UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Escola Superior d'Enginyeries Industrial,
Aeroespacial i Audiovisual de Terrassa

FUNDAMENTALS OF INDUSTRIAL WIRELESS COMMUNICATIONS

MUEI / MUEA / MASE

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ESEIAAT. 2n semester, part 1, 2023

MODULE 4.1: FUNDAMENTALS

(SIGNALS, SPECTRA, FILTERS and dB)

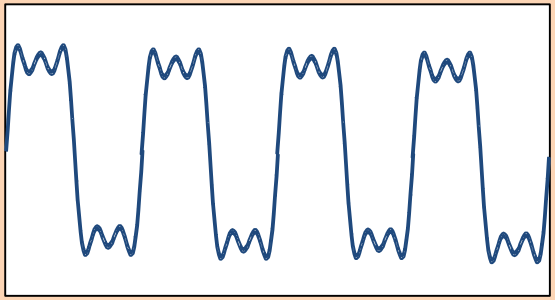
Lectures sensitive & adaptive to previous background….

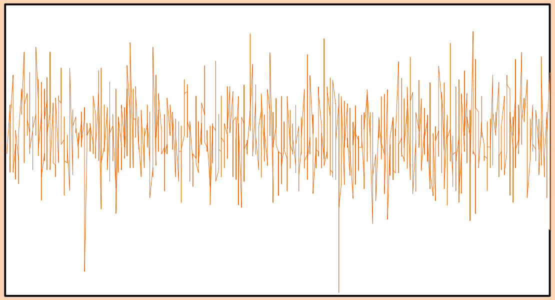
Fundamentals: Signals and Systems

Signal classification

- **Deterministic:** Can be represented by a mathematical formula and are certainty determined for every value of the time (or frequency) ,
- **Random:** at every time-instant take a value among a set of possible ones, among with certain probability.

$x(t)$
Amplitude
Frequency
Delay
Phase, ...





$\tilde{x}$

(random variable)
Mean
vaiance
PDF, …

- **Continuous:**
  - Continuous-time: defined at every time.
  - Continuous-amplitude: All values are possible between a max. and min.
- **Discrete:**
  - Discrete-time: only defined in certain time instants.
  - Discrete-amplitude: A finite set of possible values (between max. and min)

Sequences from sampling

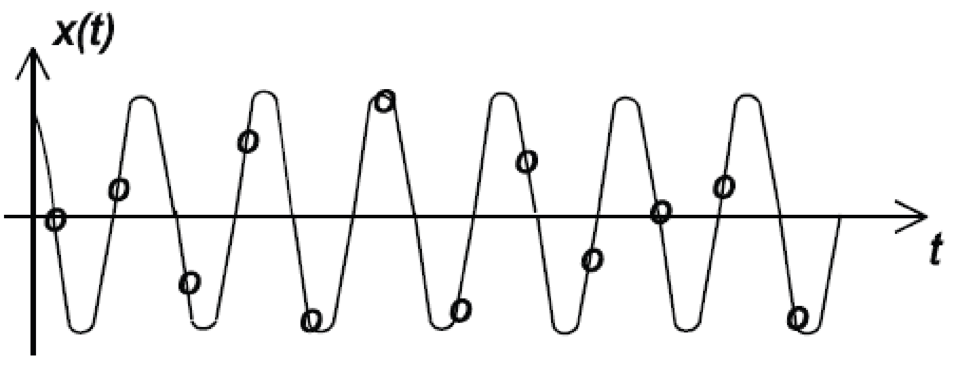
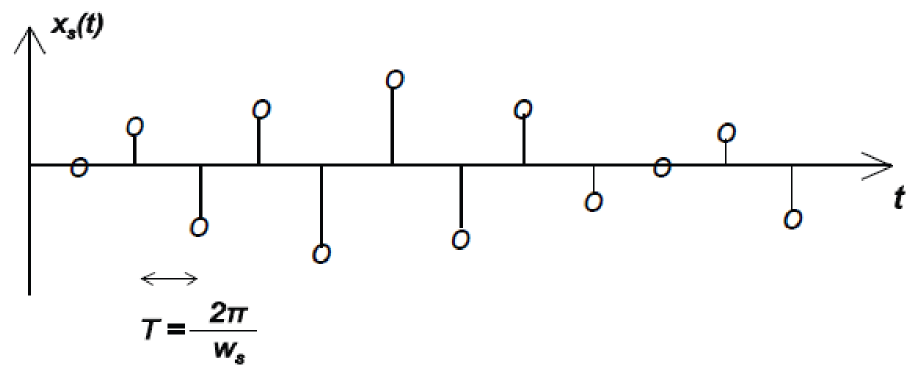


