Wireless Security

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Course Outline

- **Course Outline**
  - <u>**Review of basic concepts for digital communications**</u>
  - Security at the physical layer
  - Global Navigation Satellite Systems (GNSS) and positioning
  - Security in WiFi Networks
  - Bluetooth security
  - Security of Cellular Networks - 3G/4G/5G Network Structure and Architectures
  - Security of Near Field Communications (NFCs) and RFIDs

Basic Concepts for Digital Communications pt. 2

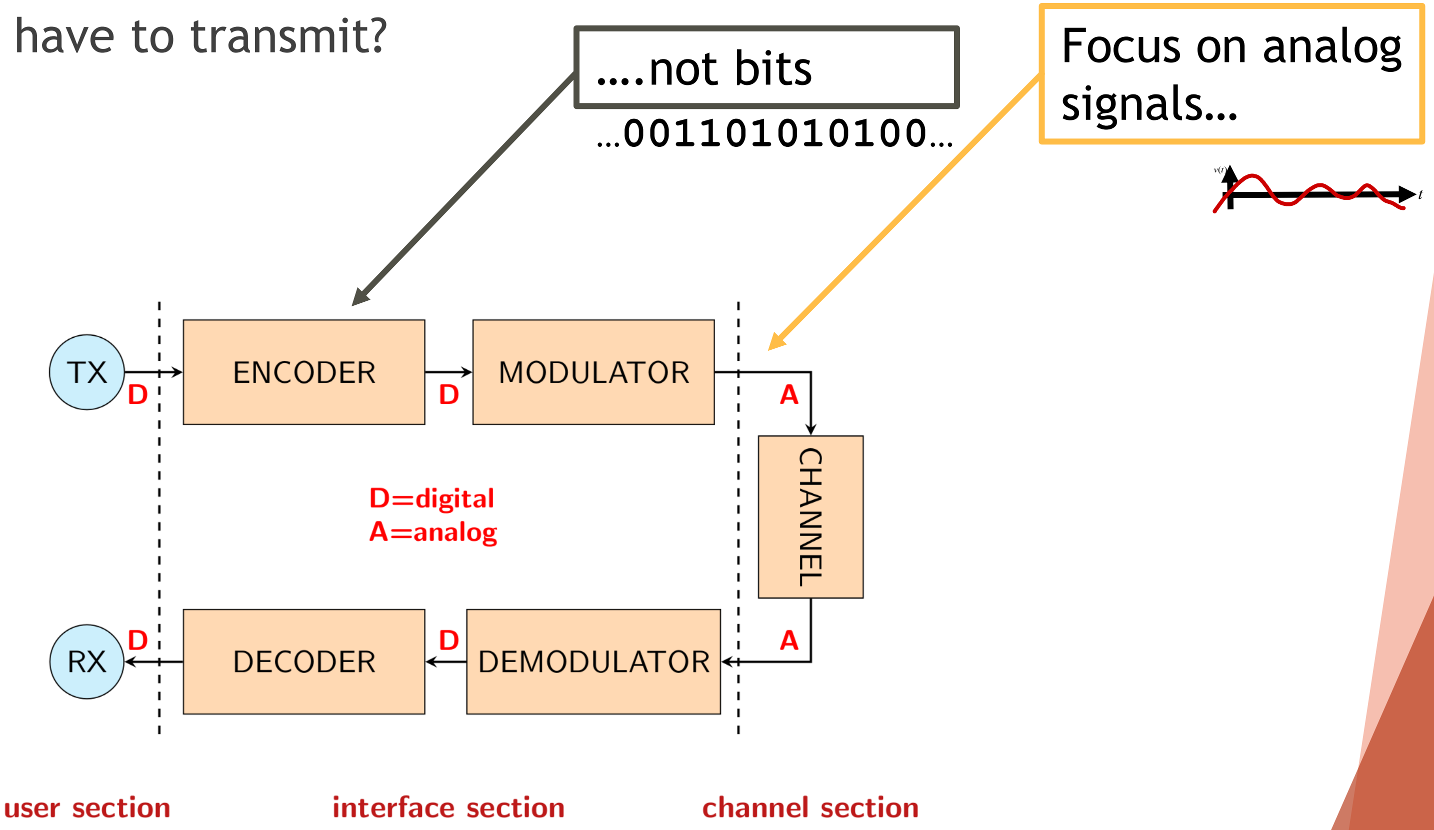
Andrea Nardin

Contents

- Review of basic concepts for digital communications
  - Introduction
  - Digital Communications Overview
  - Signals Representation and Processing
    - Signal representation
    - Frequency domain, filters, modulation
    - Sampling Theorem and Discrete Time Signals
  - <u>**Signals Transmission and Reception**</u>
    - <u>**Digital Modulations**</u>
    - AWGN channel and equalization
    - Received symbols and decision regions
    - Link Budget
    - Multiplexing / Multiple Access schemes (FDM/A, TDM/A, CDM/A)
    - Source and channel coding

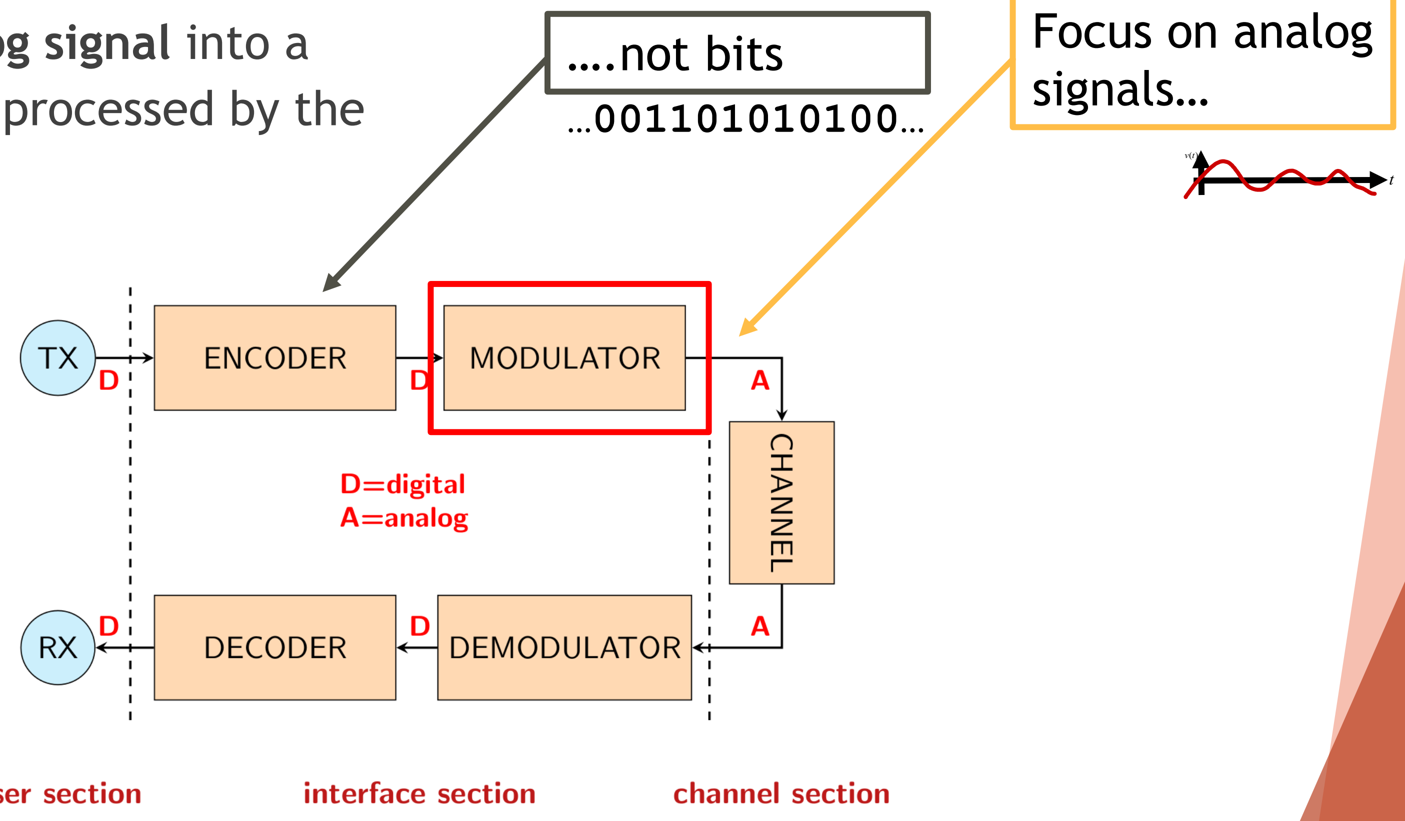
Which Waveforms Should We Transmit?

- We have now acquired the main tools to deal with signals
- Our goal is to use them to **communicate** some information (i.e. bits)
- I.e. to transmit something that will be **received correctly**
  - We talk binary, but we must transmit over analog media
- Which signal waveforms do we have to transmit?
  - (and possibly receive)



Recall: Modulator / Demodulator

- *Modulator*:
  - Converts the digital signal into an analog signal to be transmitted over the channel
- *Demodulator*
  - Converts the received **analog signal** into a **sequence of samples** to be processed by the decoder



Modulation Basics

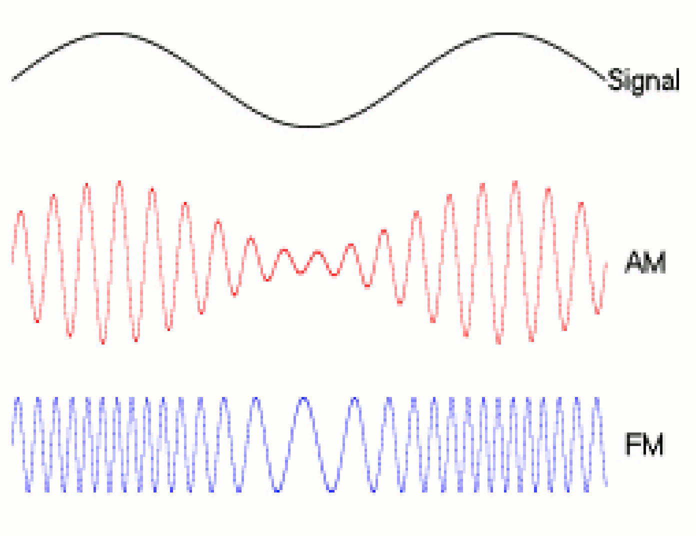
- Modulation is the process of **varying one or more properties** of a periodic waveform, called the carrier signal, with a separate signal called the modulation signal that typically contains **information** to be transmitted

- Why?
  - Multiple signals over the same channel
  - Wireless transmission (pathloss and atmospheric attenuation)
  - Etc.

- Generally, digital and analog modulations resort to basic modulation types:
  - *Amplitude Modulation*: changes the amplitude
  - *Frequency Modulation*: changes the frequency
  - *Phase Modulation*: changes the phase

Amplitude Modulation (AM)

- *Amplitude modulation* (AM):
- The amplitude of high-carrier signal is varied according to the instantaneous amplitude of the modulating message signal $m(t)$.



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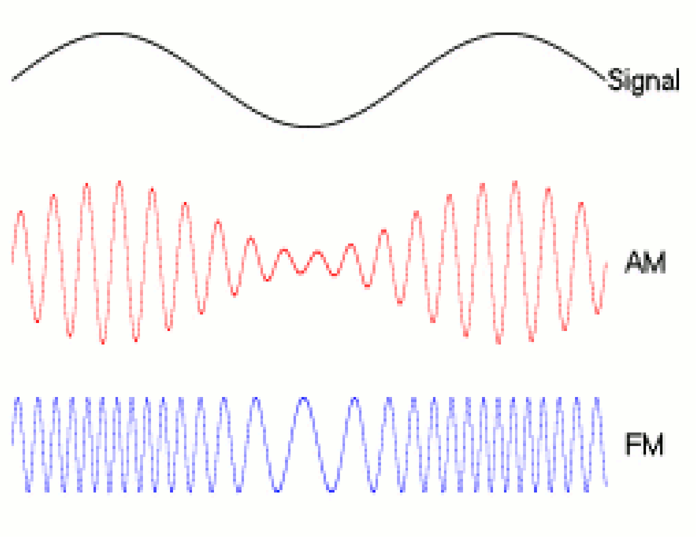
Frequency Modulation (FM)

- ***Frequency modulation*** **(FM):**
- The carrier amplitude remains constant, and the carrier frequency is changed by the modulating signal $m(t)$.
- As the amplitude of the information signal varies, the carrier frequency shifts proportionately.
  - As the modulating signal amplitude increases, the carrier frequency increases.
  - With no modulation the carrier is at its normal center or resting frequency.



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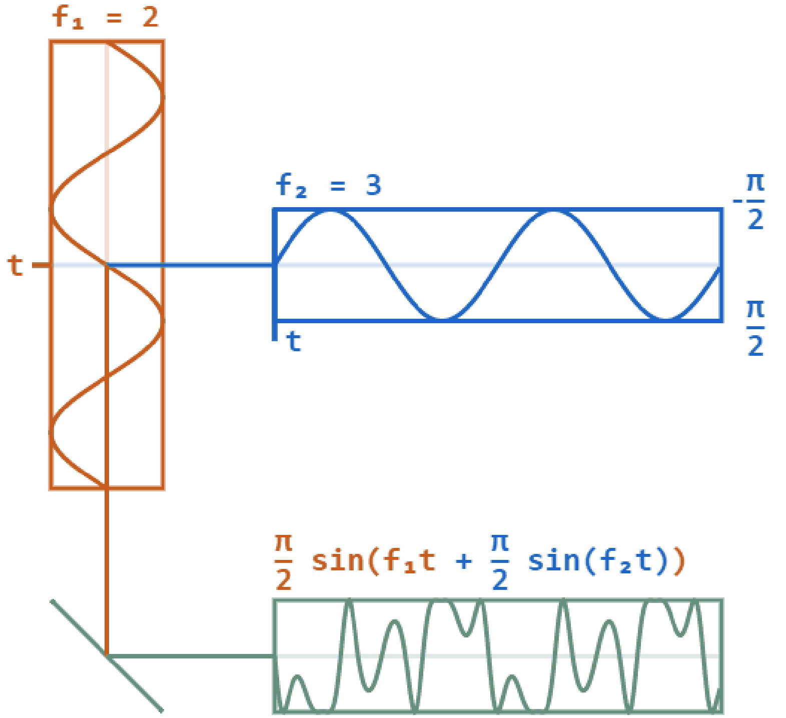
Phase Modulation (PM)

- *Phase modulation* (PM):
- It encodes a message signal $m(t)$ as variations in the instantaneous phase of a carrier wave
- The **phase of a carrier** signal is modulated to follow the changing **signal amplitude** of the message signal.
- The peak amplitude and the frequency of the carrier signal are maintained constant, but as the amplitude of the message signal changes, the phase of the carrier changes correspondingly
- The modulating wave (blue) is modulating the carrier wave (red), resulting the PM signal (green)



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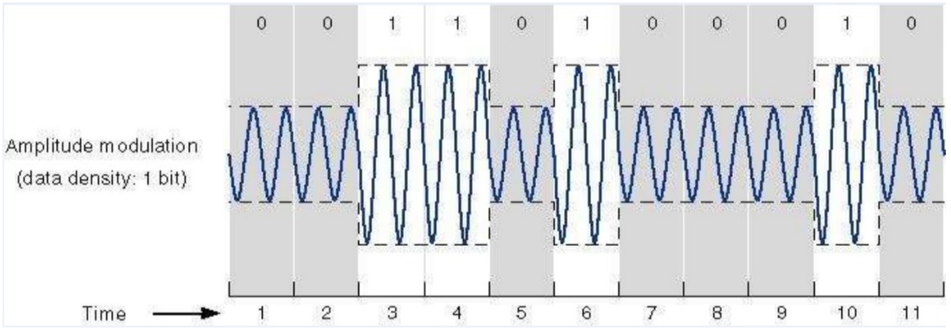
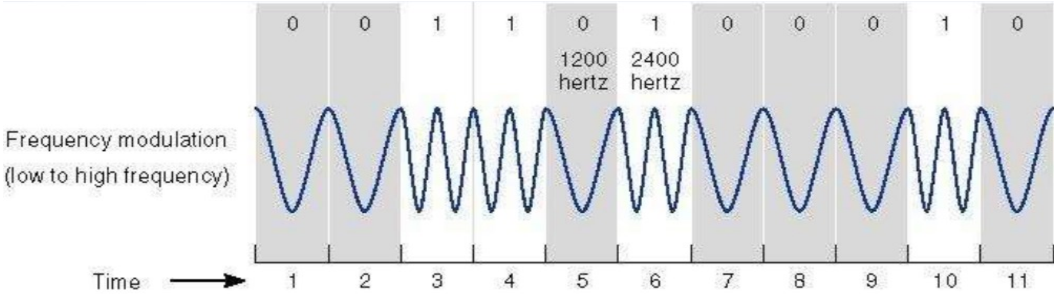
Analog and digital modulations

- Even if the world has turned to **digital**, transmitted signals are **analog**
- Similar ideas have been applied to digital signals

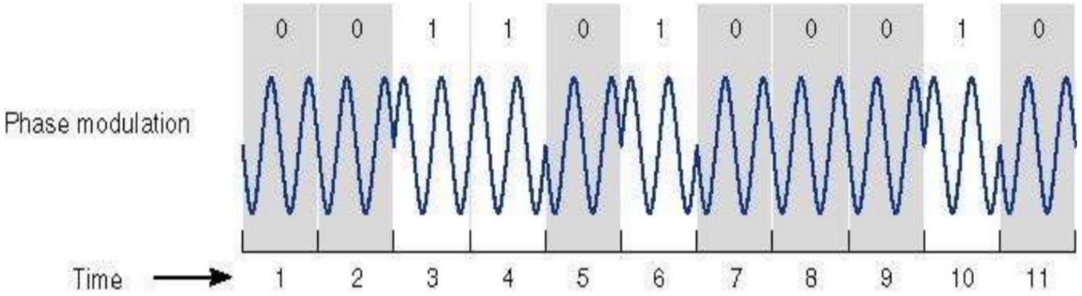
  - *Amplitude Shift Keying* (ASK)



