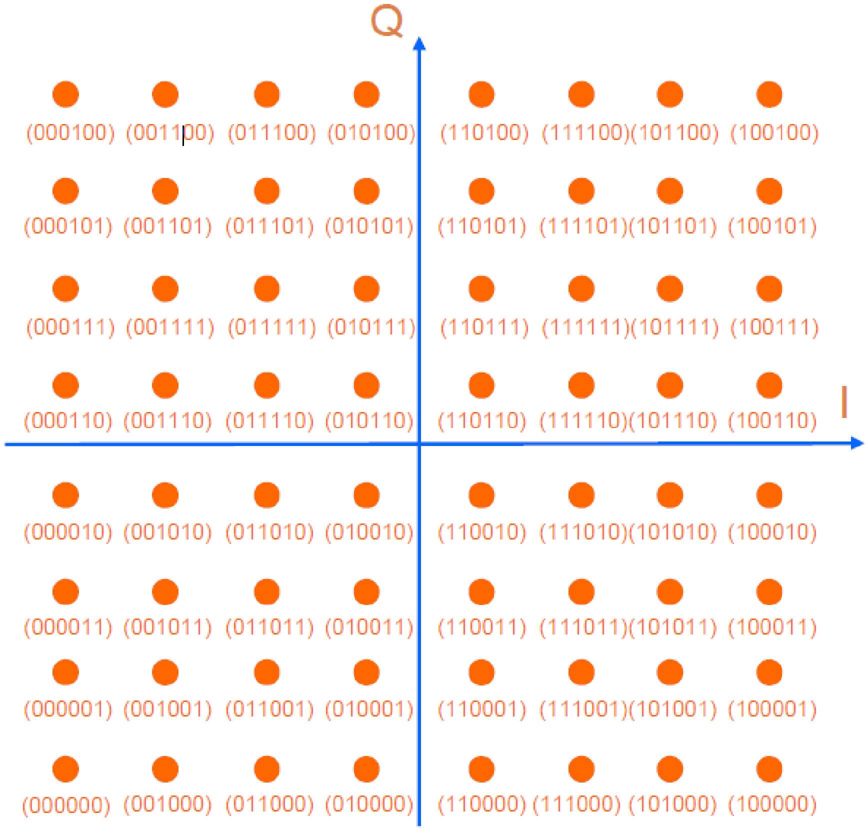
16-QAM for example:

- There are **sixteen QAM symbols** → ***4 bits per symbol***.
- **A variety of constellations diagrams can be used**

Quadrature Amplitude Modulation (QAM)

More higher order modulation

- **64-QAM** (64-Quadrature Amplitude Modulation)
  - Each symbol now **carries 6 bits (i.e., $\log_2(64)$)**



Going higher:

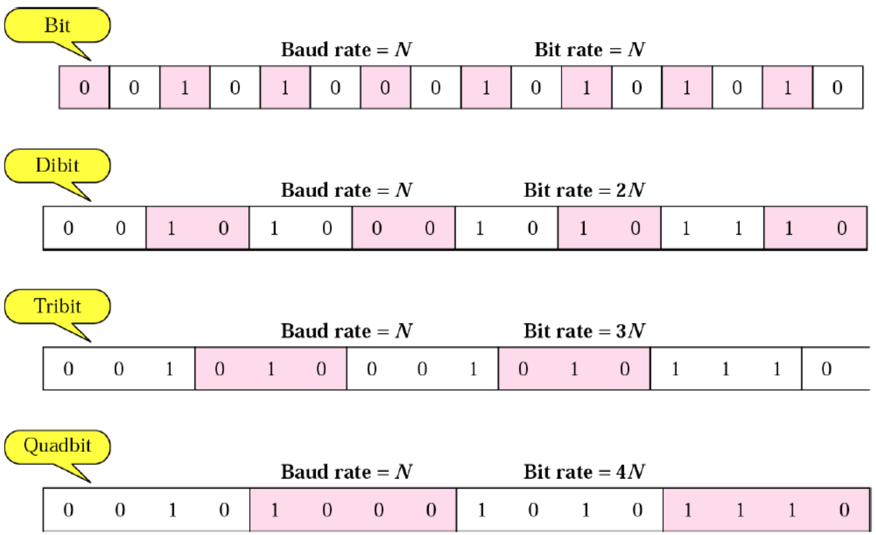
- **256-QAM**
  - **8bits/symbol ($\log_2(256)$)**
- **1024-QAM**
  - **10bits/symbol ($\log_2(1024)$)**
- ……….