Fig. 4.17. Muestreo de una sinusoide



SAMPLING

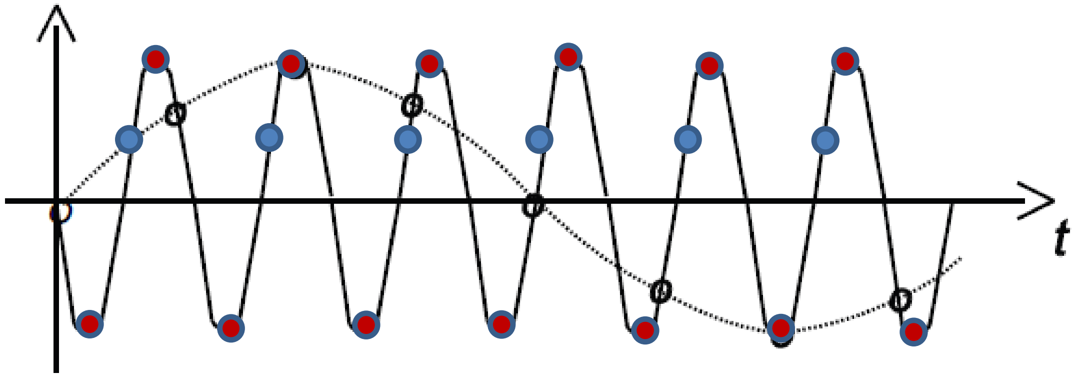


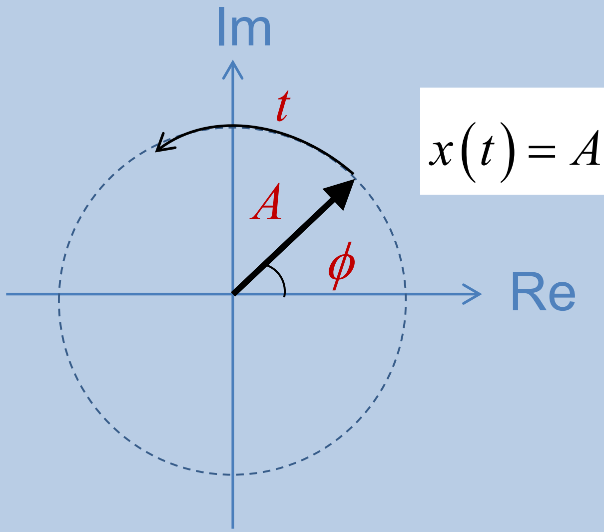
Fig. 4.20. Señal muestreada sin cumplir la condición de Nyquist

$$f_s \geq 2\, f_{\max} = f_N$$

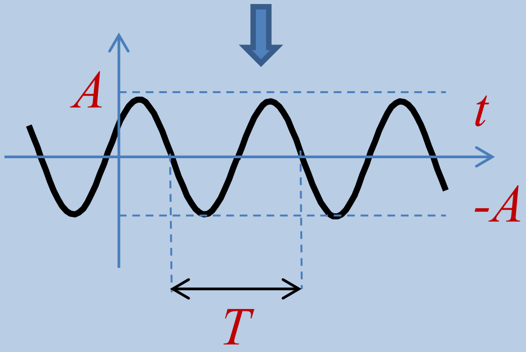
(f_N : frecuencia de Nyquist)

SINUSOIDS

- **Complex exponential: sinusoids**



$$x(t)=Ae^{j(\omega t+\phi)}=\underbrace{A\cos(\omega t+\phi)}\;+\;j\,A\sin(\omega t+\phi)$$



Parameters:

$\boldsymbol{A}$: Amplitude

$\boldsymbol{T}$: Period (s)

$\boldsymbol{\omega}$: Angular frequency (rad/s) $=2\pi/T$

$\boldsymbol{f}$: Frequency (Hz = periods/s) $=1/T$

$\boldsymbol{\phi}$: Phase (rad) - Initial phase-

SINUSOIDS

Complex exponential (Euler)

$$e^{j2\pi f_o t} = \cos(2\pi f_o t) + j\sin(2\pi f_o t)$$

$$e^{-j2\pi f_o t} = \cos(2\pi f_o t) - j\sin(2\pi f_o t)$$

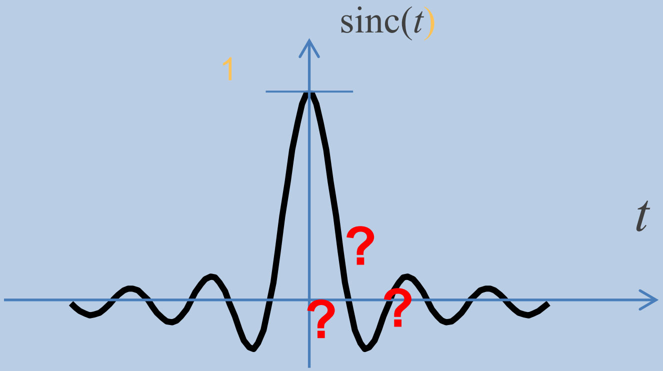
$$\cos(2\pi f_o t) = \frac{e^{j2\pi f_o t} + e^{-j2\pi f_o t}}{2}$$

$$\sin(2\pi f_o t) = \frac{e^{j2\pi f_o t} - e^{-j2\pi f_o t}}{2j}$$

Sinc function

- ***sinc(t)***

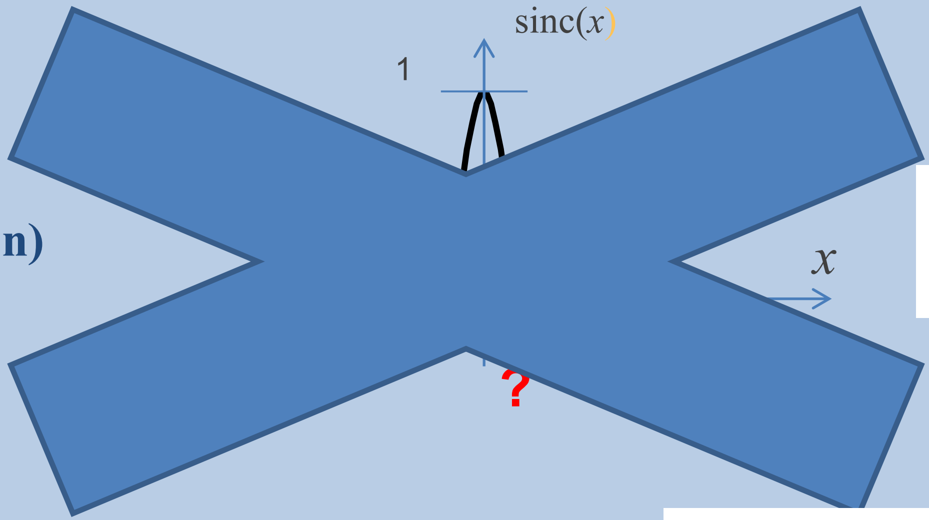
(normalized definition)



$$\operatorname{sinc}(t)=\frac{\sin(\pi t)}{\pi t}$$

- ***sinc(x)***

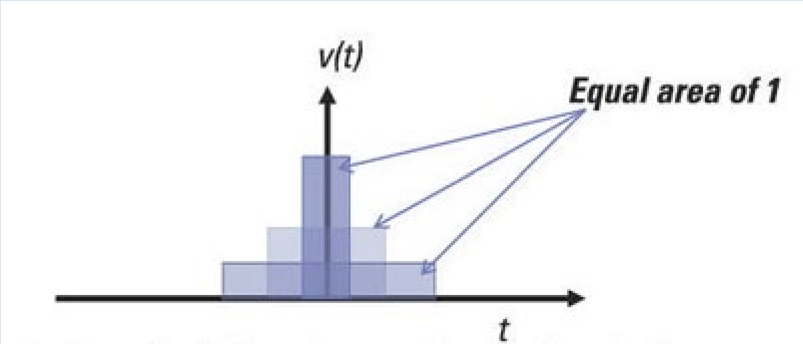
(unormalized definition)
Sometimes written as
Sa(x)