  - *Frequency Shift Keying* (FSK)



  - *Phase Shift Keying* (PSK)



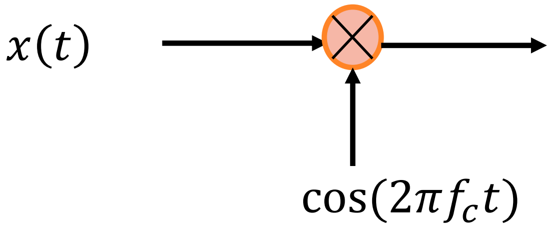
Analog and digital modulations

- Digital signals must be transmitted as **analog waveforms**

- *Baseband signals*
  - Signals whose frequency spectrum is concentrated around zero

- *Bandpass signals*
  - Signals whose frequency spectrum is centered at some frequency f_c away from zero

- **Baseband** signals can be converted to **bandpass** signals through *modulation:*
  - Multiplication by a sinusoid with frequency f_c

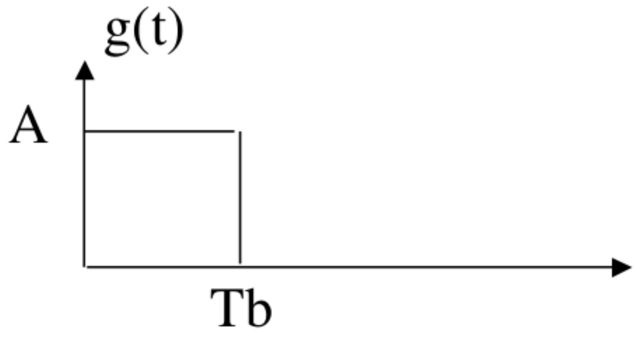


$$y(t) = x(t)\cos(2\pi f_c t)$$

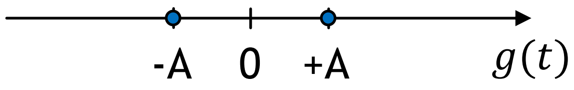
$$\mathcal{F}(x(t)\cos(2\pi f_c t)) = \frac{1}{2}[X(f - f_c) + X(f + f_c)]$$

Baseband Signals

- The simplest digital modulation is ***Pulse Amplitude Modulation*** **(PAM)**
  - E.g. binary PAM or 2-PAM:
    - a pulse $g(t)$ of amplitude A is used to represent a "1"
    - a pulse $g(t)$ of amplitude -A to represent a "0"
- The simplest pulse is a rectangular pulse, but in practice other type of pulses are used



- We transmit the signal $s(t)$ corresponding to ***symbol*** s
- If we let $g(t)$ be the basic pulse shape, than with 2-PAM:
  - $s(t) = g(t)$ => "1"
  - $s(t) = -g(t)$ => "0"



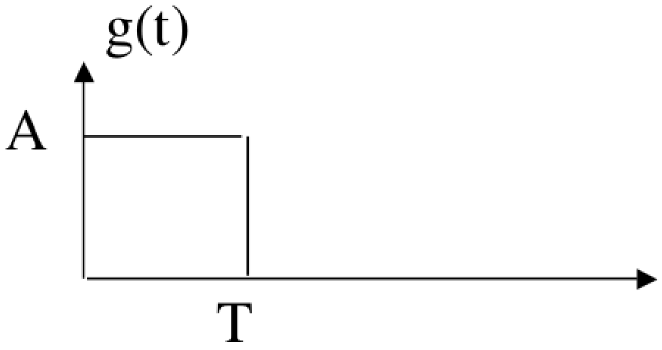
Signals representation over the basis g(t)

Can we do better? Ideas?

M-ary PAM

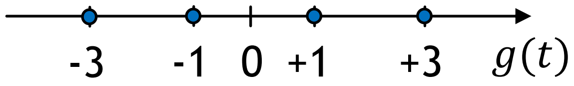
- Use M signal levels, $A_1 \ \ldots A_M$

- E.g., $M = 4 \Rightarrow A_1 = -3, \ A_2 = -1, \ \ A_3 = 1, \ \ A_4 = 3$
  - $s_i\,(t) = A_i\; g(t)$



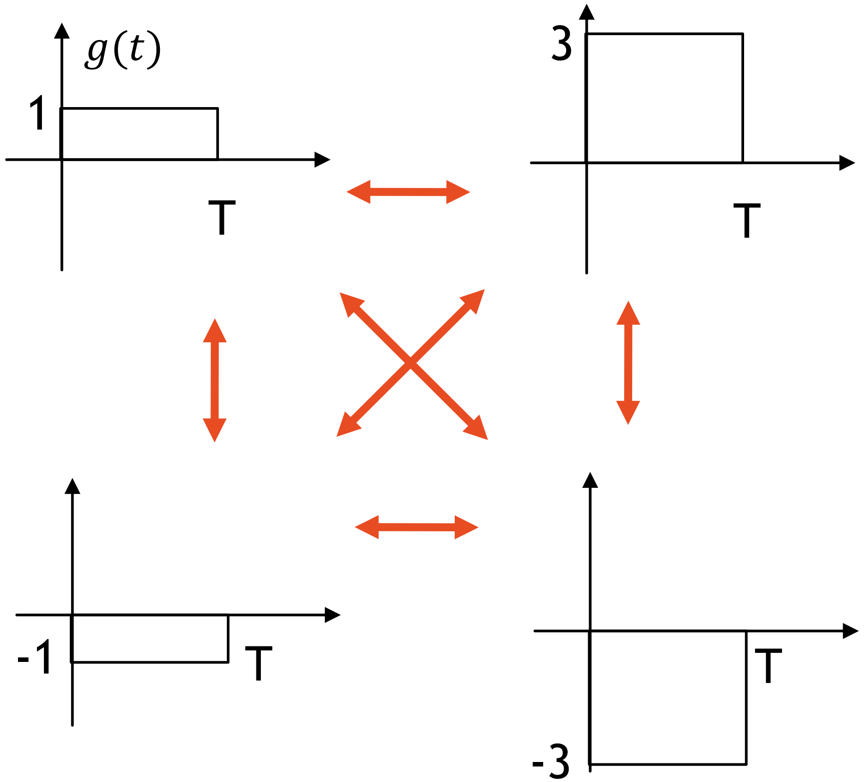
- Mapping of bits to signals:
  - Each signal level can be used to represent $\log_2 M$ bits
  - E.g. $s_1(t) = 00;\ s_2(t) = 01;\ s_3(t) = 10;\ s_4(t) = 11$

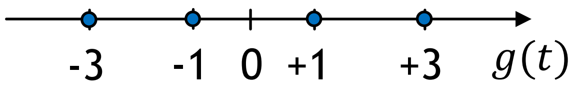
- Does the choice of bits matter?



A look at signal detection

- Does the choice of bits matter?
  - What mistake is more likely?

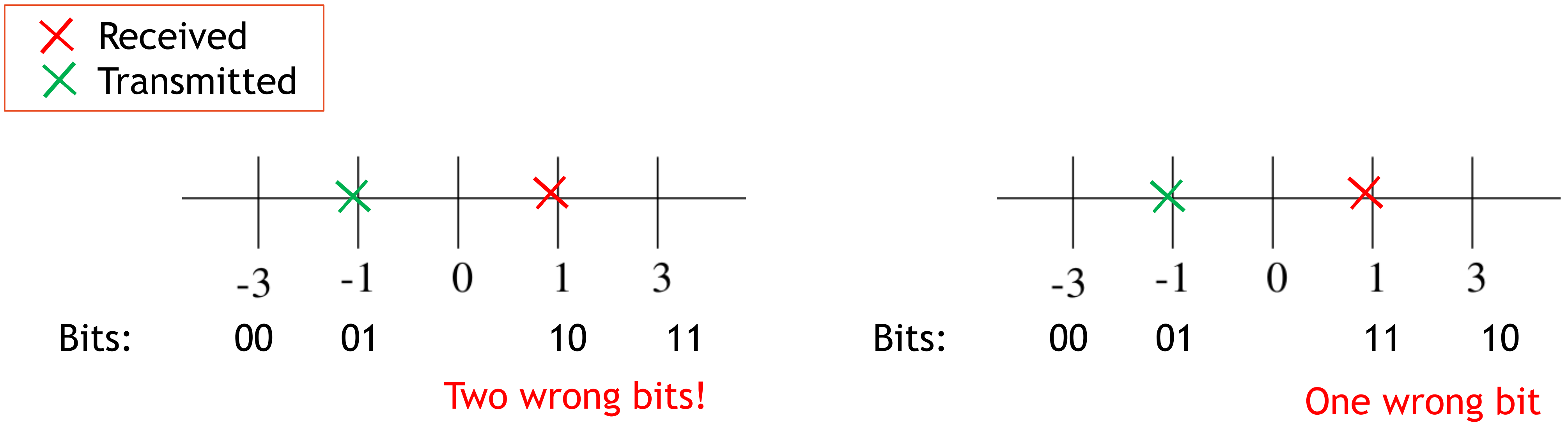




Signals representation over the basis g(t)

Gray Coding

- ***Gray coding***: strategy for **mapping bits to symbols** so that the number of bit errors is minimized
  - Most likely symbol errors are between adjacent levels
  - The number of bits that differ between adjacent levels is minimized
- Gray coding achieves 1 bit difference between adjacent levels
  - Most Likely error on symbols = error on one bit only

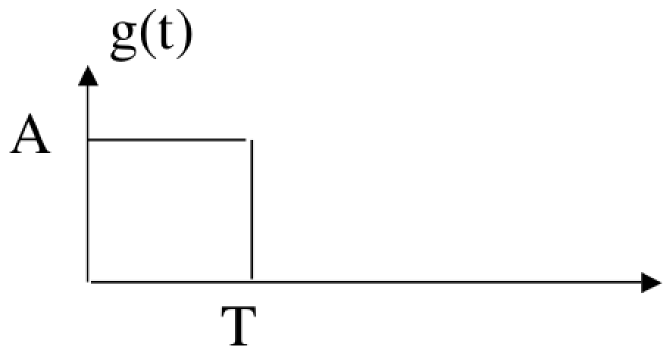


Energy per bit

- A measure of the ***energy efficiency*** of the modulation can be obtained from the **average** ***energy per bit***

$$E_b = E_s / \log_2 M$$

  - is the average energy per symbol divided by the number of bits carried by each symbol

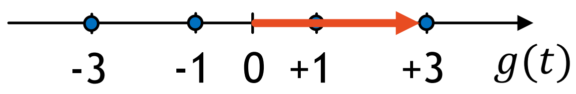


- Energy per symbol:

$$E_m = \int_0^T (S_m(t))^2 dt = (A_m)^2 \int_0^T (g_t)^2 dt = (A_m)^2 E_g$$

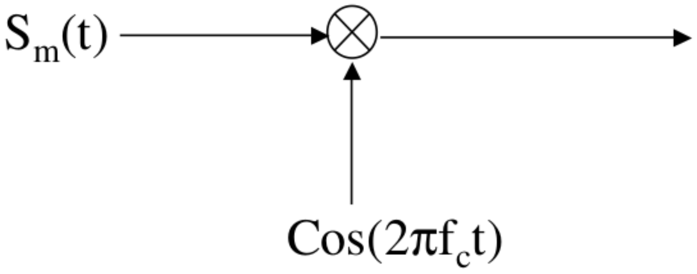
- Average energy per symbol E_m/M
- E.g., $M = 4 \Rightarrow A_1 = -3,\ A_2 = -1,\ A_3 = 1,\ A_4 = 3$
  - $s_i(t) = A_i\, g(t)$
  - $E_s = \frac{3^2T + 1^2T + 1^2T + 3^2T}{4} = 5T$

The distance from the origin is proportional to the energy of the symbol

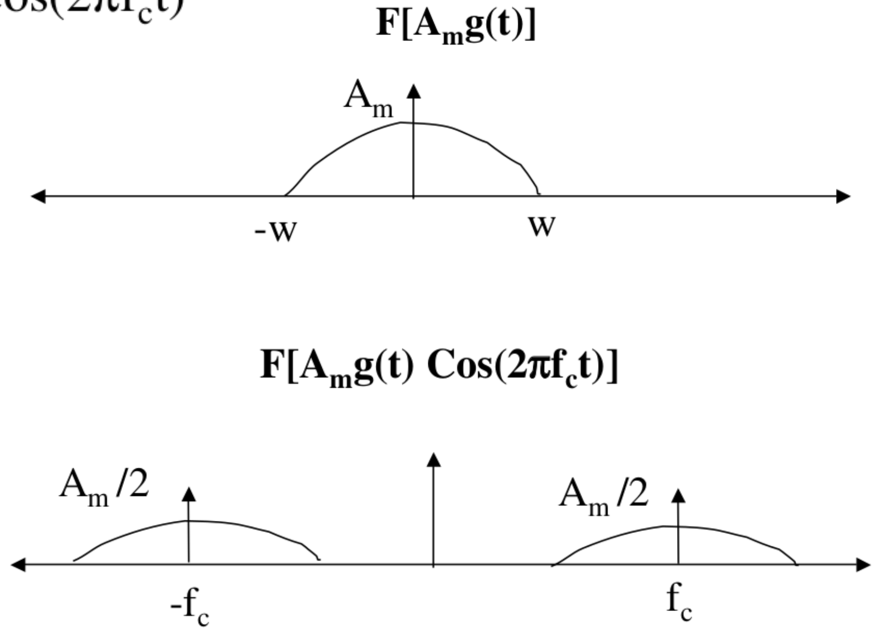


Bandpass signals

- To transmit a baseband signal $s(t)$ through a pass-band channel at some center frequency f_c, we multiply $s(t)$ by a sinusoid with that frequency
- The Fourier transform of $s_m(t) = A_m g(t)$ depends on $g(t)$

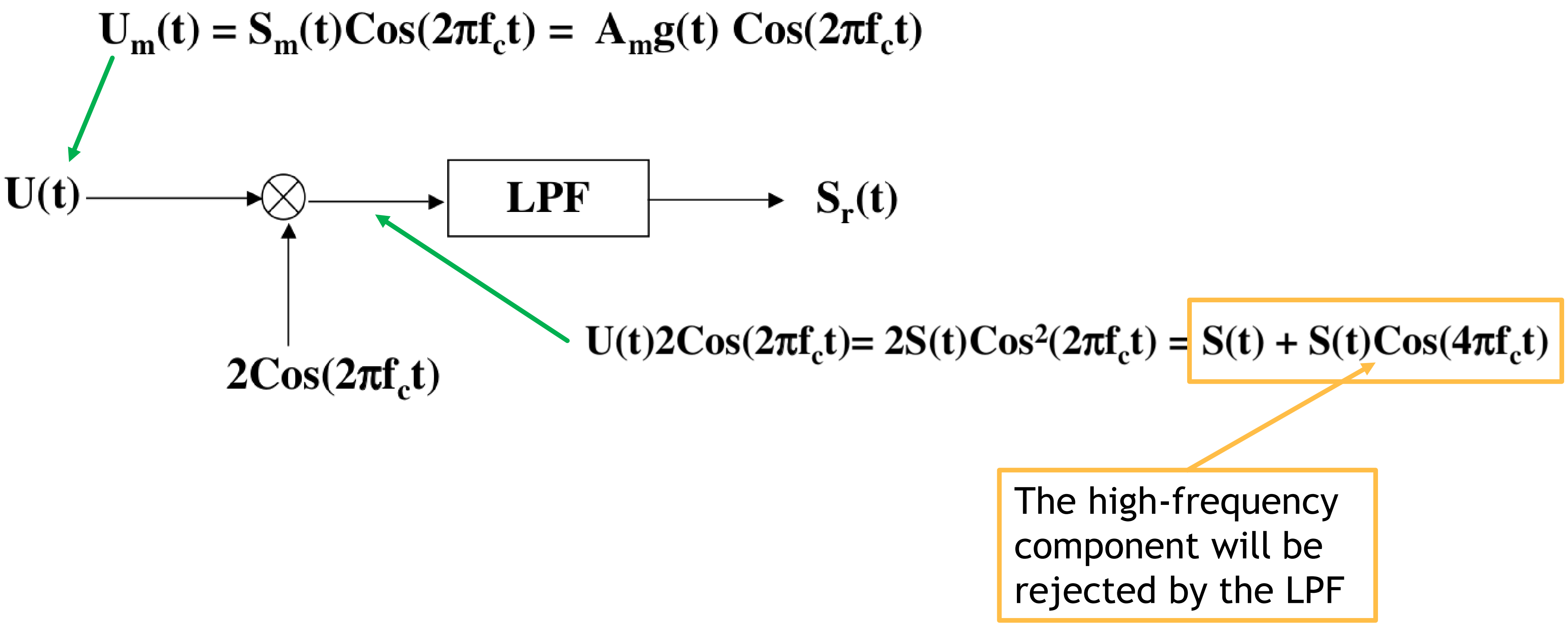


$$U_m(t) = S_m(t)\mathrm{Cos}(2\pi f_c t)$$
$$= A_m g(t)\ \mathrm{Cos}(2\pi f_c t)$$



Demodulation

- To recover the original signal, multiply the received signal $U_m(t)$ by a cosine at the same frequency