Why Not Just Keep Going?

- **With Higher Order Modulation schemes**
  - **Minor errors** during **modulation** could **create symbol errors** in transmission
  - **Even a little noise** in the transmission channel could create symbol errors
  - **Minor inaccuracies** in the Receiver could create errors
  - **Signal-to-Noise requirements increases** with higher order modulations (thus more power have to be used during transmission → more interference caused in the cells)

Bid and Baud Rate Comparison

- Assuming a **Binary-FSK signal** can send **1200 bps**, it requires **1200 signal units (symbols)** to send **1200 bits** (each symbol represents one bit, **Baud Rate = 1200** bauds/s)
- Assuming an **8-QAM (3 bits per symbol)**, using the **same baud rate** (1200 bauds/s), 3600 bits/s will be achieved (**3 x Bit Rate**).



Modulation	Units	Bits/Baud	Baud rate	Bit Rate
ASK, FSK, 2-PSK	Bit	1	N	N
4-PSK, 4-QAM	Dibit	2	N	2N
8-PSK, 8-QAM	Tribit	3	N	3N
16-QAM	Quadbit	4	N	4N
32-QAM	Pentabit	5	N	5N
64-QAM	Hexabit	6	N	6N
128-QAM	Septabit	7	N	7N
256-QAM	Octabit	8	N	8N

Bid and Baud Rate Comparison Examples

- **A constellation diagram consists of eight equally spaced points on a circle. If the bit rate is 4800 bps, what is the baud rate?**
  - The constellation **indicates an 8-PSK** with the **points 45 degrees apart**. Since $2^3 = 8$ ($N = \log_2(8) \rightarrow N = 3$) then **3 bits** are transmitted with each **signal unit (symbol)**.
  - Therefore, the baud rate is **4800 / 3** = **1600 baud/s**.

- **What is the bit rate for a 1000 baud/s 16-QAM signal?**
  - A 16-QAM signal has **4 bits per signal unit (symbol)** since $\log_2 16 = 4$. Thus, (1000 x 4) = **4000 bps**

- **Compute the baud rate for a 72,000bps 64-QAM signal.**
  - A **64-QAM** signal has **6 bits per signal unit** ($\log_2 64 = 6$).
  - Therefore **72,000 / 6** = **12,000 baud/s**

Factors that influence the choice of Digital Modulation Scheme

- **Some Performance factors considered (depending on the environment):**
  - **Achieve Low Bit Error Rate** (BER) at **low SNR or SINR** (Να επιτυγχάνει χαμηλό ποσοστό σφάλματος δεδομένων με χαμηλή ενέργεια σήματος)
  - **Efficient use** of **battery power** in Mobile Device (Να κάνει αποδοτική χρήση της μπαταρίας στις κινητές συσκευές)
  - **Resistance to Interference and Noise** (Ανοχή στις παρεμβολές και το θόρυβο)

Factors that influence the choice of Digital Modulation Scheme

- **Occupying** a **minimum amount of Bandwidth** to **send the data** (Να δεσμεύει όσο το δυνατό πιο λίγο εύρος ζώνης για να στείλει τα δεδομένα)
- **Easy and cheap** to **implement** in a Mobile Device (Η τεχνική να είναι φτηνή και εύκολη να υλοποιηθεί στις κινητές συσκευές)

- **No existing modulation scheme simultaneously satisfies all of these requirements well.**
- **Each one is better in some areas** with **tradeoffs of being worse in others**.