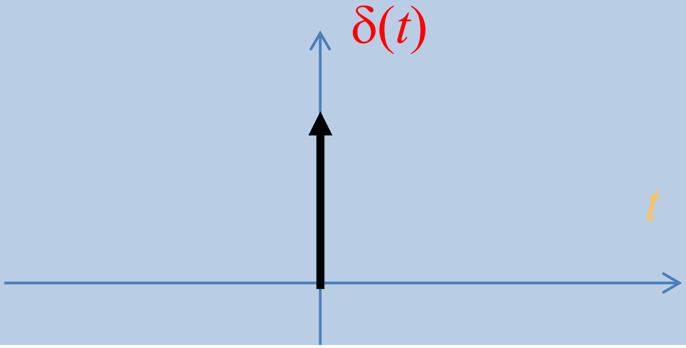


$$\operatorname{sinc}(x)=\frac{\sin(x)}{x}$$

Plot: $$\frac{\sin(\pi t/T)}{\pi t}$$

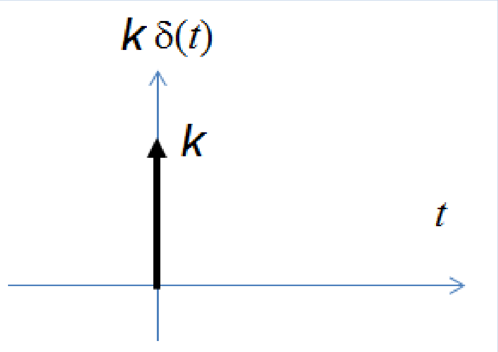
Unit impulse (Dirac delta)





$$\delta(t)=0\ ;\ \forall t\neq 0\ ;\quad \text{with}\ \int_{-\infty}^{\infty}\delta(t)\,dt=1$$

$$\Rightarrow\ \delta(0)\to\infty$$



Weigthed impulse

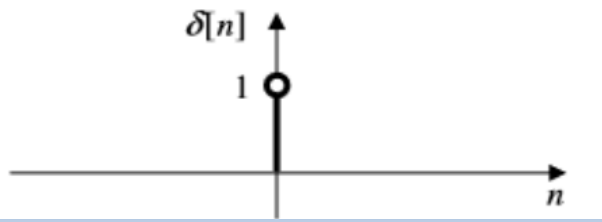
$$\int_{-\infty}^{\infty}k\,\delta(t)\,dt=k$$

$$\int_{-\infty}^{t}k\,\delta(t)\,dt=k\,u(t)$$

Unit impulse (Dirac delta): discrete time

- In the discrete-time case is the **delta of Kronecker** (more simple to understand)

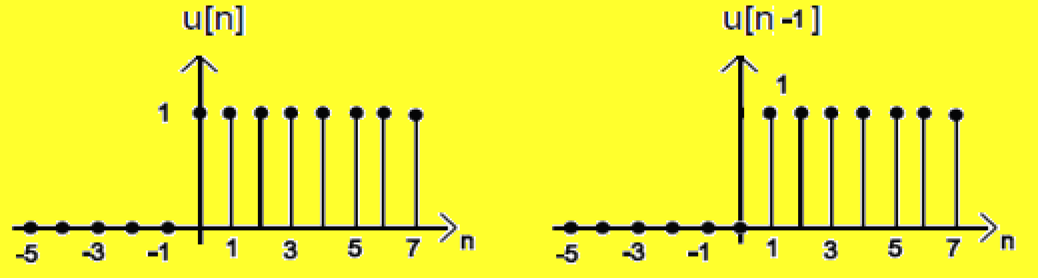
$$\delta[n] \doteq \begin{cases} 1 & \text{si } n = 0 \\ 0 & \text{si } n \neq 0 \end{cases}$$



Properties:

[n] : discrete time, dimensionless (ordinal quantity)

- $\delta[n] = u[n] - u[n-1]$



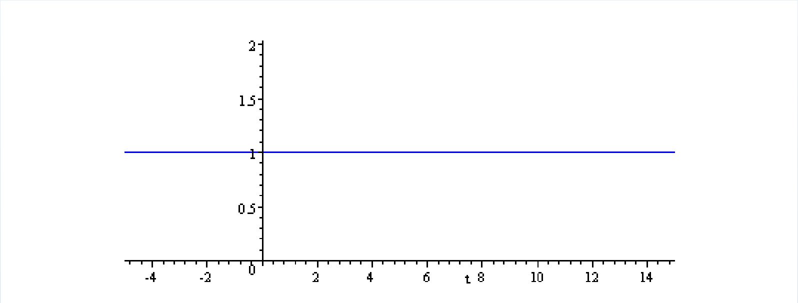
- $x[n] \cdot \delta[n] = x[0] \cdot \delta[n]$
- $x[n] \cdot \delta[n-m] = x[m] \cdot \delta[n-m]$

FOURIER ANALYSIS: SPECTRUM

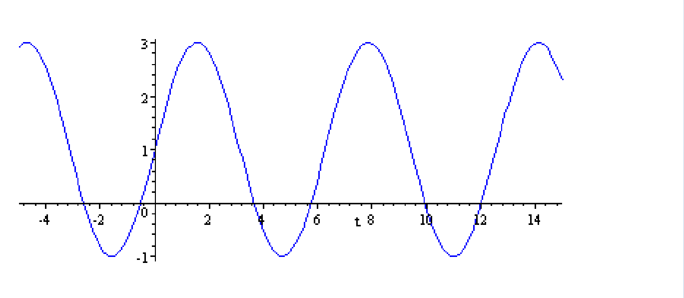
Fourier series (background)