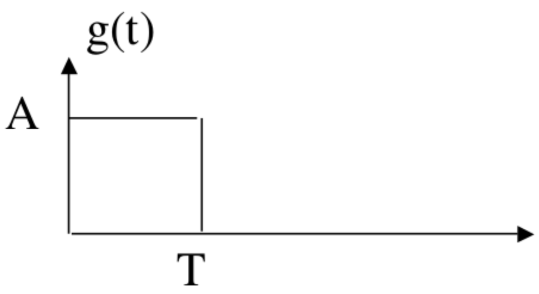
Bandwidth Occupancy

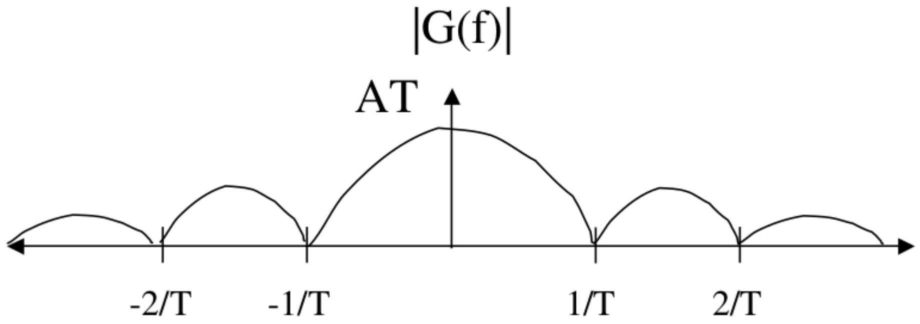
- Ideal rectangular pulse has unlimited bandwidth

$$G(f) = F[g(t)]$$

$$G(f) = \int_{-\infty}^{\infty} g(t)e^{-j2\pi ft}dt = \int_{0}^{T} Ae^{-j2\pi ft}dt$$

$$G(f) = (AT)Sinc(\pi fT)e^{-j\pi fT}$$

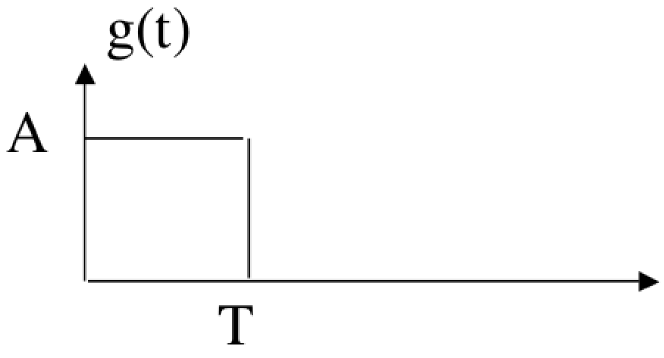


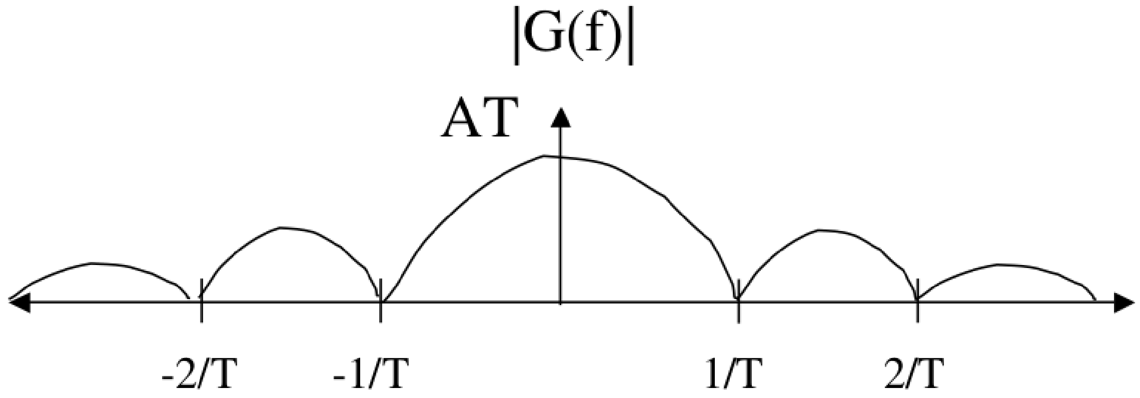


- Other types of pulses might be better
  - They shape the signal bandwidth!
  - We would like to put most of the energy in a small bandwidth

Bandwidth Efficiency

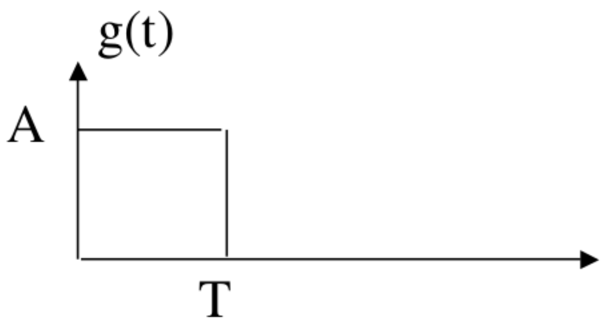
- Generally, we want to choose the pulse shape $g(t)$ in order to put more energy in a small bandwidth
- For a pulse of duration T,
  - the ***symbol rate*** is $R_s = 1/T$
- There are $\log_2(M)$ bits per symbol, therefore
  - the ***bitrate*** $R_b = \log_2(M)\, R_s$
- Roughly, the two-sided bandwidth is $BW \ = \ 2R_s = \frac{2}{T}$
  - The ***bandwidth efficiency*** is $\eta = \frac{R_b}{BW} = \frac{\log_2(M)}{T} * \left(\frac{T}{2}\right) = \frac{\log_2(M)}{2} \ bps/Hz$



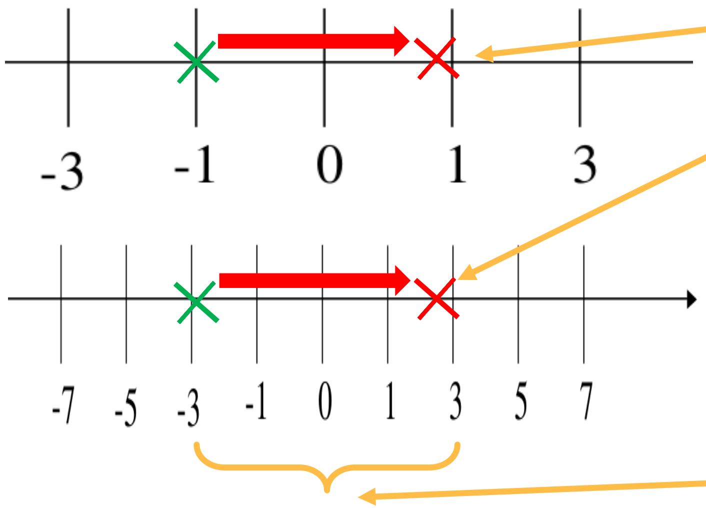


Bandwidth Efficiency (cont'd)

- The ***bandwidth efficiency*** is $\eta = \frac{R_b}{BW} = \frac{\log_2(M)}{2}\ bps/Hz$
- Increased BW efficiency with increasing M
- Example
  - M = 2 ⇒ BW efficiency = 1/2
  - M = 4 ⇒ BW efficiency = 1
  - M = 8 ⇒ BW efficiency = 3/2
- However, as M increases we are more prone to errors as symbols are closer together (for a given energy level)



Transmitted
Received

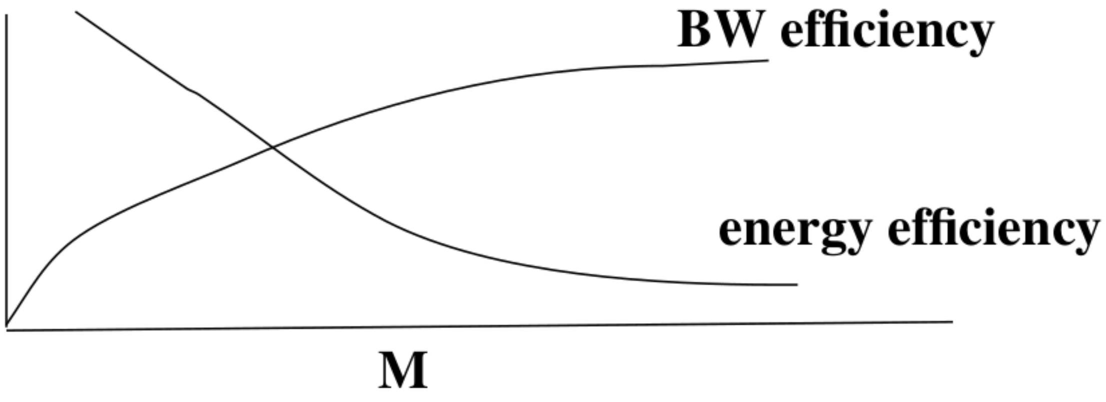


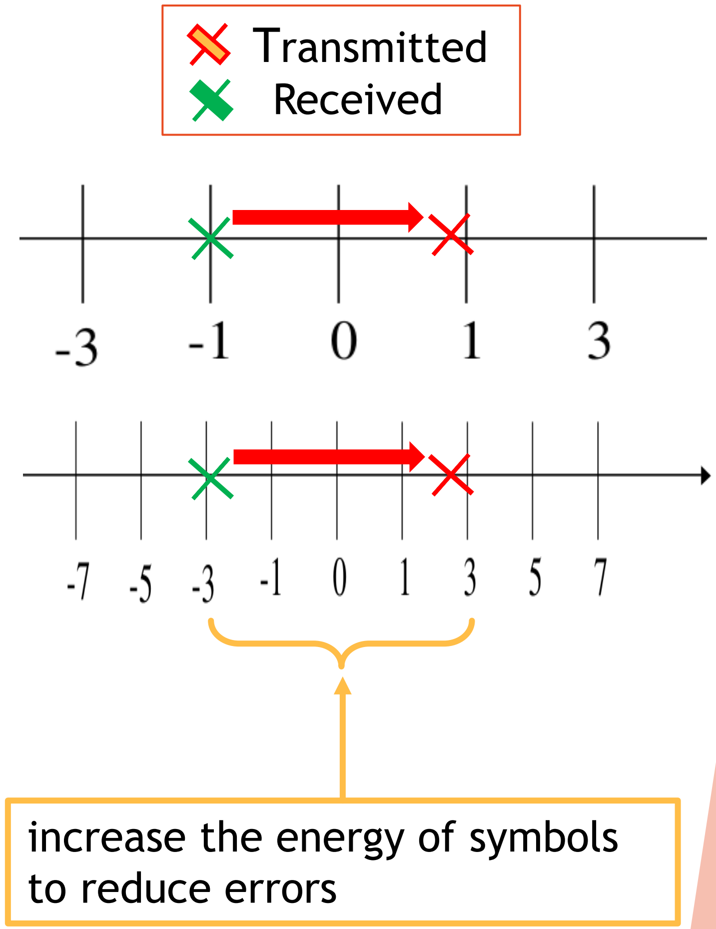
- The noise "moves" the received symbol

- The same amount of noise would result in a bigger error

Bandwidth Efficiency Vs Energy Efficiency

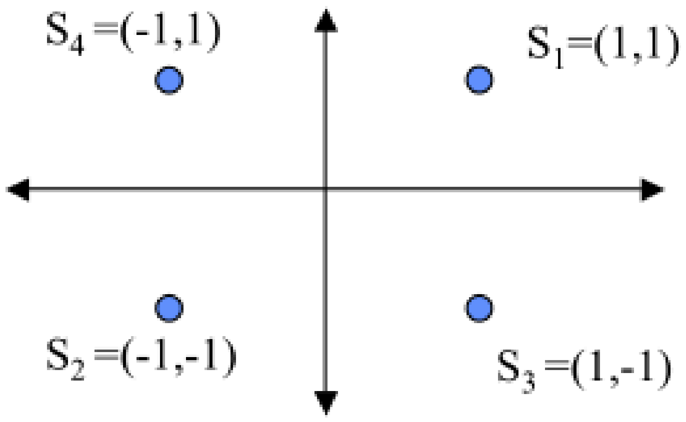
- BW efficiency increases with increasing M
- For a fixed energy level, as M increases, we are more prone to errors (closer symbols)
- Need to increase symbol energy level to overcome errors
- **Tradeoff** between **BW efficiency and energy efficiency**





Two-dimensional Modulations

- Signals can be represented over two orthonormal basis
  - A Set of signal points s_i is called a *constellation*
- 2-D constellations are commonly used
- Large constellations can be used to transmit many bits per symbol
  - More bandwidth efficient (higher bitrate)
  - More error prone
- The “shape” of the constellation can be used to **minimize error probability** by keeping symbols as far apart as possible
- Common constellations:
  - *QAM: Quadrature Amplitude Modulation*
    - a PAM in two dimensions
  - *PSK: Phase Shift Keying*
    - Special constellation where all symbols have equal power



Symmetric M-QAM

- M is the total number of signal points (symbols)
- $\sqrt{M}$ signal levels on each axis

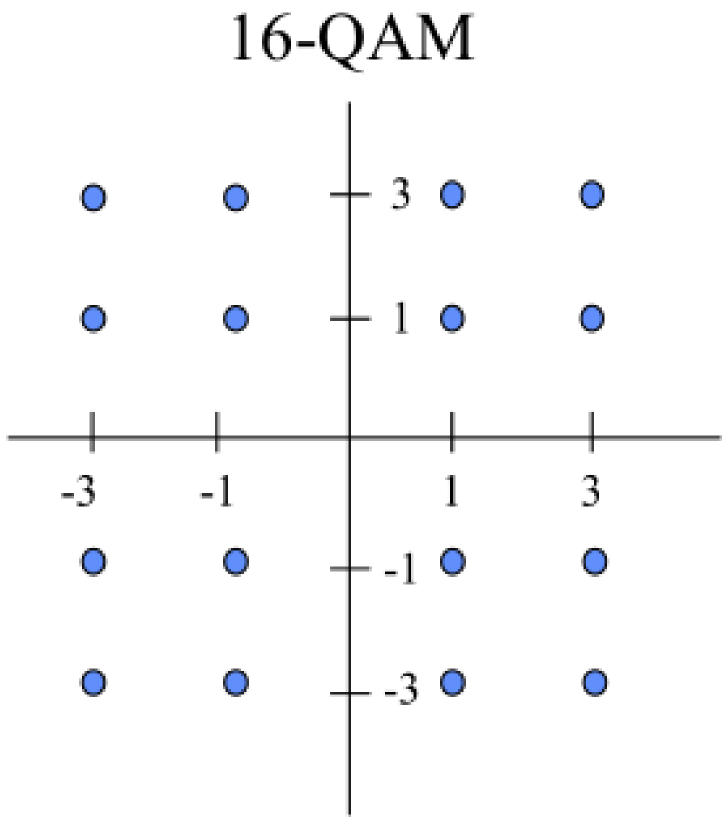
$$S_m = (A_m^x, A_m^y),\ A_m^x, A_m^y \in \left\{+/-1, +/-3, \ldots, +/-(\sqrt{M}-1)\right\}$$

- Constellation is symmetric => $M=K^2$, for some K
- Signal levels on each axis are the same as for PAM

$$E.g., 4-QAM \Rightarrow A_m^x, A_m^y \in \{+/-1\}$$

$$16-QAM \Rightarrow A_m^x, A_m^y \in \{+/-1, +/-3\}$$

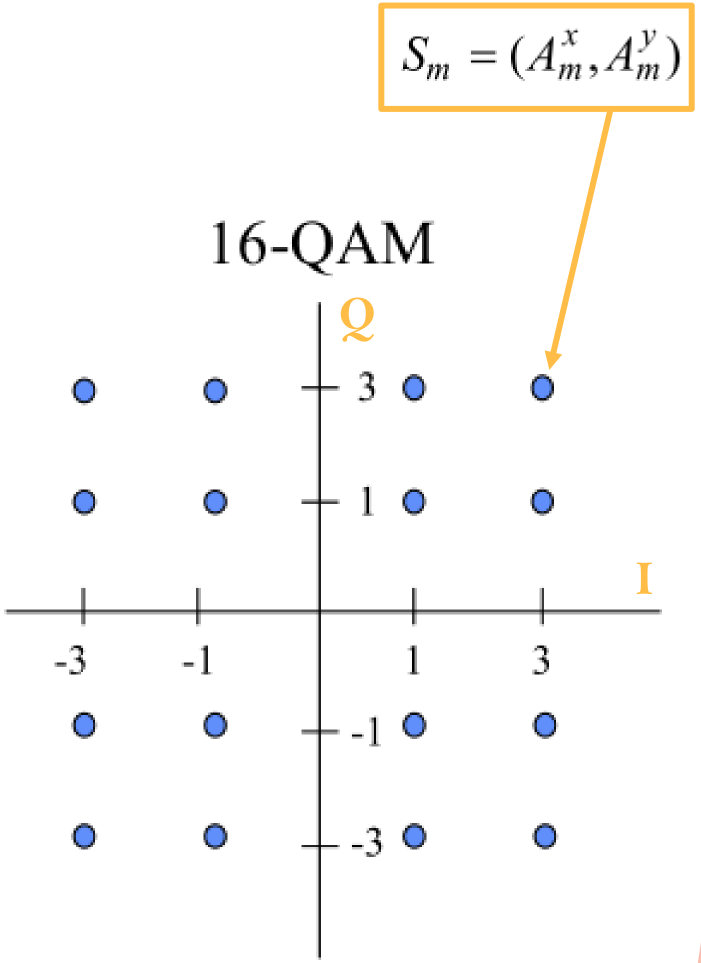
- Using the same pulse $g(t)$, the **bandwidth efficiency** is the same of M-PAM
- But QAM has a larger **energy efficiency** than PAM