Factors that influence the choice of Digital Modulation Scheme

- **The performance of a modulation scheme is often measured in terms of its:**
  - **Power Efficiency:** Refers to the **ability to preserve the fidelity (no errors) of a digital message at low power levels (i.e., low SNIR)** (Περιγράφει την ικανότητα διατήρησης της ακεραιότητα ενός μηνύματος (no errors) σε χαμηλά επίπεδα ισχύος του σήματος)
  - **Bandwidth (or Link Spectral) Efficiency**: Refers to **ability to "squeeze" as much data** into the **least amount of bandwidth available** (Περιγράφει την ικανότητα "συμπίεσης" όσον περισσότερων δεδομένων στο ελάχιστο διαθέσιμο εύρος ζώνης)

Factors that influence the choice of Digital Modulation Scheme

Power Efficiency:

- In order to **increase noise immunity**, it is necessary to **increase the signal power**. (Για να αυξήσουμε την ανοσία ενός σήματος στο θόρυβο πρέπει να αυξήσουνε την ενέργεια (ισχύ) με την οποία θα το στείλουμε)
  - The **amount** by which the **signal power should be increased** to **maintain a certain BER depends on the modulation scheme.**
  - **Higher Order Modulation → Higher Signal Power.**
- The **Power Efficiency is expressed by** the value of **SNIR required at the Receiver** to **decode the signal correctly** and **guarantee a certain BER** (The **lower the SNIR required** the **higher the Power Efficiency**).

Factors that influence the choice of Digital Modulation Scheme

Bandwidth (Link Spectral) Efficiency:

- Is typically used to **analyse how efficiently the allocated bandwidth is used by the modulation technique** (Χρησιμοποιείται για να αναλύσουμε πόσο αποδοτικά χρησιμοποιείται το διαθέσιμο εύρος ζώνης από την τεχνική διαμόρφωσης).
- It is defined as the **average number of bits per unit of time** (bits per second) that can be transmitted **per unit of bandwidth** (per Hertz).

Factors that influence the choice of Digital Modulation Scheme

Bandwidth (Link Spectral) Efficiency:

- Is the ***net* data rate** (**useful information rate excluding error-correcting codes**) or **maximum throughput*** **divided** by the available **Bandwidth (in hertz)** of a communication channel.
- It is measured in bits per second per Herz (**bps/Hz**)

$$\eta_B = \frac{R}{B} \ \text{bps/Hz}$$

R : data rate B: RF BW

*** *Throughput*** *or* ***network throughput*** *is the* ***rate of successful message delivery over a communication channel****. A typical method of performing a measurement is to transfer a 'large' file from one system to another system and measure the time required to complete the transfer or copy of the file. The* ***throughput is then calculated*** *by* ***dividing*** *the* ***file size by the time required to complete the transfer****. Then the throughput can be measured in megabits, kilobits, or bits per second.*

Factors that influence the choice of Digital Modulation Scheme

- **Bandwidth Efficiency Examples:**
  - **Example 1: What is the bandwidth efficiency of the modulation technique when 2 Kilohertz of bandwidth is required to transmit 1000 bps?**
    - 1000bps/2000Hz = 0.5 bps/Hz
  - **Example 2: What is the bandwidth efficiency of the modulation technique when 3 Kilohertz of bandwidth is required to transmit 12000 bps?**
    - 12000bps/3000Hz = 4bps/Hz

Factors that influence the choice of Digital Modulation Scheme

Very often there is a tradeoff:

- **M-ary** schemes **increase the Bandwidth Efficiency** but **require Higher Transmission Power (than Binary modulation schemes)** to **keep the same Bit Error Rate → Lower Power Efficiency**. (Κάνουν την χρήση του εύρους ζώνης πιο αποδοτική άλλα χρειάζεται περισσότερη ισχύς κατά την αποστολή των δεδομένων για να είναι το σήμα πιο δυνατό και να μπορεί ο Receiver να το αναγνωρίσει και να το αποκωδικοποιήσει σωστά διατηρώντας έτσι το BER στα επίπεδα που πρέπει)

Factors that influence the choice of Digital Modulation Scheme

Very often there is a tradeoff:

- **Power Efficiency can be increased by adding Error Control Coding in the packets transmitted** but **reduces** the **Bandwidth Efficiency** as **Redundancy** is transmitted too. (Μπορούμε να αυξήσουμε το Power Efficiency με το να προσθέσουμε error control codes κατά την αποστολή των πακέτων αλλά αυτό μειώνει το Bandwidth Efficiency αφού στέλλουμε επιπλέον (μη χρήσιμη) πληροφορία)