SERIES: For periodic signals

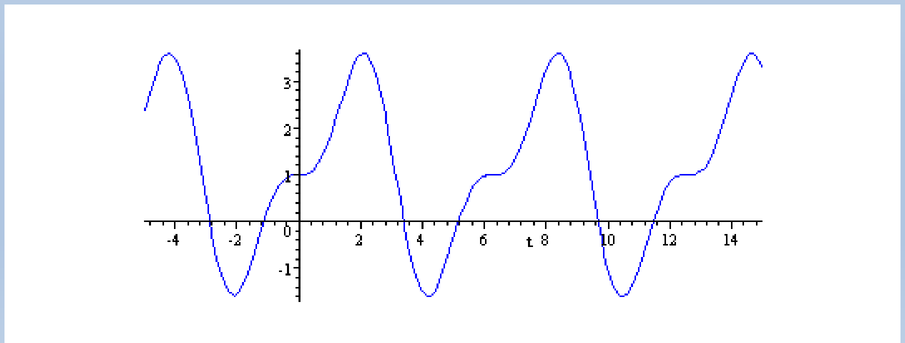
$f(t) = 1$



$f(t) = 1 + 2 \sin t$:

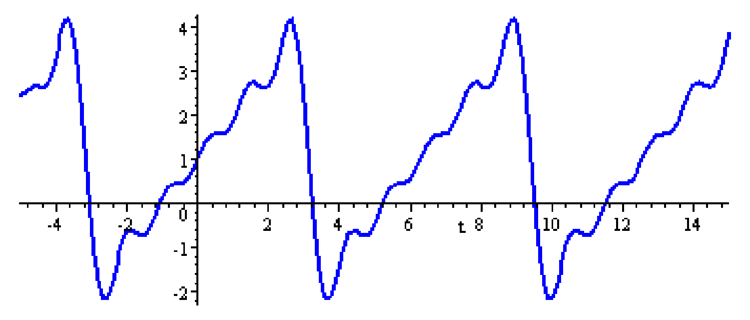


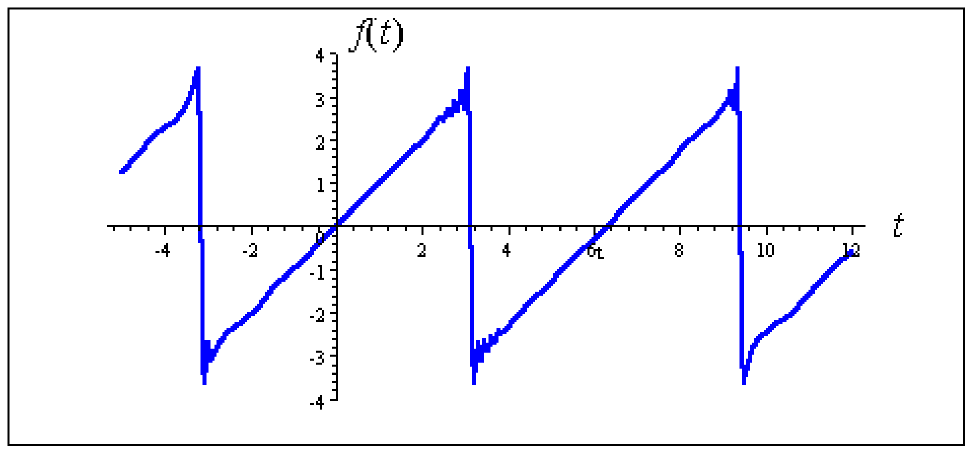
$f(t) = 1 + 2 \sin t - \sin 2t$

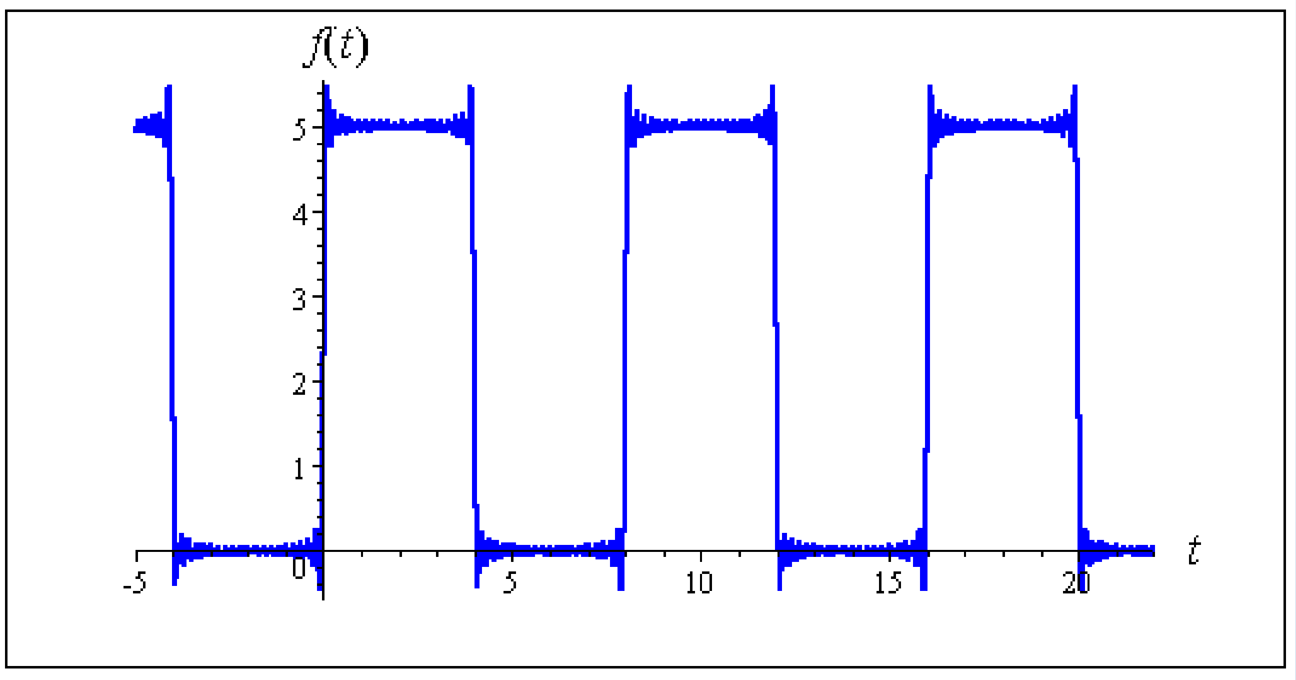


Fourier series (background)

$$f(x) = 1 + 2\sin t - \sin 2t + \frac{2}{3}\sin 3t - \frac{1}{2}\sin 4t + \frac{2}{5}\sin 5t + \dots$$