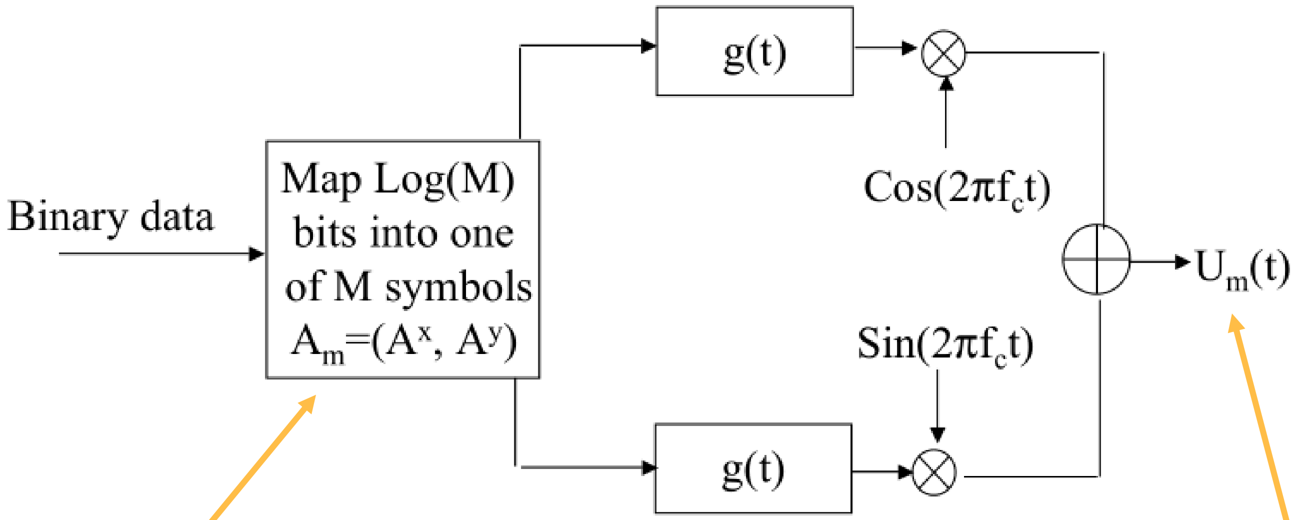
Bandpass QAM

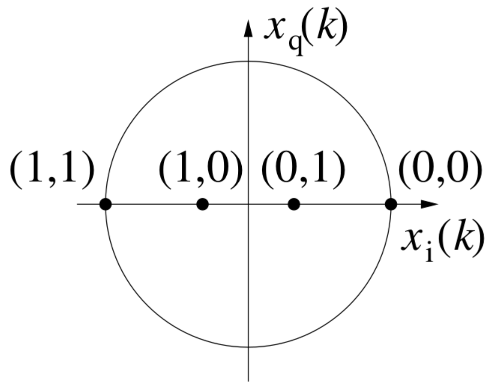
- Modulate the two dimensional signal by multiplication by orthogonal carriers (sinusoids): Sine and Cosine
  - This is accomplished by multiplying the A^x component by Cosine and the A^y component by sine
- The two carriers are a complete basis for the transmitted signals
  - Referred to as the ***In-phase*** **(I)** and ***quadrature phase*** **(Q)** axes
  - The constellation is the same, the basis accounts for the frequency modulation
- The transmitted signal, corresponding to the m-th symbol is:

$$U_m(t) = A_m^x g(t) Cos(2\pi f_c t) + A_m^y g(t) Sin(2\pi f_c t), \; m = 1..M$$

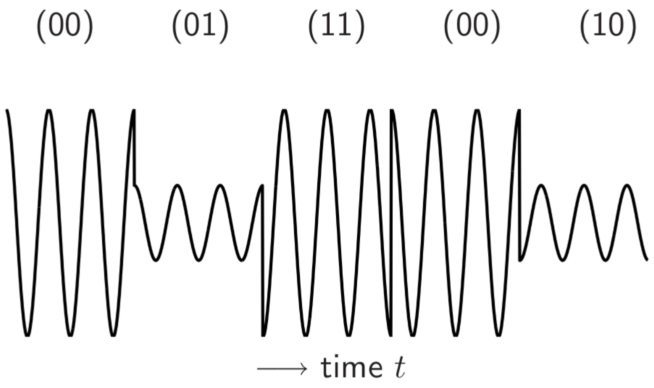


M-QAM Modulator





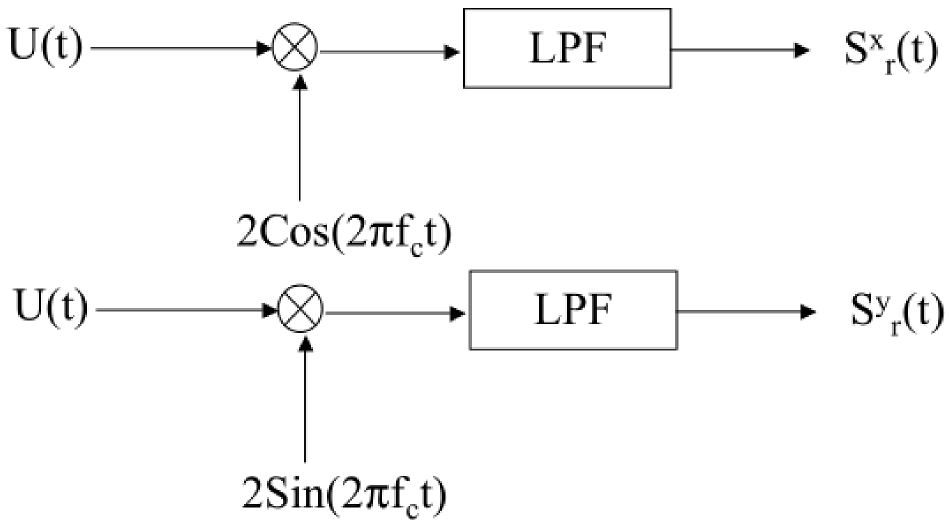
$00 \Rightarrow S_1$
$01 \Rightarrow S_2$
$11 \Rightarrow S_3$
…



M-QAM Demodulation: Recovering the baseband signals

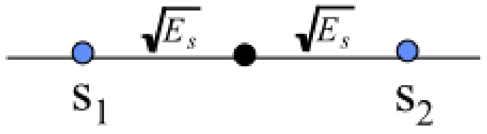
- Over a symbol duration, $\sin(2\pi f_c t)$ and $\cos(2\pi f_c t)$ are orthogonal
- As long as the symbol duration is an integer number of cycles of the carrier wave
  - i.e. $f_c = n/T$ for some n
- When multiplied by a sine, the cosine component of $U(t)$ disappears after filtering
- Similarly, the sine component disappears when multiplied by cosine

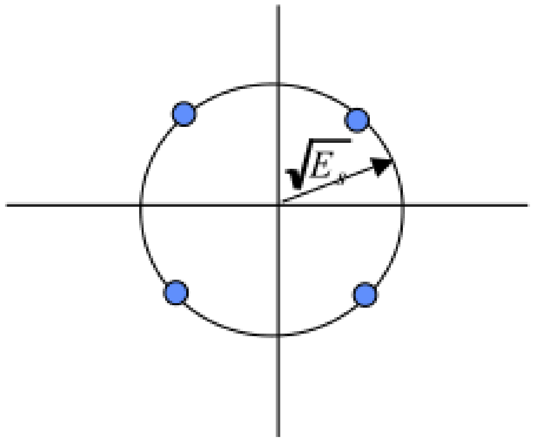
$$U_m(t) = A_m^x g(t) Cos(2\pi f_c t) + A_m^y g(t) Sin(2\pi f_c t),\ m = 1..M$$



Phase Shift Keying (PSK)

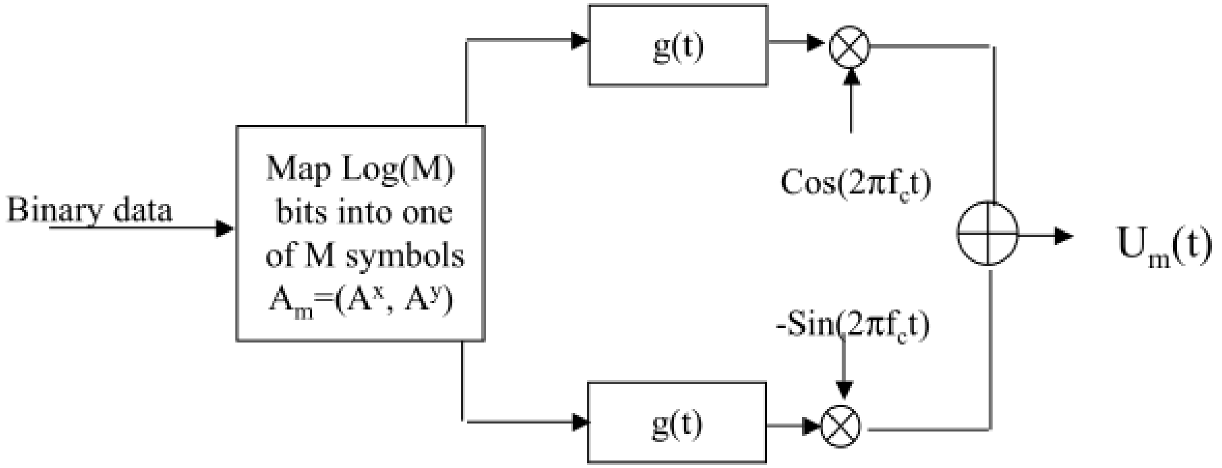
- *Phase Shift Keying*
- Two Dimensional signals where all symbols have equal energy levels
  - I.e., they lie on a circle or radius $\sqrt{E_s}$
- Symbols are equally spaced to minimize likelihood of errors
  - E.g., Binary PSK
  - 4-PSK (same as 4-QAM)
- M-PSK
  - Constellation of M phase-shifted symbols
  - All have equal energy levels
  - $\log_2 M$ bits per symbol

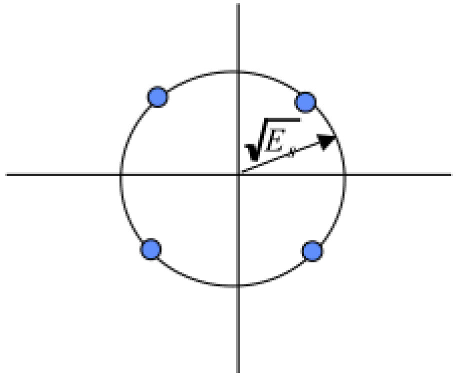


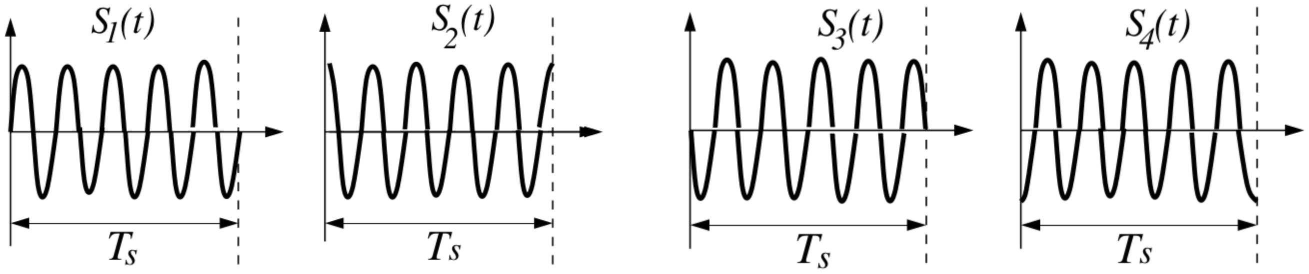


M-PSK Modulator

- Essentially the same modulator and demodulator of M-QAM







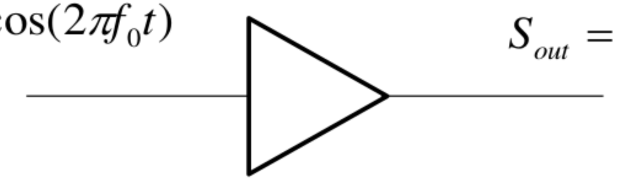
bit (0,0): $\phi_1 = 0$ bit (0,1): $\phi_2 = \frac{\pi}{2}$ bit (1,1): $\phi_3 = \pi$ bit (1,0): $\phi_4 = \frac{3\pi}{2}$

Power Amplifiers

- Power is proportional to amplitude
- To increase amplitude (hence power) the last block of the transmitter before entering the antenna is always the amplifier

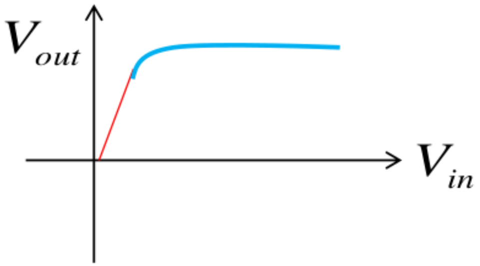
Increase of signal amplitude → Increase of Power

$$S_{in} = V_{in} \cos(2\pi f_0 t)$$



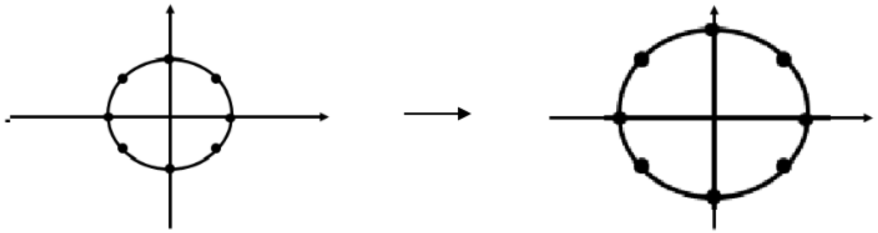
$$S_{out} = V_{out} \cos(2\pi f_0 t)$$

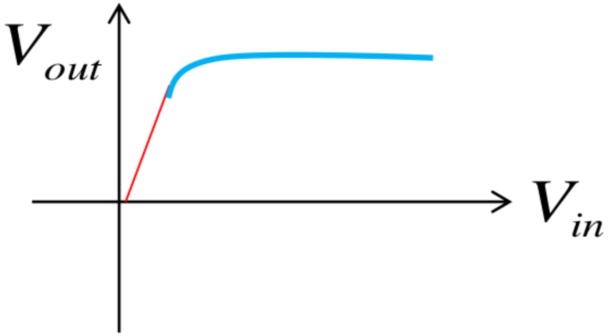
- operating point in the saturation region → maximum power transfer.
- operating point in the linear region → no maximum power transfer



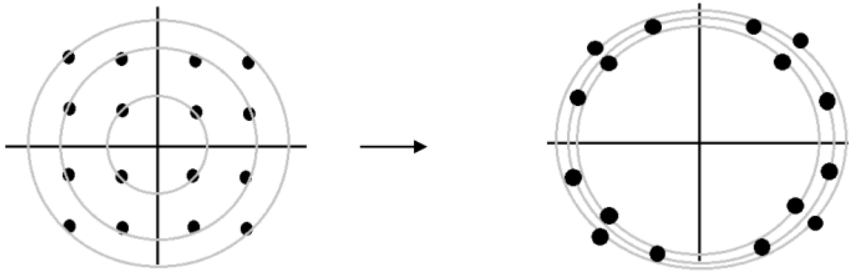
Power Amplifiers: PSK vs QAM

- PSK: even when working at maximum power, the constellation is amplified uniformly.





- QAM: if we work in the saturation zone the signals are deformed and get due to power amplifier saturation (the constellation is not ideal and its ber performance are worse)



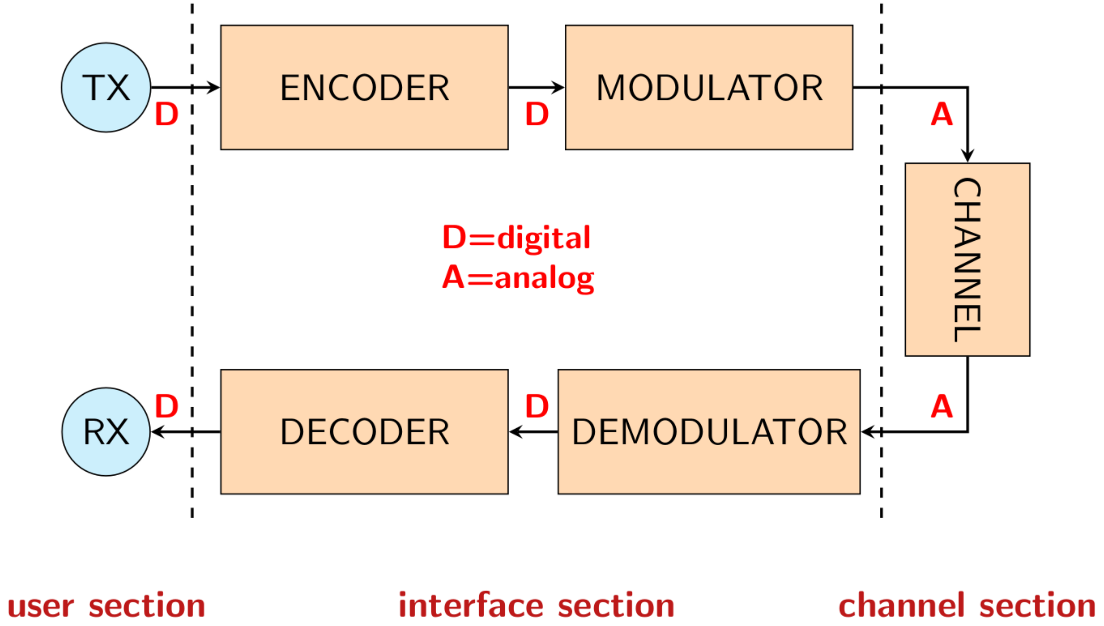
- If we work in the linear zone all the circle are multiplied by the same factor.
- The constellation is not distorted.
- But the power is not maximum.
- There is a trade-off between transmitted power and signal quality (input back-off)

Contents

Challenges of the wireless medium

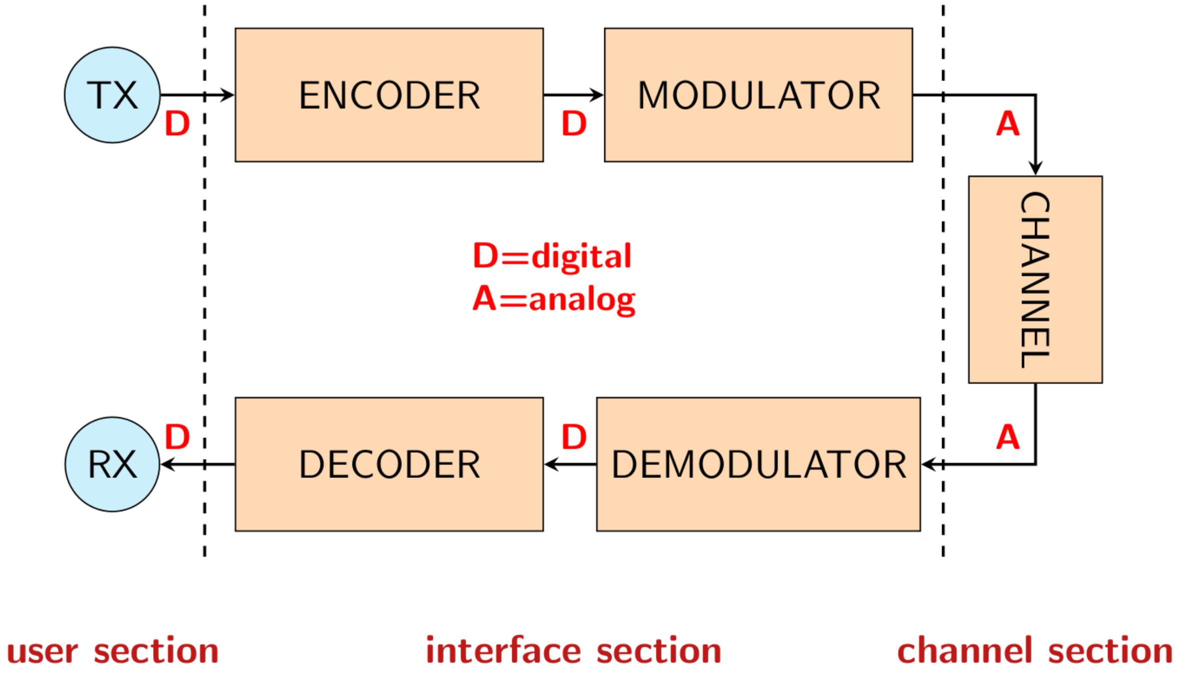
- We have now acquired the main tools to deal with signals
- Our goal is to use them to communicate information (i.e. bits)
  - I.e. to transmit something that will be received correctly
- We talk binary, but we have to transmit over analog media