Error control (error detection and correction) *are techniques that* ***enable reliable delivery of digital data*** *over* ***unreliable communication channels****. Many communication channels are subject to channel* ***noise****, and* ***thus errors may be introduced during transmission*** *from the source to a receiver. Error detection techniques allow* ***detecting such errors****, while error correction enables* ***reconstruction of the original data in many cases****.*

Ερωτήσεις;

Additional Slides

Modulation

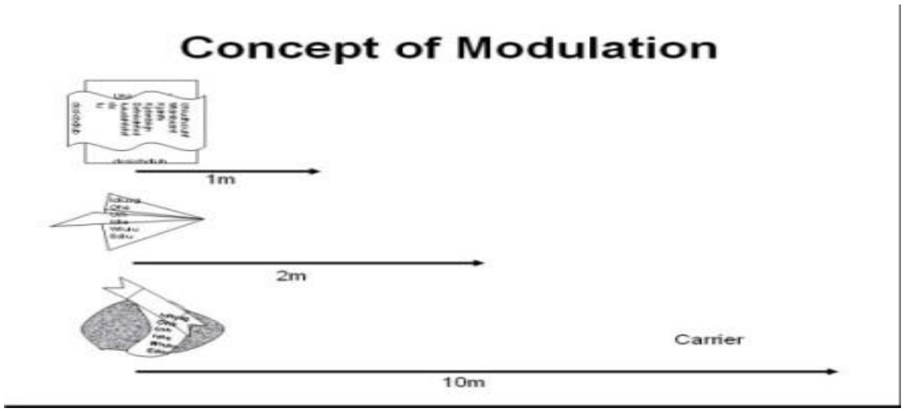
- **Modulation** is the process of **encoding information (the data that we want to transmit) from a message source in a manner suitable for transmission** **through a medium** (i.e., the air) (Είναι η διαδικασία κωδικοποίησης της πληροφορίας (του πηγαίου μηνύματος) που θέλουμε να στείλουμε, σε μια μορφή η οποία είναι κατάλληλη για μετάδοση μέσω κάποιου μέσου (π.χ., στον αέρα))
- Modulation is used to **modify the parameters** of a **high frequency carrier signal** (i.e., **Amplitude**, **Frequency**, **Phase**), so as to include a **message signal** (which contains the information) onto the carrier (i.e., the channel).

Why Modulate?

- **Ease of radiation (Ευκολία εκπομπής) → Reduce antenna size**: The **size** of an antenna **is proportional to the signal wavelength**.
- By modulating the baseband signal (i.e., the message) into higher frequency carrier, the **wavelength decreases, and thus the size of the antenna decreases**.
  - The size of antenna $\propto$ $\boldsymbol{\lambda/4 = c/4f}$. E.g.:
    - 3 kHz → 25 Km antenna
    - 3 GHz → 2.5 cm antenna

Why Modulate?

- **Allows the message data to be encoded into a form (i.e.,** into a **Carrier signal** with **higher frequencies) suitable for Traveling Long Distances over the air:**
  - E.g., If we wish to throw a piece of paper, it cannot go too far by itself. But by wrapping it around a stone (carrier signal), it can be **thrown over a longer distance**!



Why Modulate?