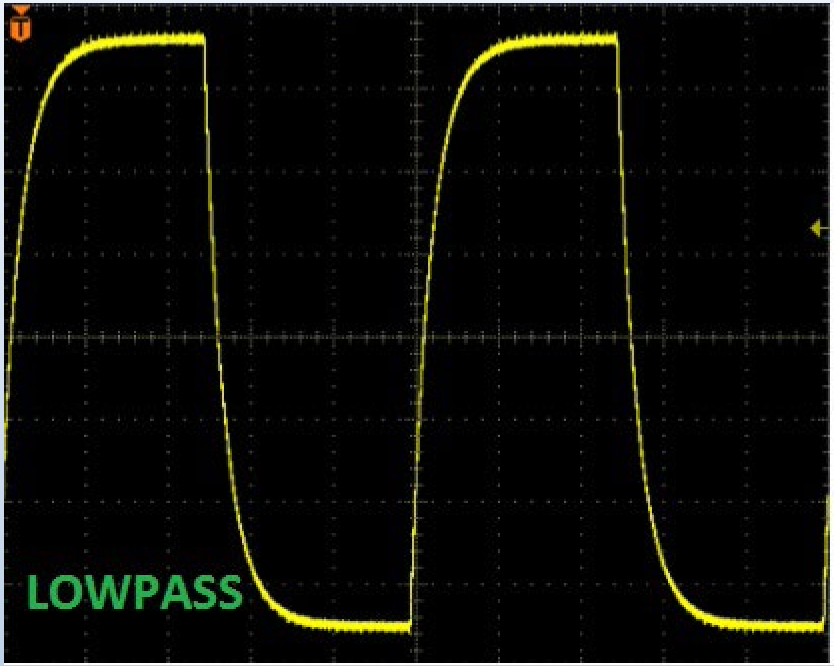


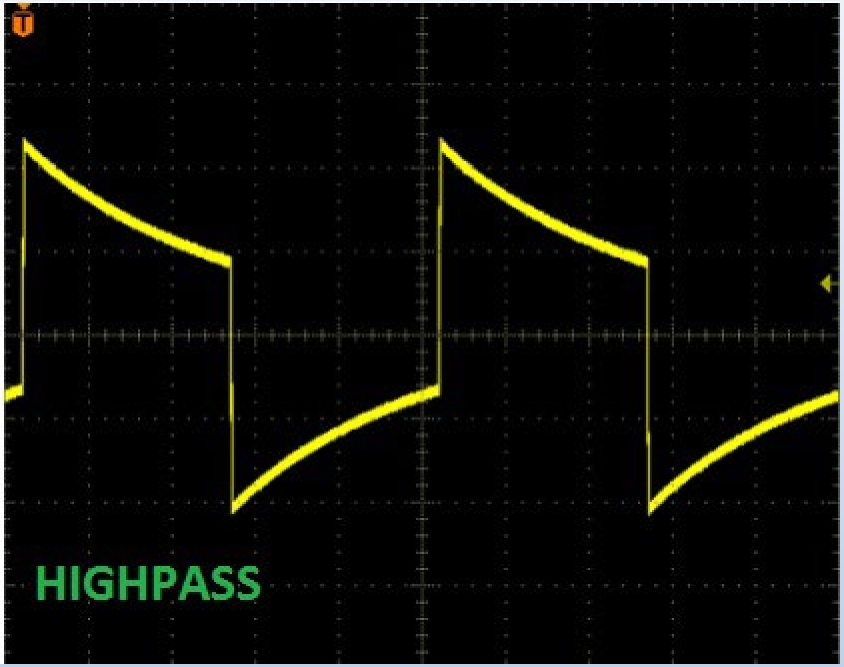


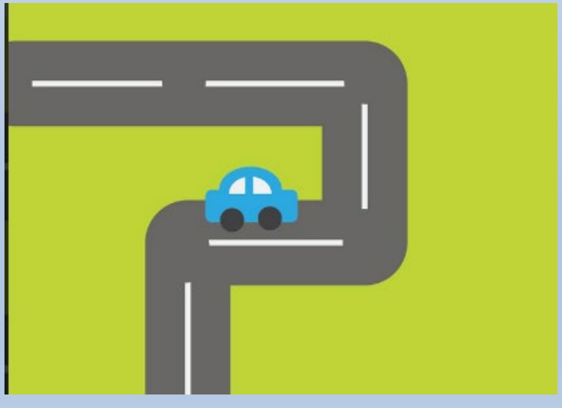


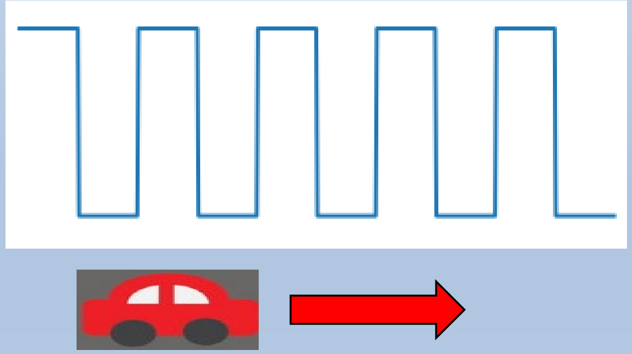
Gibbs phenomenon

Fourier series (background)