- Possible Challenges:
  - Share a medium (multiplexing)
  - Fight **noise** and channel **impairements**



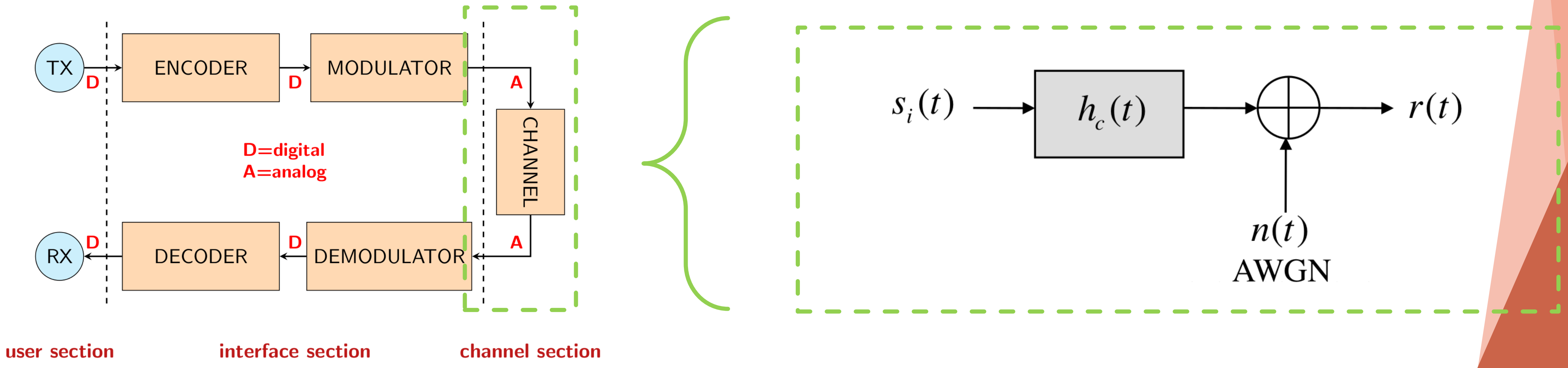
Digital Communication System: Channel

- *Channel*
  - The channel transfers an analog signal from the transmitter to the receiver.
  - Its operation is affected by different types of disturbances such as:
    - frequency-domain distortion
    - wireless fading
    - additive noise
    - impulsive noise
    - interference from other frequency channels (interchannel interference)
    - interference from the same frequency channel (cochannel interference)
    - Intentional interference



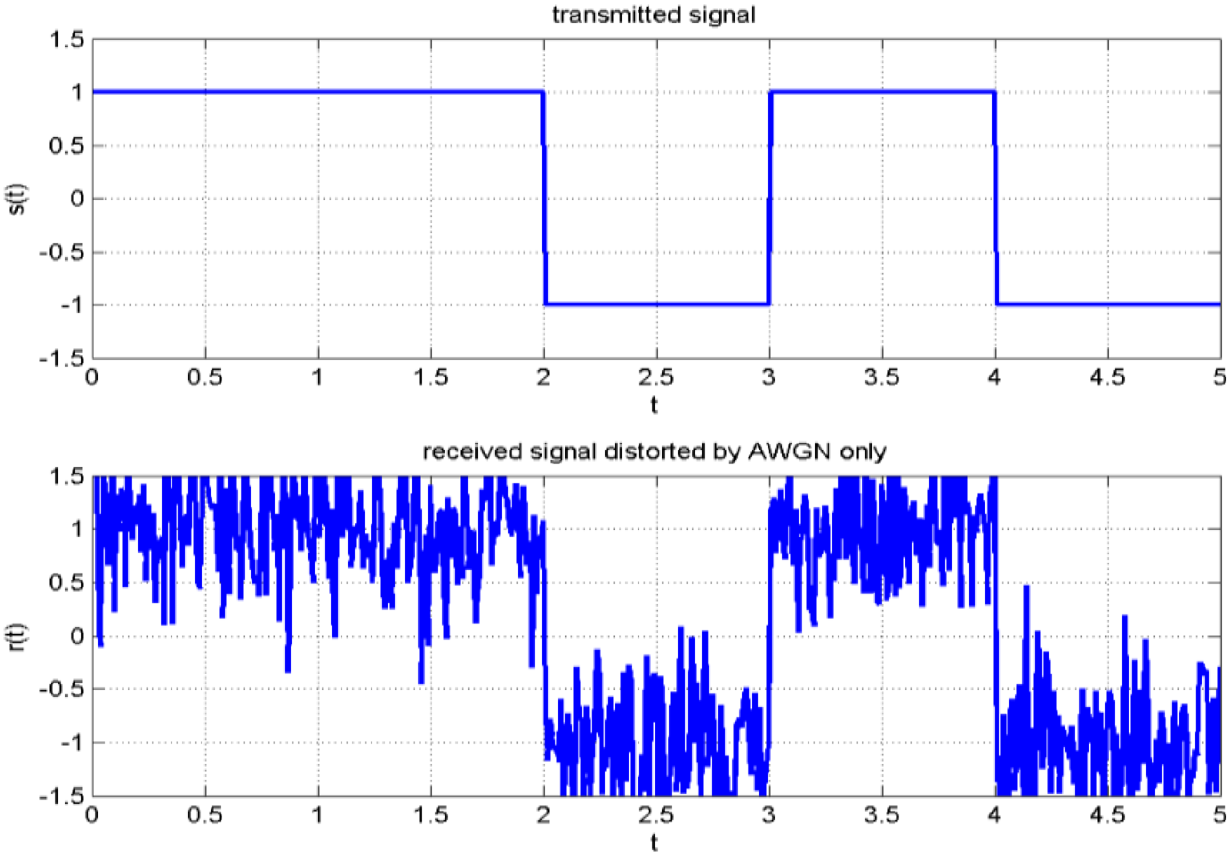
The Communication Channel

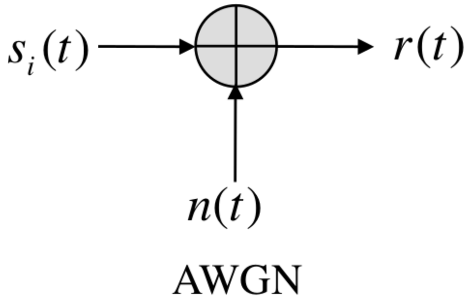
- Major sources of error:
  - *Thermal Noise (AWGN)*
    - disturbs the signal in an additive fashion (Additive)
    - has flat spectral density for all frequencies of interest (White)
    - is modeled by Gaussian random process (Gaussian Noise)
  - *Inter-Symbol Interference (ISI)*
    - Due to the filtering effect of transmitter, channel and receiver, symbols are “smeared”



Impact of the channel

- Simplifying our model, the received signal experience additive noise
- Example:

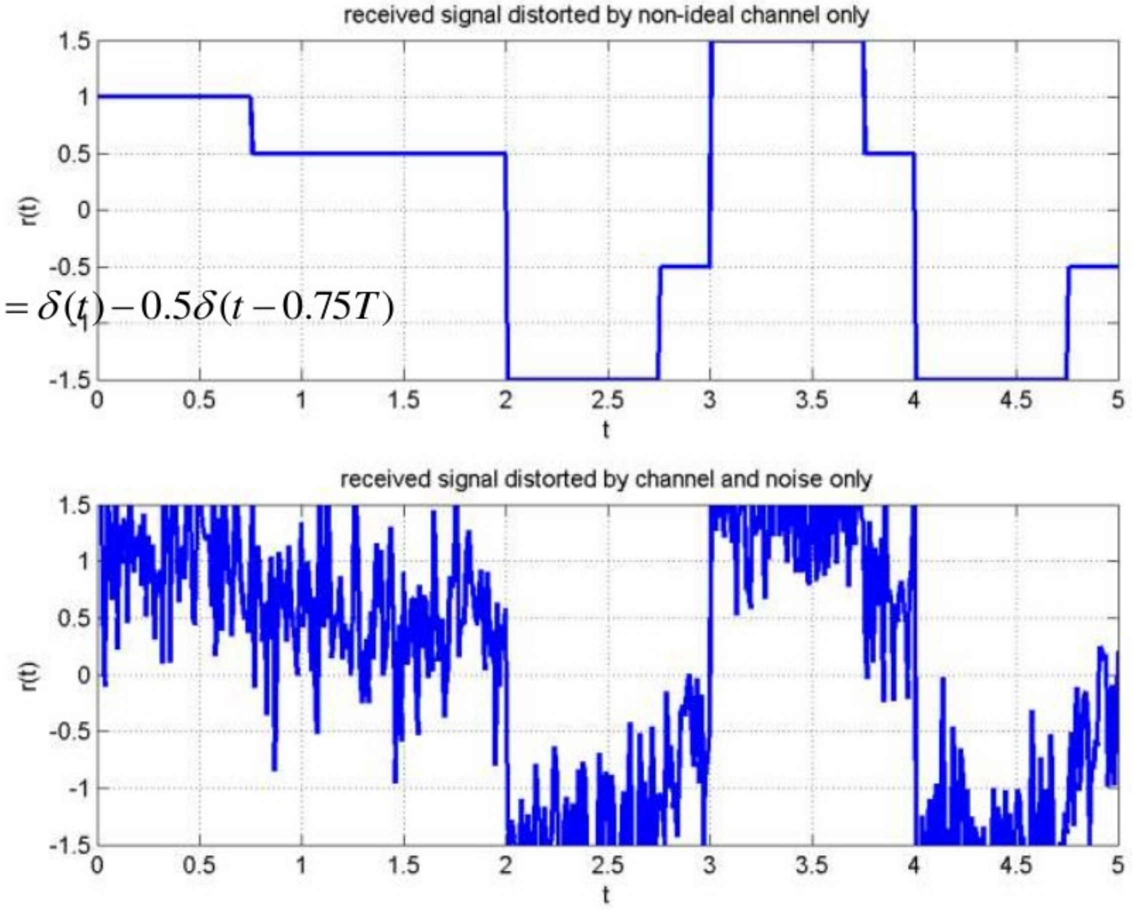




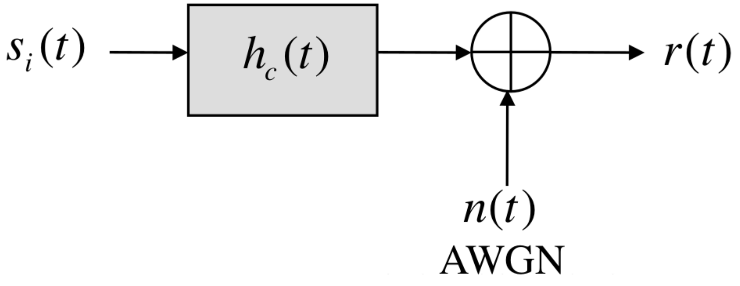
$$\boxed{r(t) = s_i(t) + n(t)}$$

Impact of the channel

- According to our model, the received signal is both filtered and noisy
- Example:



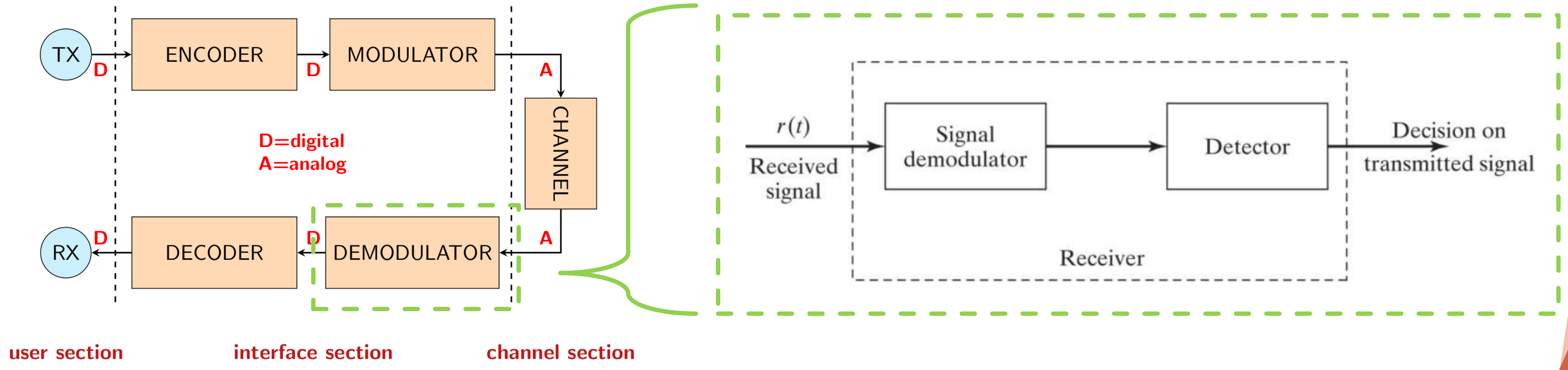
$$h_c(t) = \delta(t) - 0.5\delta(t - 0.75T)$$



$$\boxed{r(t) = s_i(t) * h_c(t) + n(t)}$$

Receiver Tasks

- <u>Demodulation and sampling</u>
  - Waveform recovery and preparing the received signal for detection
    1. Improving the signal power to the noise power (SNR) using ***matched filter***
    2. Reducing ISI using ***equalizer***
    3. **Sampling** the recovered waveform
- <u>Detection</u>
  - **Estimate** the transmitted symbol based on the received **sample**



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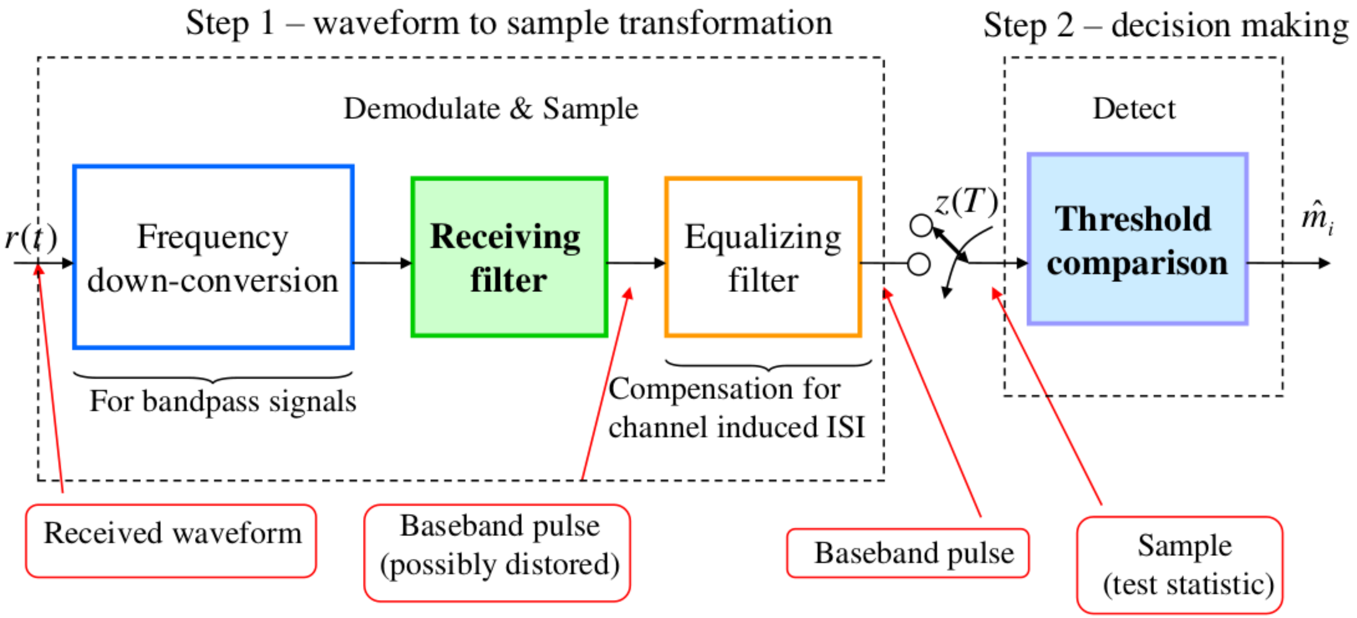


Designing the Receiver

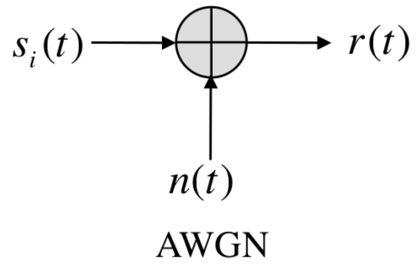
- Find optimum solution for receiver design with the following goals:
  - Maximize SNR
  - Minimize ISI

- Steps in design:
  - Model the received signal
  - Find separate solutions for each of the goals