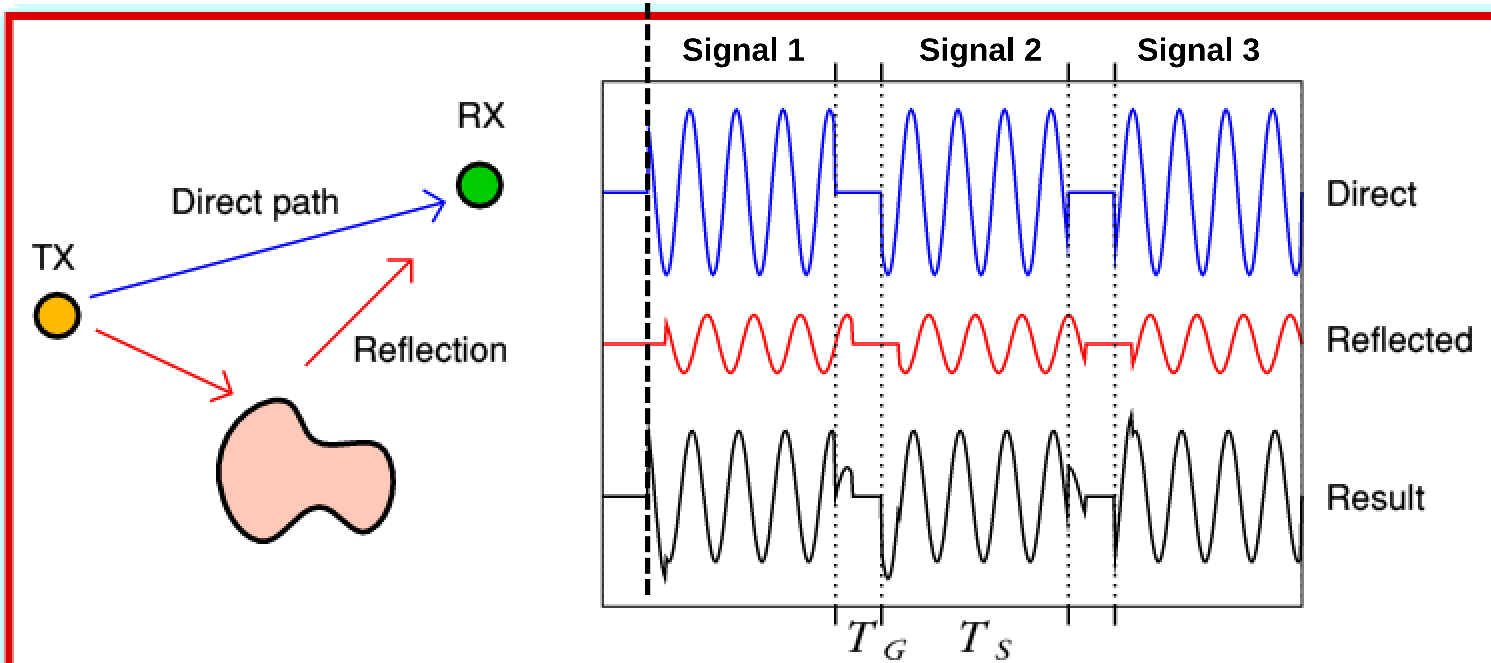
- **Bandwidth Efficiency (Αποδοτική χρήση του διαθέσιμου εύρου ζώνης)**
  - By modulation we can use a **narrow bandwidth (χρήση μικρού εύρος ζώνης)** to send a **large amount of data** → Higher order modulation schemes (8-PSK: 3 bits/symbol, 16-QAM: 4 bits/symbol, 64-QAM: 5 bits/symbol) can be used depending on the environmental conditions.
    - Effective use (Αποτελεσματική χρήση) of limited frequency resources
- **A carrier alone conveys no information**
  - A carrier signal by itself is like a “train wagon” without letters → Modulation makes the signal carrier “usefull”. Includes the information that will be transmitted.

Why Modulate?

- **Allows simultaneous transmission of several signals (Multiplexing; Πολυπλεξία** – Πολλοί χρήστες μπορούν να στείλουν τα δεδομένα τους την ίδια ώρα χωρίς να προκαλούνται παρεμβολές**)**
  - By **modulating different signals** into **different carriers** (with different frequencies) **several users can transmit their signals at the same time** (avoid interference). The Received parties will **just tune (**συντονίζονται**) to the correct Frequency Carrier** to receive the signal.
- **Good Security features (Ασφάλεια δεδομένων)**
  - Greater security (encryption - κρυπτογράφηση) on the data can be applied during modulation.
- **….**

Multipath Propagation Effect on Signal Demodulation at the Receiver

- In the example illustrated below, we assume that the Receiver receives two copies of each signal, from two different paths (Direct Path, Reflected) each path having a **different length** --> Each signal copy will arrive to the Receiver in **different times (delays)** and with **different amplitudes**.