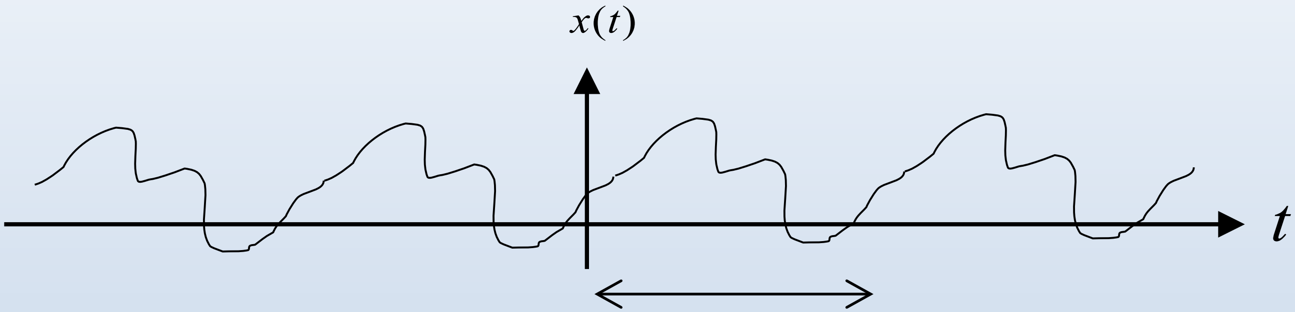








Fourier series (background)



períod: T_0

$$x(t) = x(t + T_0) \qquad \forall t$$

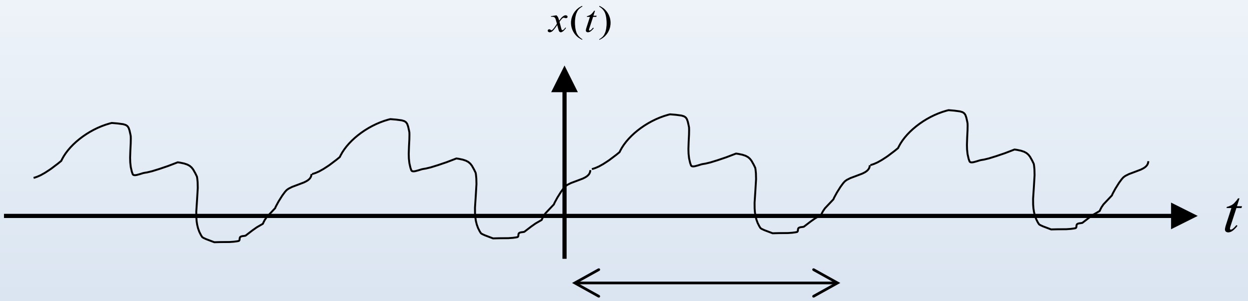
Trigonometric series of Fourier:

$$\boxed{f_p(t) = a_0 + \sum_{n=1}^{\infty}\left[a_n \cos\left(n\omega_0 t\right) + b_n \sin\left(n\omega_0 t\right)\right]}$$

T_0 is the period of the *fundamental frequency* f_0

$$\boxed{\omega_0 = 2\pi / T_0}$$

Fourier series (background)



períod: T_0 $\qquad x(t) = x(t+T_0) \quad \forall t$

Complex series of Fourier:

$$x(t) = \sum_{n=-\infty}^{\infty} c_n e^{j2\pi n f_0 t}; \qquad c_n = \frac{1}{T_0}\int_{T_0} x(t) e^{-j2\pi n f_0 t}\, dt$$

Fourier coefficients

$$c_0 = \frac{1}{T_0}\int_{T_0} x(t)\, dt$$

Mean value (dc level)

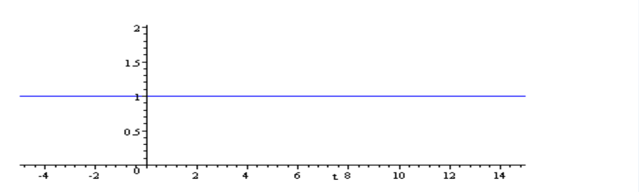
$$\boxed{\omega_0 = 2\pi f_0 = \frac{2\pi}{T_0}, \qquad f_0 = \frac{1}{T_0}}$$

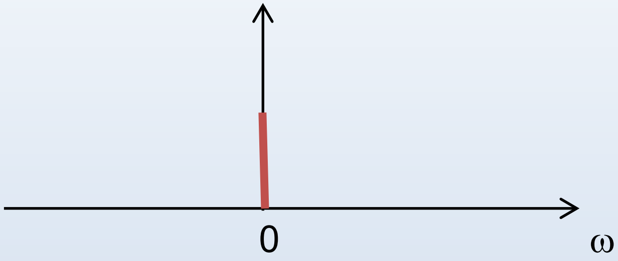
Fundamental frequency

$$\frac{a_0}{\cancel{2}\,1} = c_0, \qquad 2|c_n| = \sqrt{a_n^2 + b_n^2}, \qquad \measuredangle c_n = \arctan\left(\frac{-b_n}{a_n}\right)$$

f(*t*) = 1

$a_0 = 1$

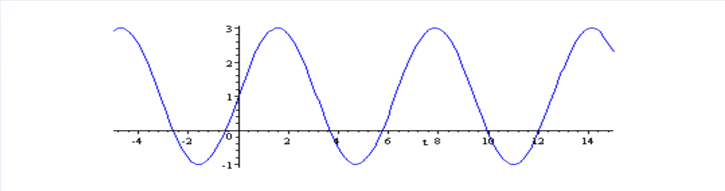


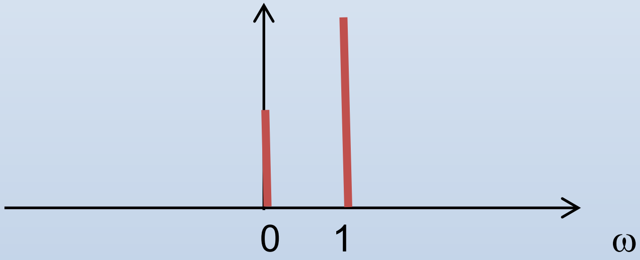


f(*t*) = 1 + 2 sin *t*:

$b_1 = 2$

$a_1 = 0$

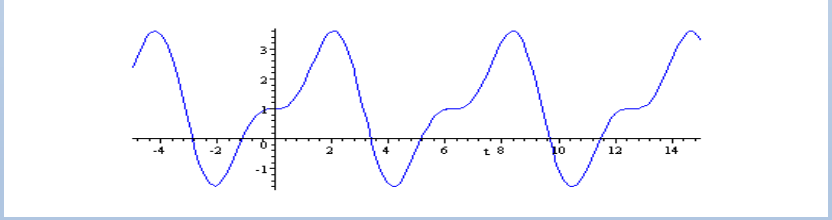


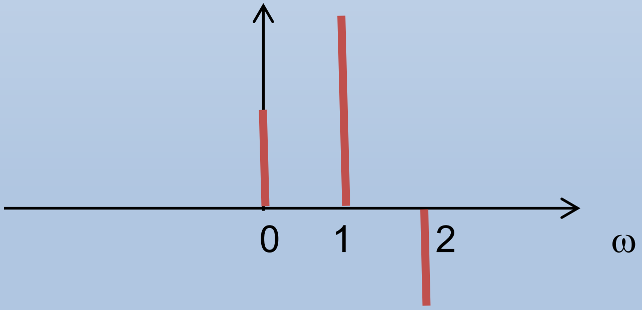


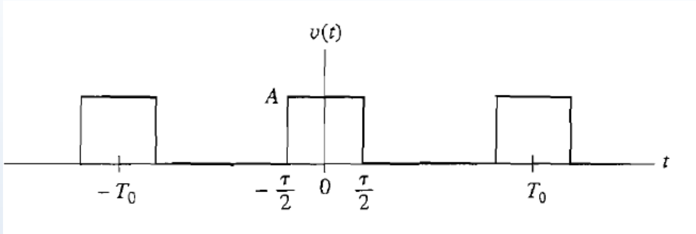
f(*t*) = 1 + 2 sin *t* - sin 2*t*

$b_2 = -1$

$a_2 = 0$



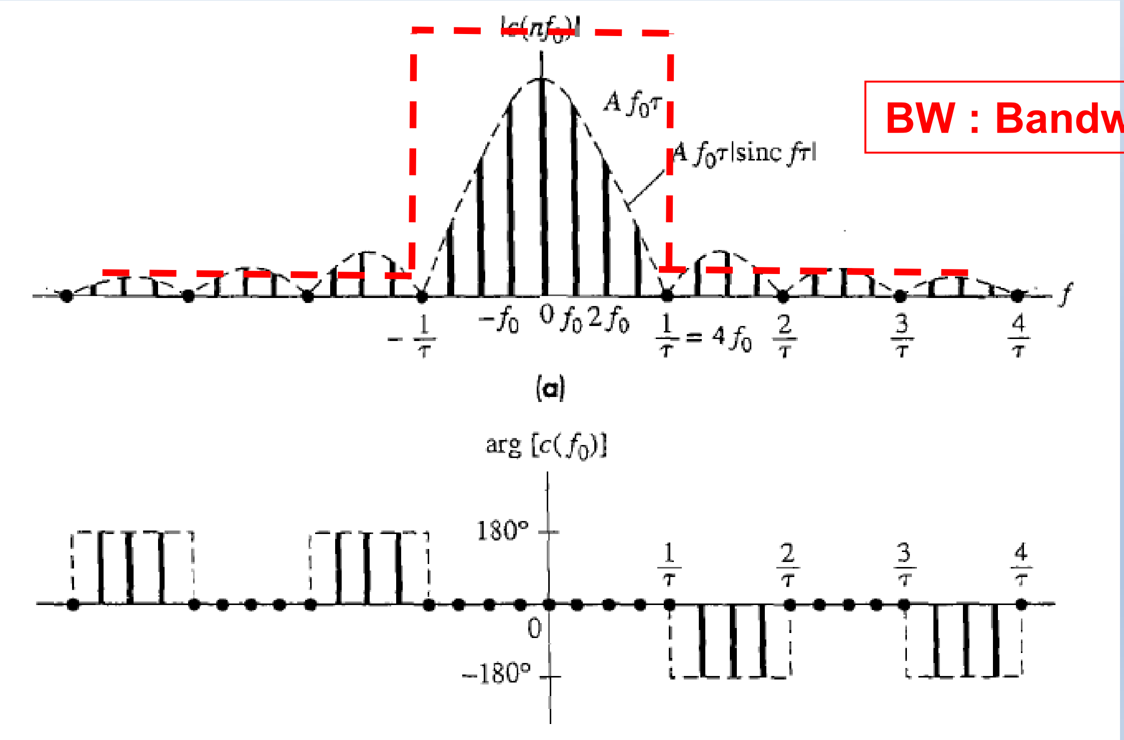




Rectangular pulse train.

$$c_n = \frac{1}{T_0}\int_{-T_0/2}^{T_0/2} v(t)\, e^{-j2\pi n f_0 t}\, dt = \frac{1}{T_0}\int_{-\tau/2}^{\tau/2} A e^{-j2\pi n f_0 t}\, dt = \frac{A}{-j2\pi n f_0\, T_0}\left(e^{-j\pi n f_0 \tau} - e^{+j\pi n f_0 \tau}\right) =$$

$$= \frac{A}{T_0}\,\frac{\sin \pi n f_0 \tau}{\pi n f_0} = \frac{A\tau}{T_0}\,\frac{\sin \pi (n f_0 \tau)}{\pi (n f_0 \tau)} = \frac{A\tau}{T_0}\,\mathrm{sinc}\, n f_0 \tau$$



BW : Bandwidth ??