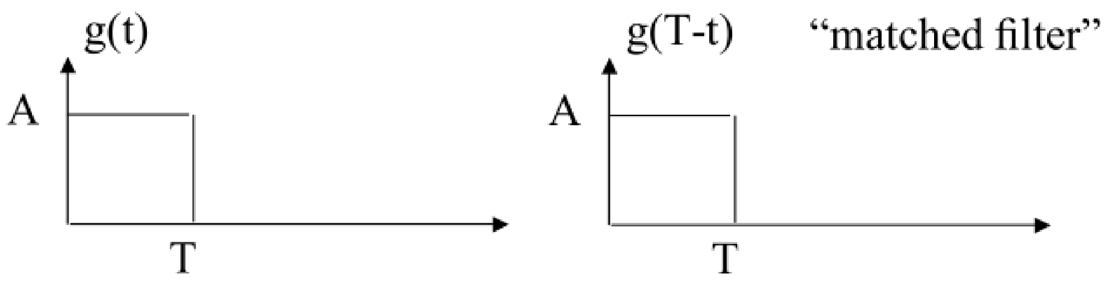
Maximize SNR

- How to Maximize SNR?
- Simplified noise model

$$\boxed{r(t) = s_i(t) + n(t)}$$

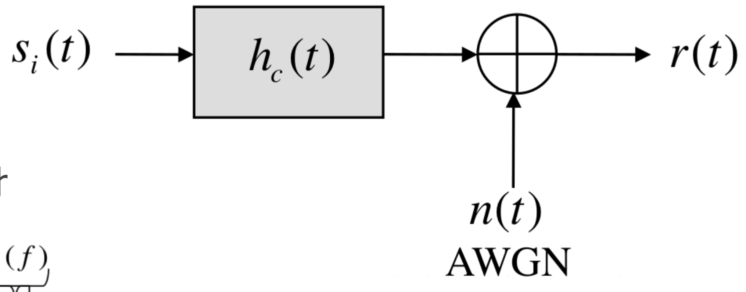


- SNR is maximized by the matched filter



Minimize ISI

$$\boxed{r(t) = s_i(t) * h_c(t) + n(t)}$$



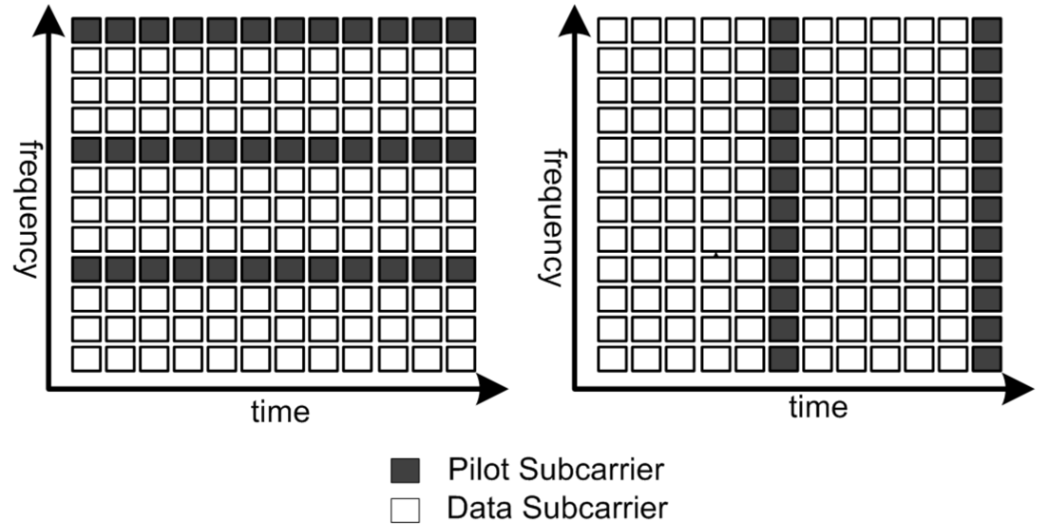
- How to minimize ISI?
- Channel impulse response must be reverted
- ISI due to filtering effect of the communications channel (e.g. wireless ch
  - Channels behave like band-limited filters

$$H_c(f) = \underbrace{|H_c(f)|}_{\substack{\text{Non-constant amplitude} \\ \Downarrow \\ \text{Amplitude distortion}}} e^{j\underbrace{\theta_c(f)}_{\substack{\text{Non-linear phase} \\ \Downarrow \\ \text{Phase distortion}}}}$$

- *Channel Estimation* is the process that takes place before equalization in the communication system
  - The channel transfer function is estimated in some way
- Types based on the density of Training symbols
  - Blind Channel Estimation
  - Semi-Blind Channel Estimation
  - Pilot Assisted Channel Estimation

Fading

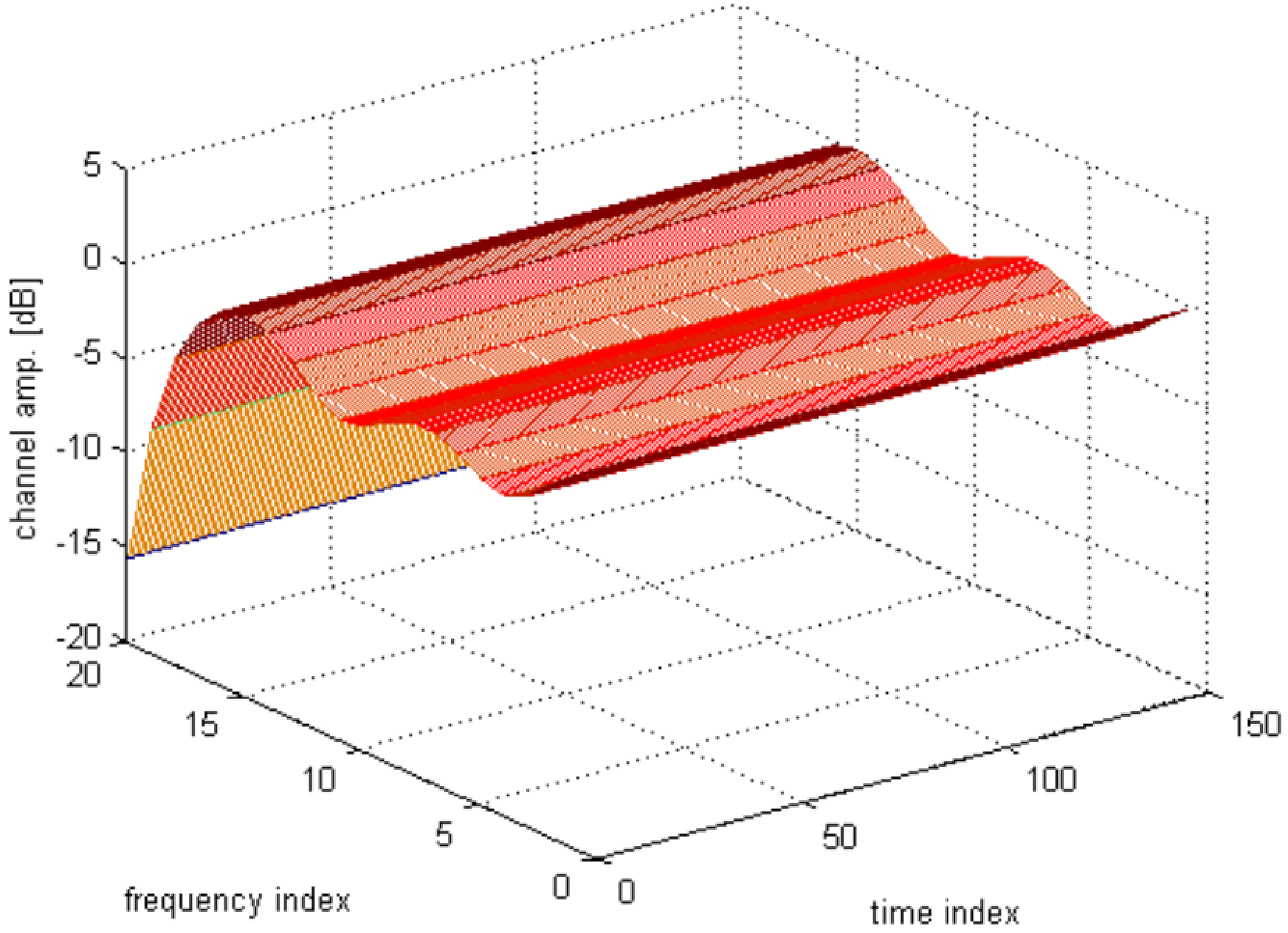
- Slow Fading Channel
  - Channel impulse response variations are slow
  - Pilot Symbols are transmitted less frequently
- Fast Fading
  - Channel Impulse response variations are fast
  - Pilot symbols are transmitted more frequently
- Examples of Pilots Arrangement for Slow and Fast Fading Channel in OFDM



(a) Comb-Type Channel Estimation (b) Block-Type Channel Estimation

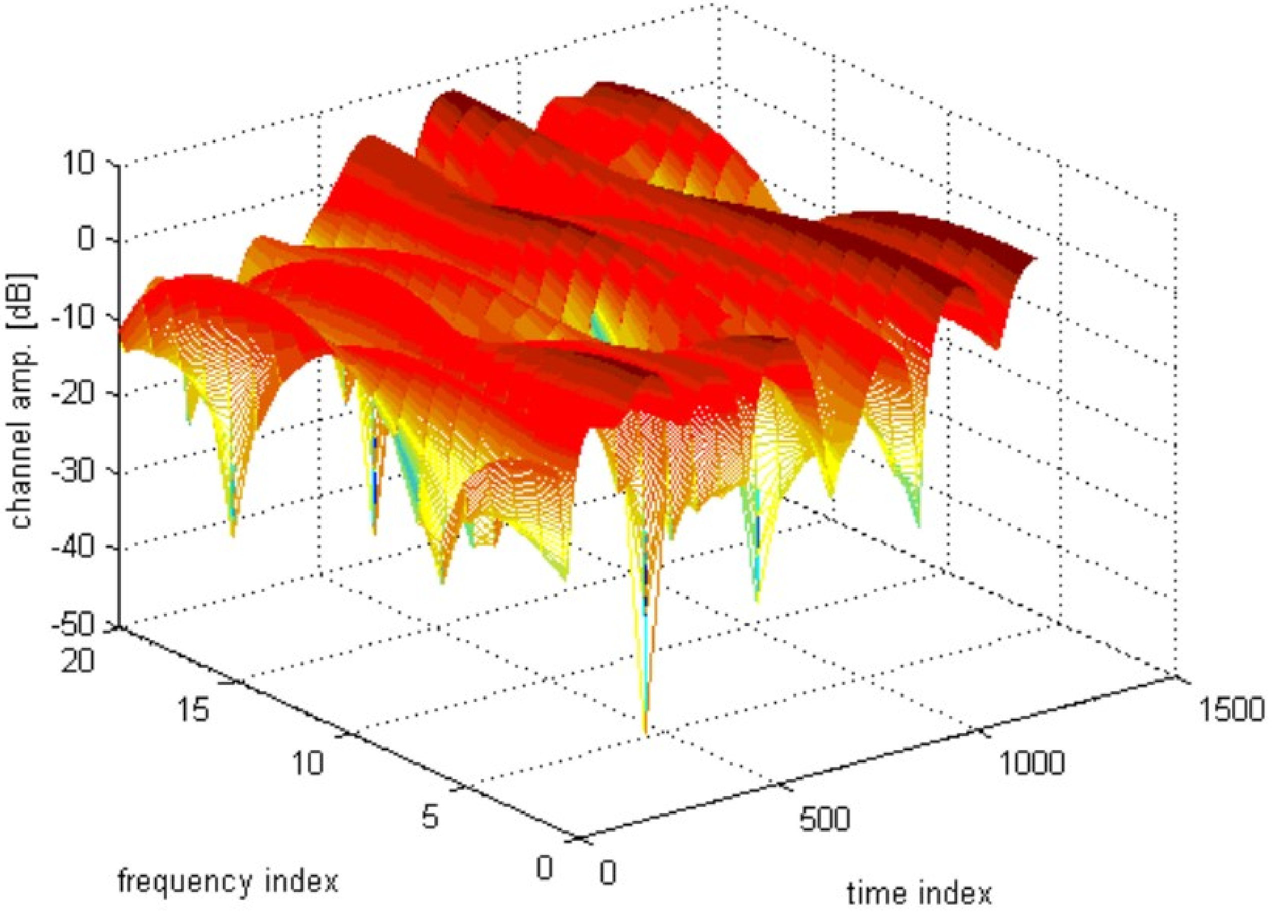
Slow Fading

- Example of a frequency selective, slowly changing (slow fading) channel for a user at 35 km/h



Fast Fading

- Example of a frequency selective, fast changing (fast fading) channel for a user at 35 km/h

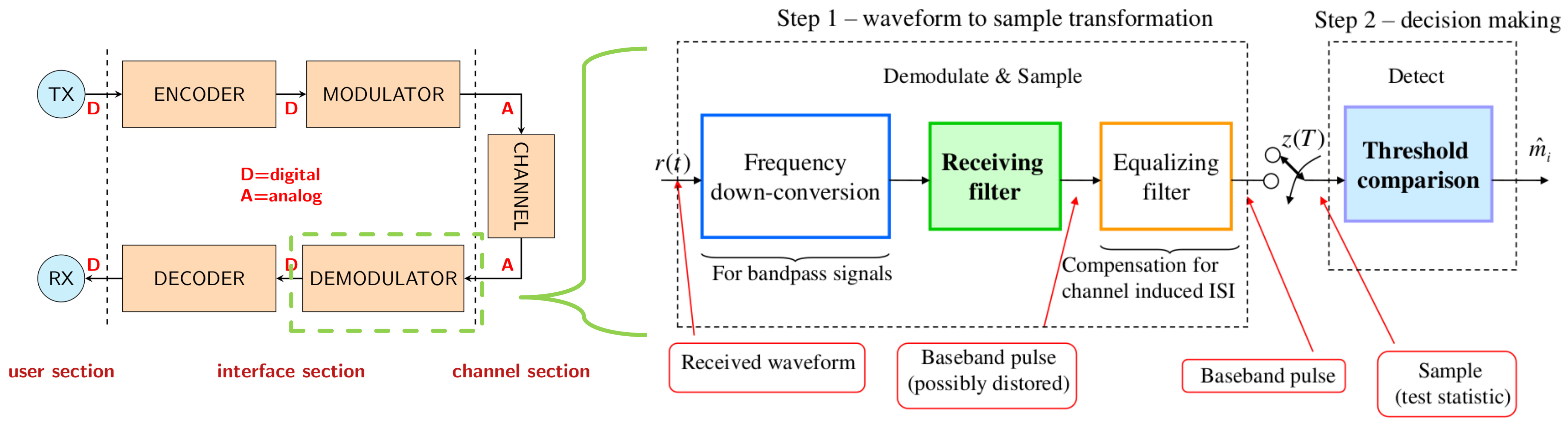


Contents

Symbols Detection

- After matched filtering we get $r = S\_m \; + n$ with $S\_m \; \in \{S\_1 \;\; ,..S\_M \;\; \}$

- How do we determine from r which of the M possible symbols was sent?
  - Without the noise we would receive what sent, but the noise can transform one symbol into another



Symbols Detection

- Hypothesis testing
  - Objective: minimize the probability of a decision error
  - Decision rule: Choose S_m such that $P(S\_m$ sent | r received) is maximized

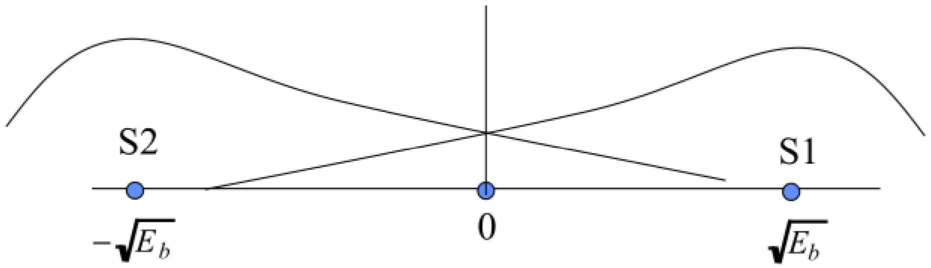
- This is known as ***Maximum a posteriori*** probability (MAP) rule
- MAP Rule: Maximize the conditional probability that S_m was sent given that r was received
  - Turns out to be equivalent (under certain conditions) to **minimum distance decoding**

$$d_{rS_m} = (r - S_m)^2$$

  - E.g. 2-PAM
    - If S_1 was sent then the received signal r = S_1+n
    - If S_2 was sent then the received signal r = S_2+n

$$f_{r|s}(r \mid s1) = \frac{1}{\sqrt{\pi N_0}} e^{-(r-\sqrt{E_b})^2 / N_0}$$

$$f_{r|s}(r \mid s2) = \frac{1}{\sqrt{\pi N_0}} e^{-(r+\sqrt{E_b})^2 / N_0}$$

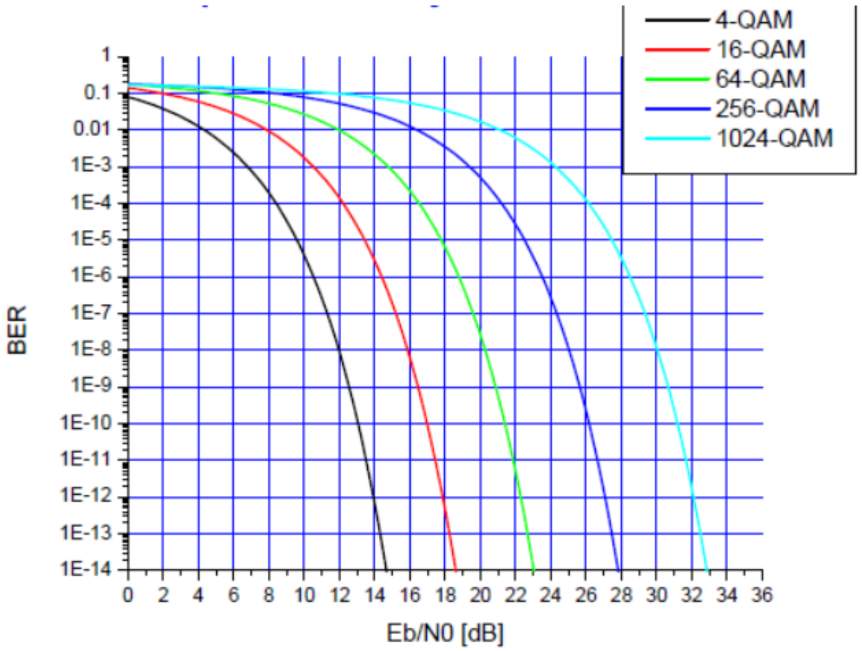


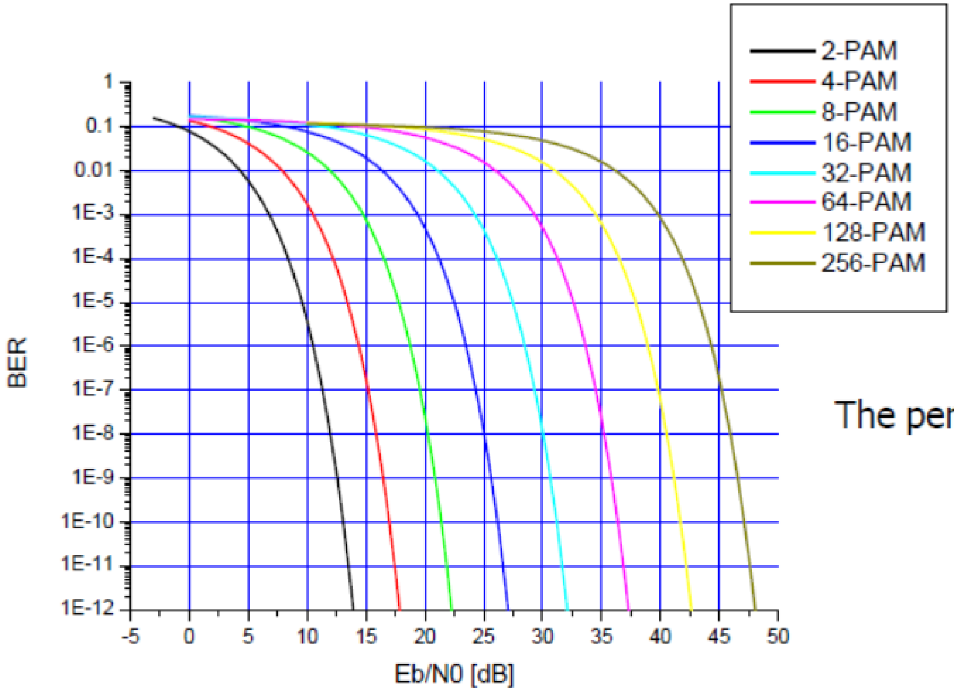
Probability of Error

- In general, the probability of error between two symbols separated by a distance d is given by:

$$P_e(d) = Q\left(\sqrt{\frac{d^2}{2N_0}}\right)$$

- Based on that it is possible to compute a ***bit error rate*** (**BER**) for each modulation