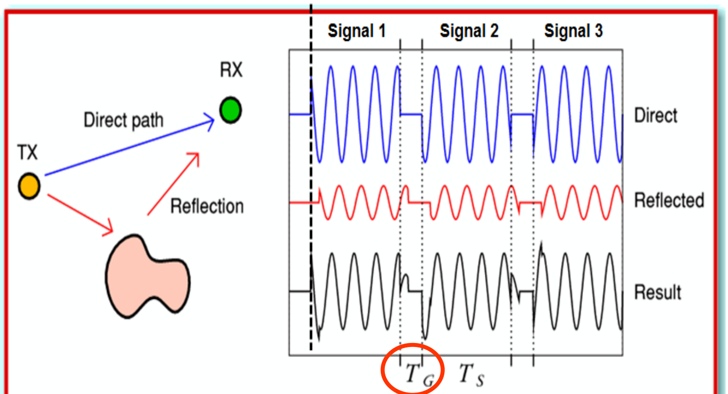
Effect of Multipath Propagation

Multipath Propagation Effect on Signal Demodulation at the Receiver

- The two paths are of lengths we can call **Z** (direct) and **Z'** (indirect). This allows us to define the time delay (**dt**) between their relative arrivals to be

  dt = (Z' – Z)/C *C is the speed of light*

- The above shows why it is useful to have a **Guard Interval** (T_G), in between the **Useful Symbol Periods** (T_s).
- For this case, if we arrange for T_G **> dt** then the **delayed version of each symbol** will have **finished arriving before the next symbol in the sequence starts to arrive**.
- This prevents the pattern transmitted for a given symbol from affecting what we see during the <u>next</u> symbol period.
- ISI makes it harder for the receiver to demodulate the symbols correctly.
- The larger the T_G → The lower the possibility for ISI → The less the number of symbols that can be transmitted per second → The lower the data rates achieved.



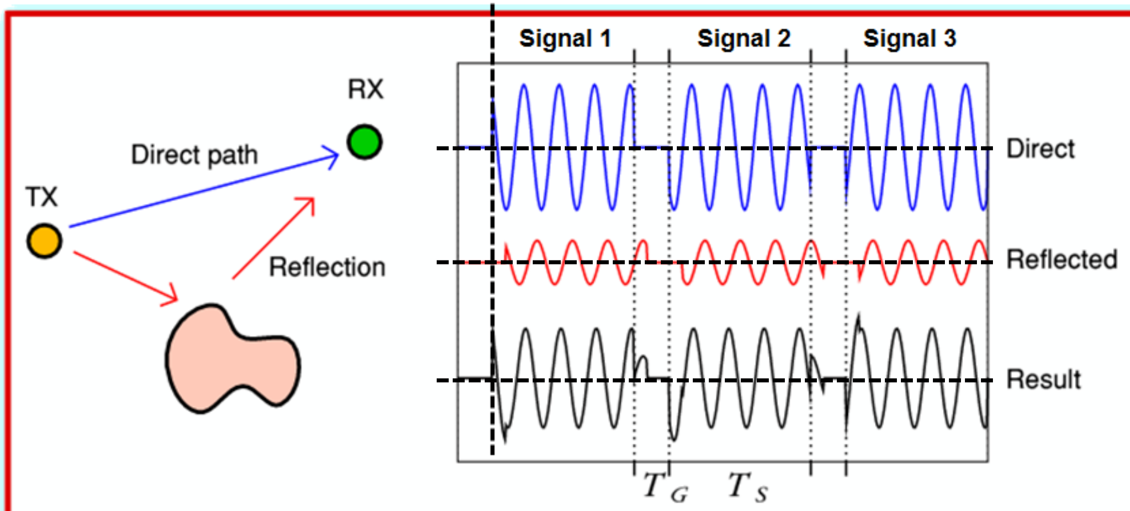
Effect of Multipath Propagation

Multipath Propagation Effect on Signal Demodulation at the Receiver

- The **addition of the delayed contribution** via the 'Reflected' path has two consequences:
  - The **symbols have been extended** and now have a **'tail'** due to the reflected contribution **continuing to arrive for a short period** after the direct symbol has ended.
  - The **Received Result** has **its effective Amplitude** and **Phase altered** by an **amount that depends on the time difference between the paths**.

If higher order modulation schemes are applied, even a minor alteration on the amplitude or phase of the signal will cause wrong signal interpretation at the Receiver

Propagation Delay: Length of the path that the signal follows to reach the receiver (Z), divided by the Speed of Light (C)



Effect of Multipath Propagation