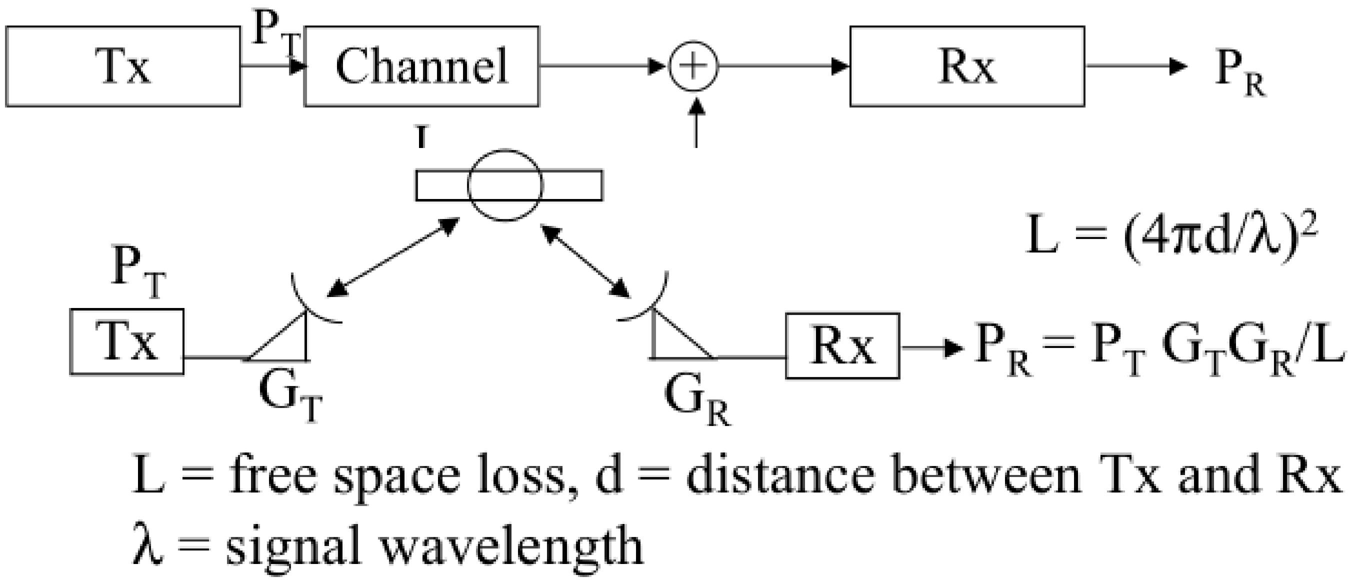


The performance decrease for increasing m

Contents

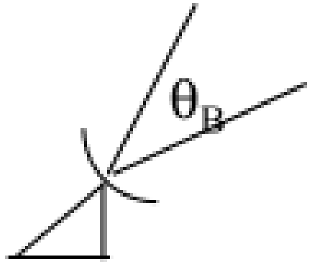
Signal attenuation

- The signal suffers an **attenuation loss** L
  - Received power: $P_R = P_T / L$
  - Received SNR: $SNR = E_b / N_0$, $E_b = P_R / R_b$
- **Antennas** are used to compensate for attenuation loss
  - Capture as much of the signal as possible



Antenna Beamwidth

- Beamwidth is a measure of the directivity of the antenna
  - A smaller beamwidth concentrates power along a smaller area
- Free space loss assumes that power is radiated in all directions
- An antenna with a smaller beamwidth concentrates the power, hence yields a gain
  - For parabolic antenna, $\theta_B \sim 70\lambda/D$
  - Gain (G_T) is proportional to $1/\theta_B^2$
  - Hence a doubling of the diameter D increases gain by a factor of 4



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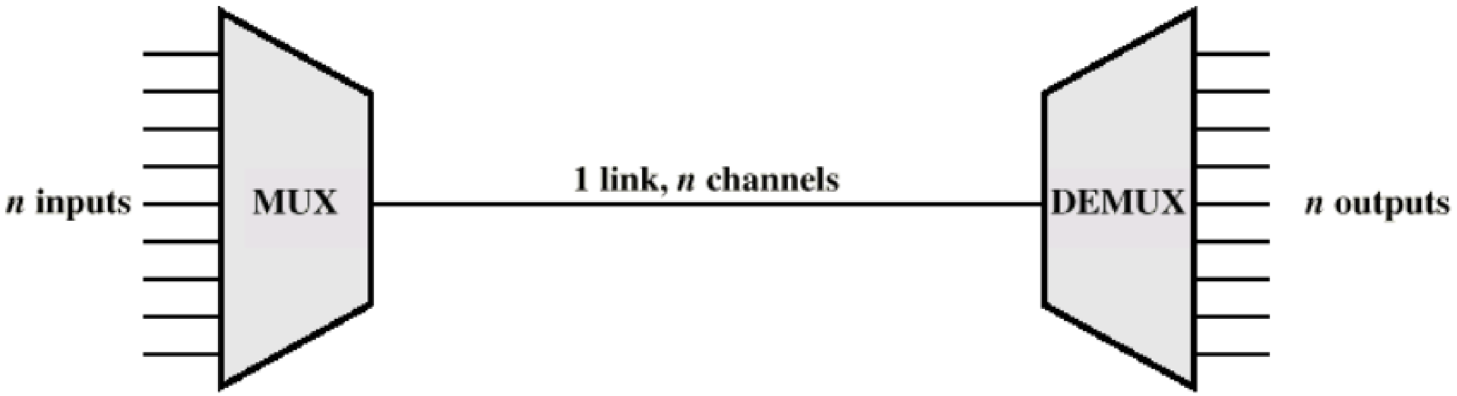
Contents

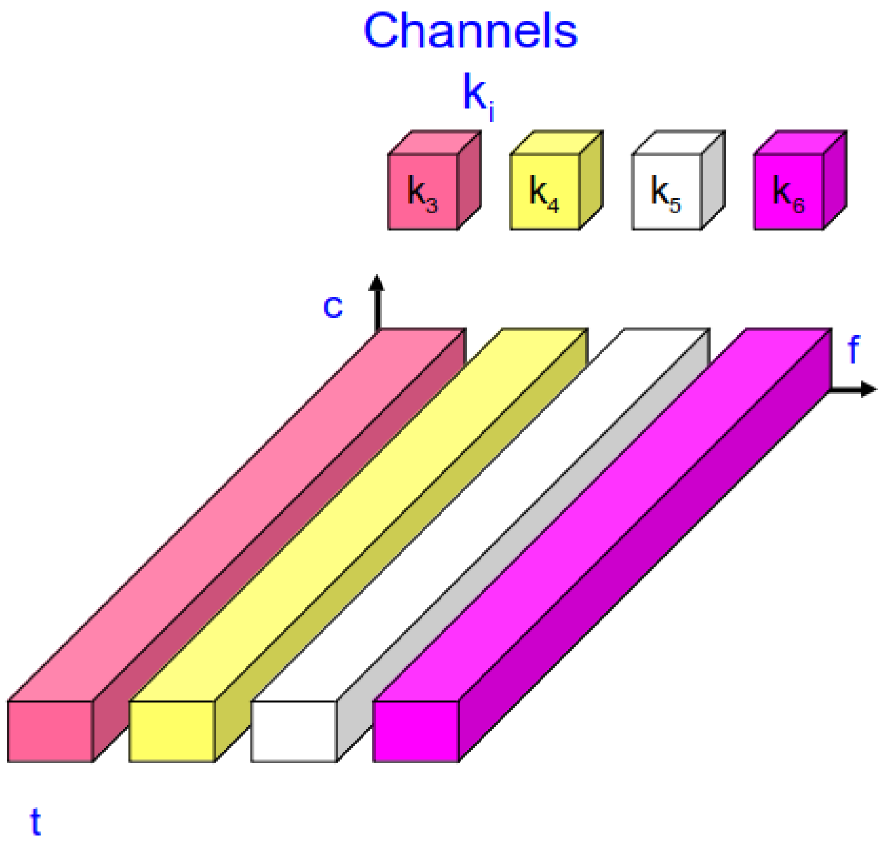
Multiplexing

- *Multiplexing* is a method by which multiple analog or digital signals are **combined into one signal** over a **shared medium**
- The multiplexed signal is transmitted over a communication channel
- The multiplexing divides the capacity of the communication channel into several **logical channels**
  - one for each message signal or data stream to be transferred.
- A reverse process, known as ***demultiplexing***, extracts the original channels on the receiver end.



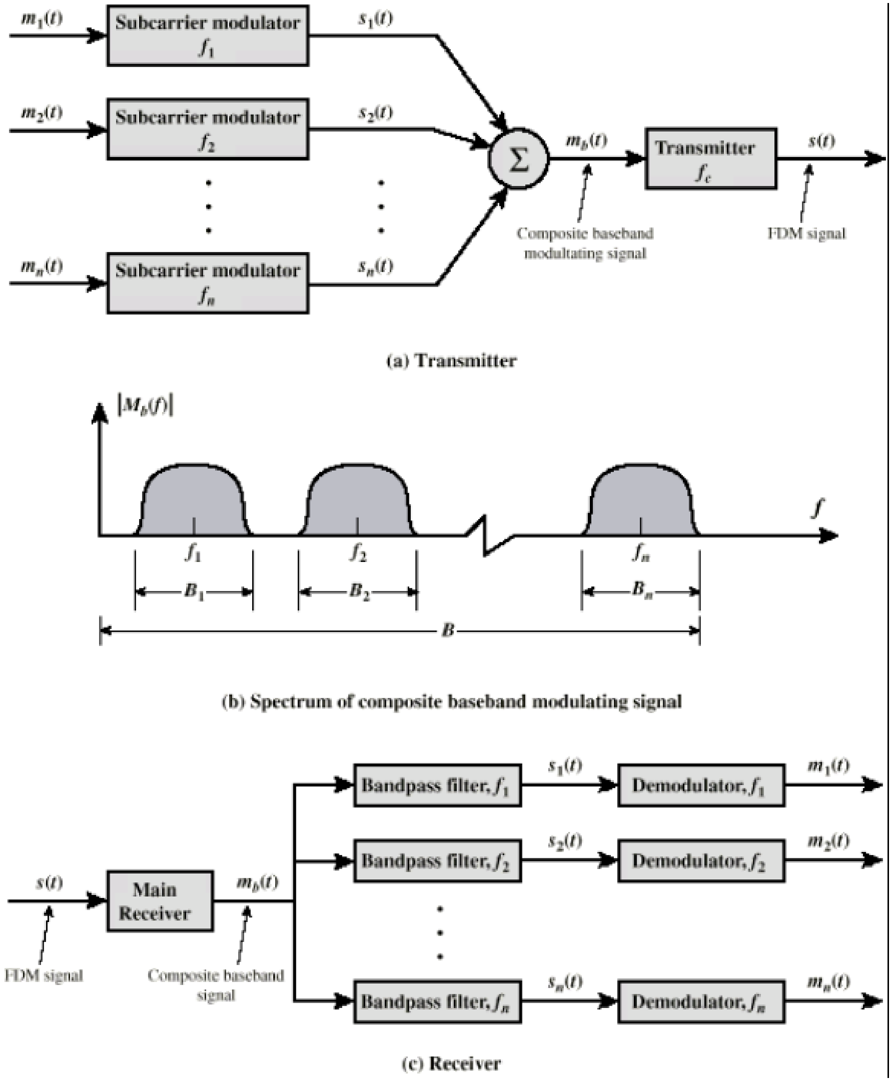
Frequency Division Multiplexing

- *Frequency Division Multiplexing* (FDM)
  - Each signal is modulated to a different carrier frequency
  - Useful bandwidth of medium exceeds required bandwidth of channel
  - Carrier frequencies separated so signals do not overlap (guard bands)
  - Channel gets band of the spectrum for the whole time
    - Channel allocated even if no data



FDM: Pro and Cons

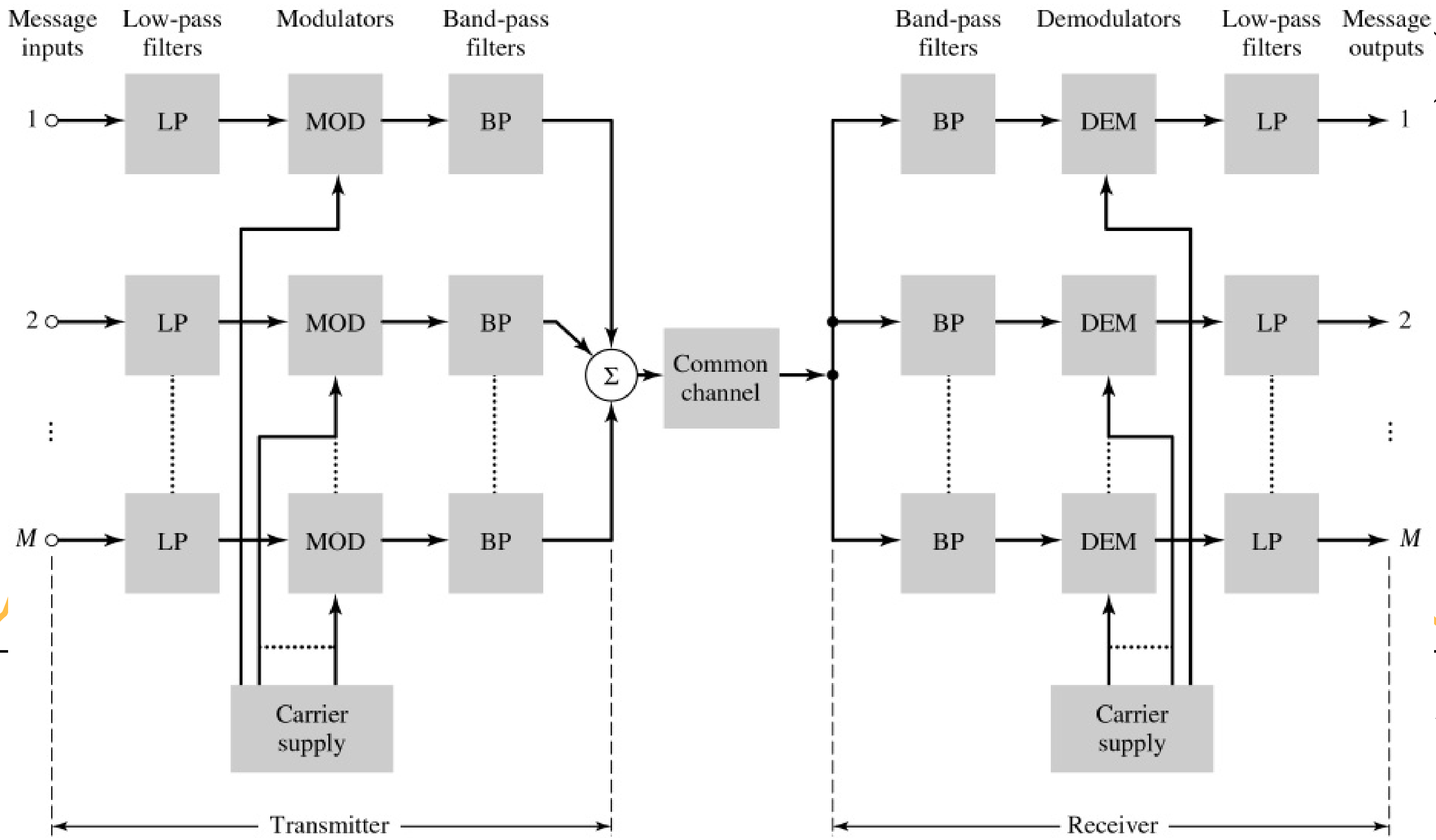
- Advantages:
  - no dynamic coordination needed
  - works also for analog signals
- Disadvantages:
  - waste of bandwidth (fixed allocation) if traffic distributed unevenly
  - guard spaces
- Applications:
  - All wireless systems basically!
  - Radio and tv broadcasting, telephone, communication satellites (uplink and downlink),DSL,…



FDM: Scheme

- Different signals can be **frequency-modulated** in different portions of the spectrum.
- Once they are received they can be **de-multiplexed** withouth distortions.

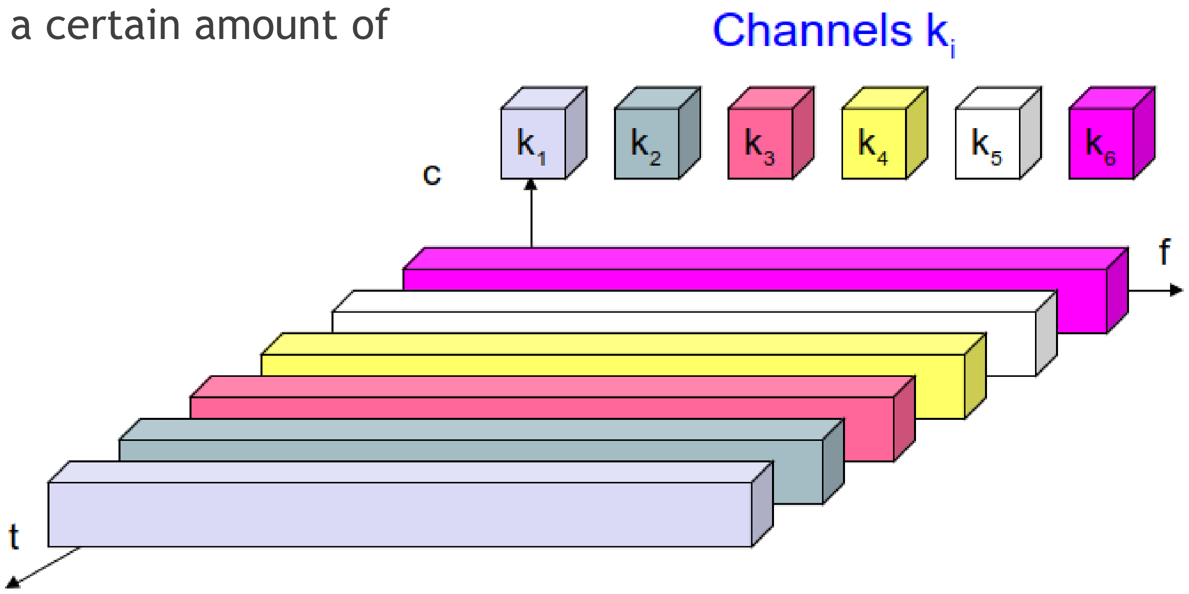
cos



$B_2 + B_3$

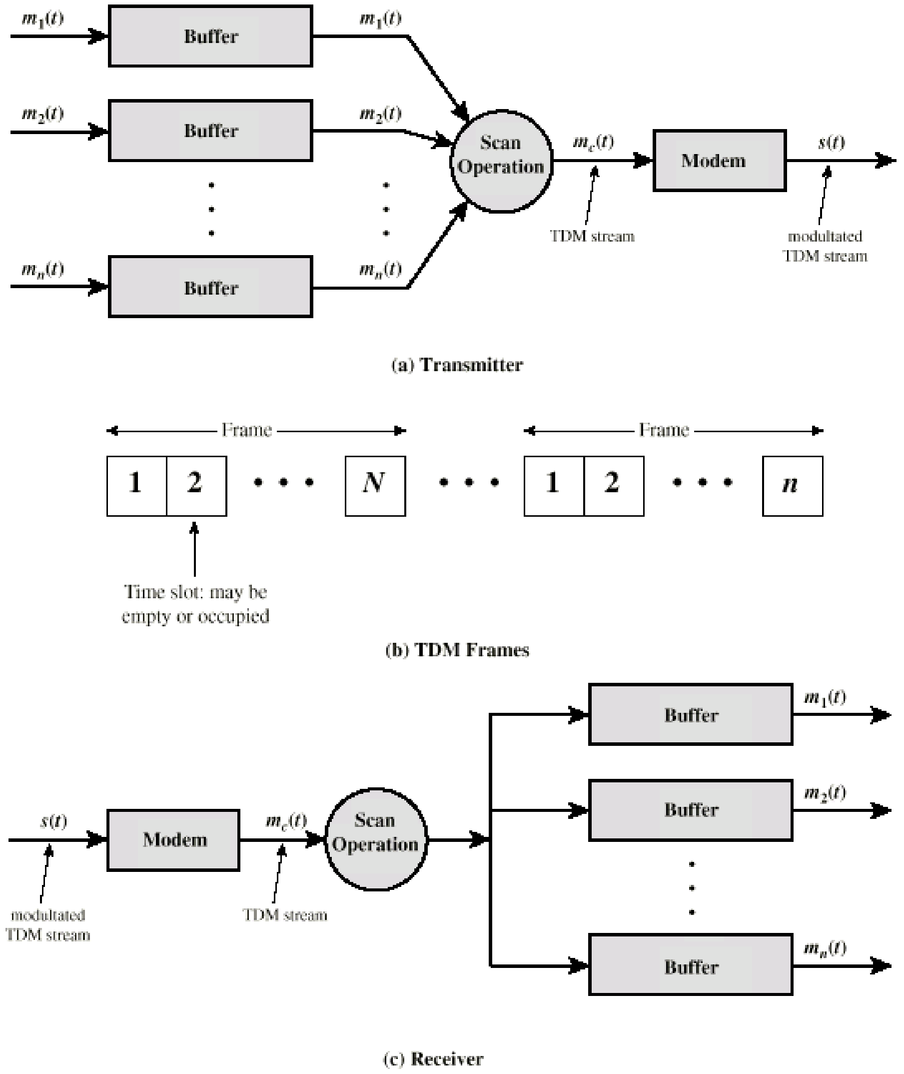
Time Division Multiplexing

- *Synchronous Time Division Multiplexing* (TDM)
  - Multiple digital signals interleaved in time
  - Time slots preassigned to sources and fixed
    - Time slots allocated even if no data
  - Data rate of medium exceeds data rate of digital signal to be transmitted
  - Channel gets the whole spectrum for a certain amount of time



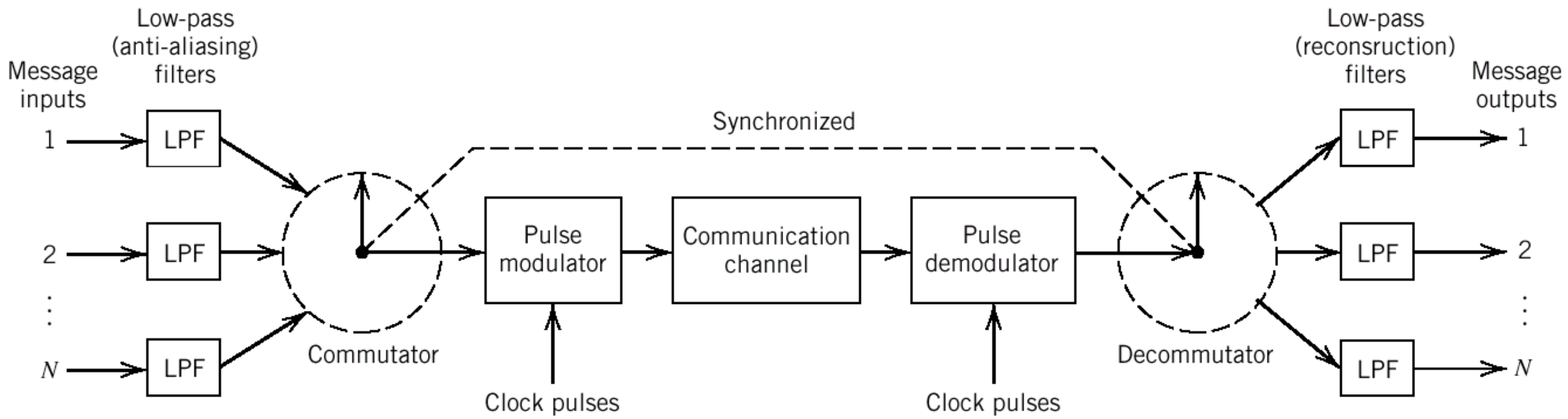
TDM: Pro and Cons

- Advantages:
  - only one carrier in the medium at any time
  - throughput high even for many users
- Disadvantages:
  - precise synchronization necessary
- Applications:
  - Optical networks (SONET), GSM, ISDN,….



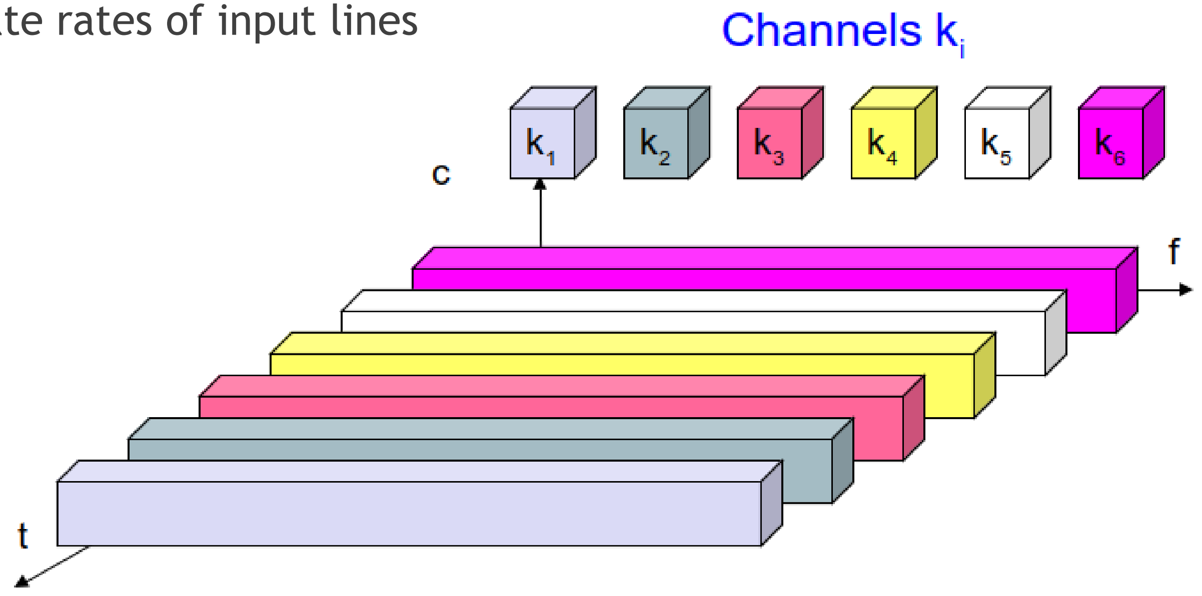
TDM: Scheme

- At the Transmitter
  - Simultaneous transmission of several signals on a time-sharing basis.
  - Each signal occupies its own distinct time slot
  - Slots may be permanently assigned on demand.
- At the Receiver
  - Decommutator (sampler) has to be synchronized with the incoming waveform => Frame Synchronization
  - Low pass filter
  - ISI – poor channel filtering
  - Feedthrough of one channel's signal into another channel => Crosstalk



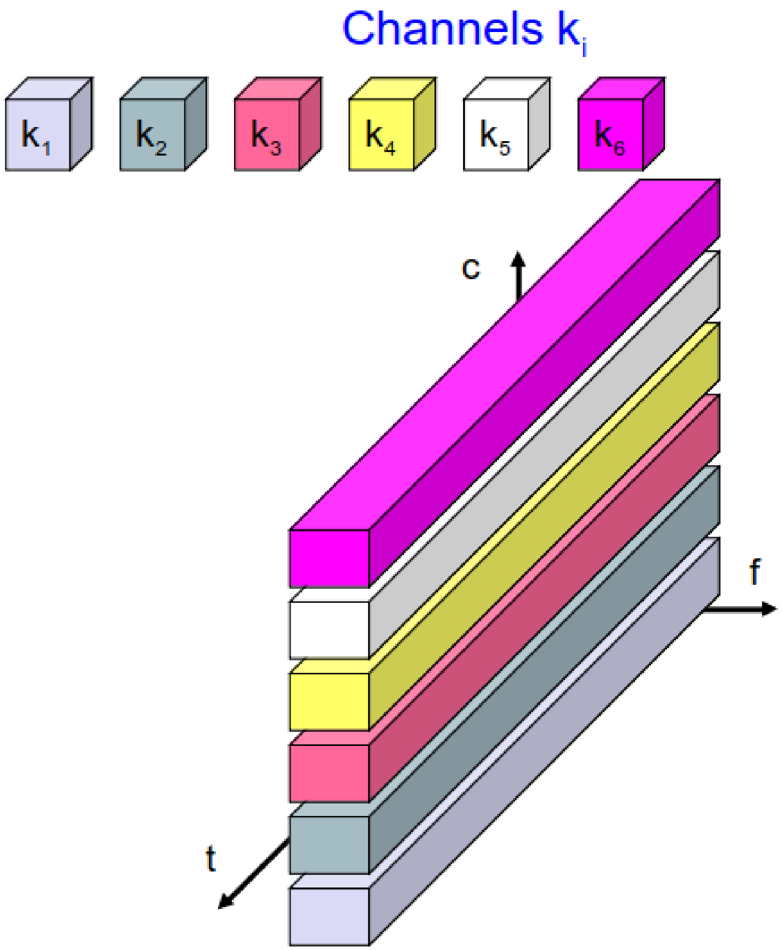
Time Division Multiplexing

- *Statistical Time Division Multiplexing*
  - In Synchronous TDM many slots are wasted
  - Statistical TDM allocates time slots dynamically based on demand
  - Multiplexer scans input lines and collects data until frame full
  - Data rate on line lower than aggregate rates of input lines
  - More advanced technique
    - It requires scheduling algorithms



Code Division Multiplexing

- *Code Division Multiplexing* (CDM)
  - Each channel has unique code
  - All channels use same spectrum at same time
  - Implemented using spread spectrum technology
    - Each sender is assigned a unique binary code c_i
    - Binary codes are orthogonal vectors
    - This means that they can be summed together and separated without interference
    - MUX: sum signals after code modulation
      - $s_{mux}(t) = s_1(t)c_1 + s_2(t)c_2$
    - DEMUX performs the scalar product to get the desired signal
      - $\langle s_{mux}(t), c_1 \rangle = s_1(t)$



CDM: Pro and Cons

- *Advantages*
  - Bandwidth efficient
  - No coordination and synchronization
  - Good protection against interference
- *Disadvantages*
  - lower user data rates
  - more complex signal regeneration

- Applications:
  - UMTS (3G), Global Navigation Satellite Systems (GPS),…

Example: GPS signal

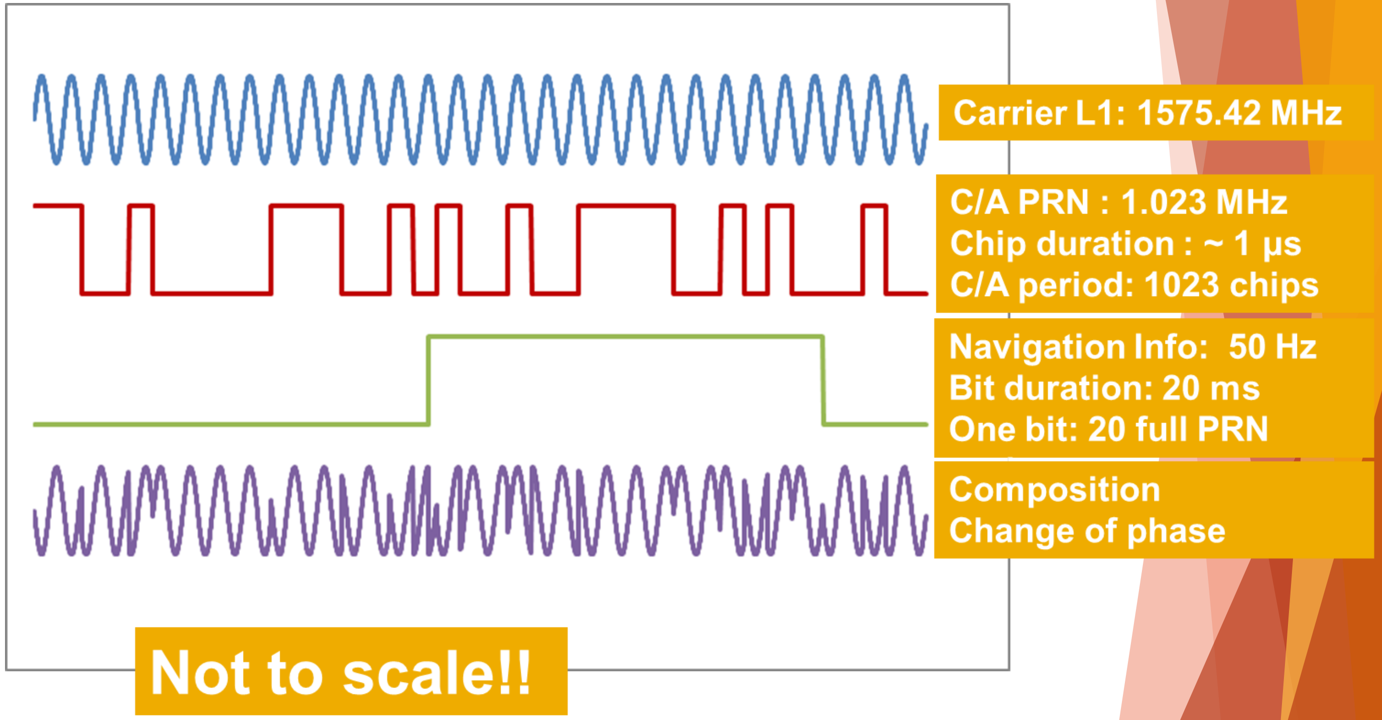


Figure: “GPS signals" by José Caro Ramón is licensed under CC BY-SA 3.0

TDM + FDM

- *Time and Frequency Division Multiplexing*
  - A channel gets a certain frequency band for a certain amount of time (e.g. GSM)
- *Advantages:*
  - better protection against tapping
  - protection against frequency selective interference
  - higher data rates compared to code multiplex
  - Precise coordination required