Fourier TRANSFORM (background)

Fourier transform

$$V(f) = \mathcal{F}[v(t)] \triangleq \int_{-\infty}^{\infty} v(t) e^{-j2\pi ft}\, dt$$

Inverse Fourier transform

$$v(t) = \mathcal{F}^{-1}[V(f)] \triangleq \int_{-\infty}^{\infty} V(f) e^{j2\pi ft}\, df$$

In electrical engineering:
- c_n have units of [V], [A]
- X(f) has units of [V/Hz] [A/Hz]


MODEL SR770 FFT NETWORK ANALYZER
STANFORD RESEARCH SYSTEMS
CONTROL
SYSTEM
ENTRY
MENU
MARKER
START
PAUSE CONT
MARKER
ACTIVE TRACE
PRINT
HELP
AUTO RANGE
AUTO SCALE
SPAN △
SPAN ▽
ALT
EXP
ENTRY
FREQ
MEAS
DISPLAY
INPUT
SCALE
ANALYZE
AVERAGE
SOURCE
SYSTEM
STORE RECALL
MODE
REF
CENTER
MAX/MIN
Format USB Drive Using This Instrument
TRIGGER IN
SOURCE OUT
SIGNAL IN
A
B
Frequency
Level
1000 mV
Return:
0.0 kHz
50.00 kHz
100.00 kHz
Top = 20 dBV 20 dB/div Wndo: BMH
File= Live
Stop
No Avg

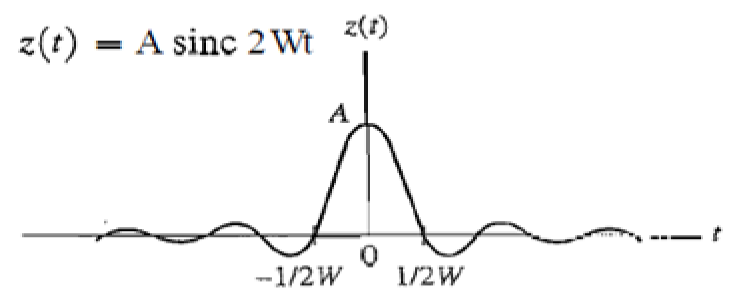
Some properties of the Fourier TRANSFORM (background)

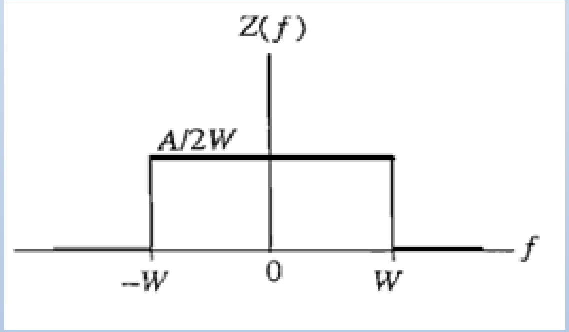
Duality …. $x(t) \leftrightarrow X(f) \Rightarrow X(t) \leftrightarrow x(-f)$

… + Time scaling: $x(at) \leftrightarrow \frac{1}{|a|}X\left(\frac{f}{a}\right)$

transform pair

$$v(t) = B\Pi(t/\tau) \qquad V(f) = B\tau \operatorname{sinc} f\tau$$





$$Z(f) = \frac{A}{2W}\Pi\left(\frac{f}{2W}\right)$$

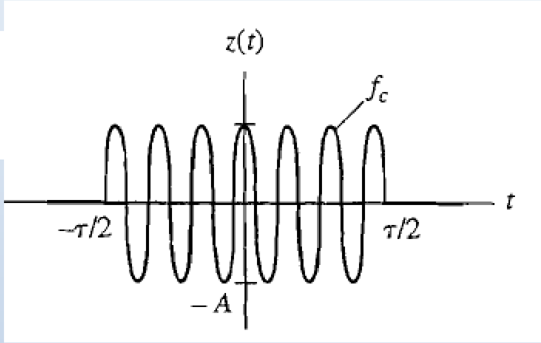
BW pulses….
Ideal filtering …

Some properties of the Fourier TRANSFORM (background)

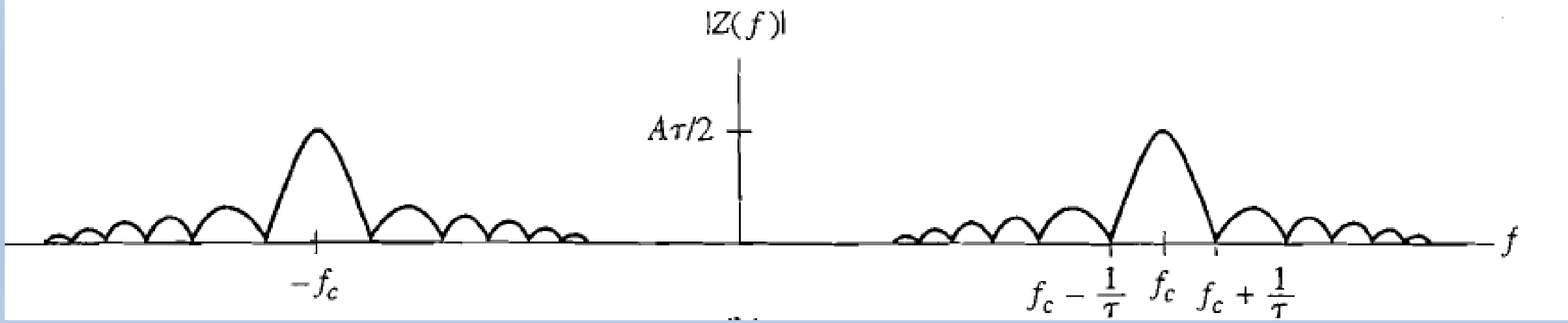
- Frequencial shifting (modulation):

$$x(t)e^{j2\pi f_0 t} \leftrightarrow X(f - f_0)$$

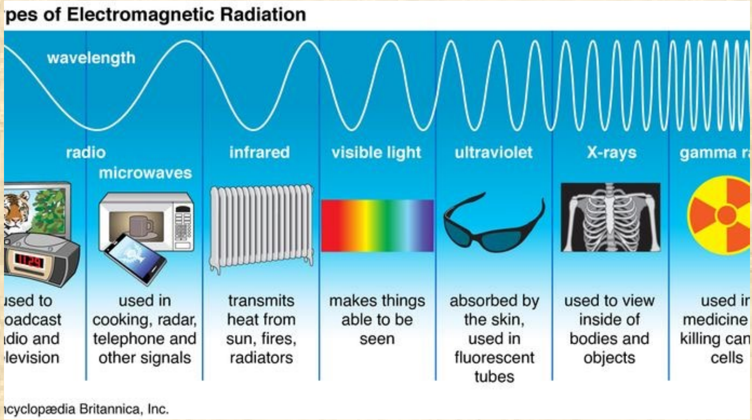
$$z(t) = A\Pi\left(\frac{t}{\tau}\right) \cos \omega_c \, t$$

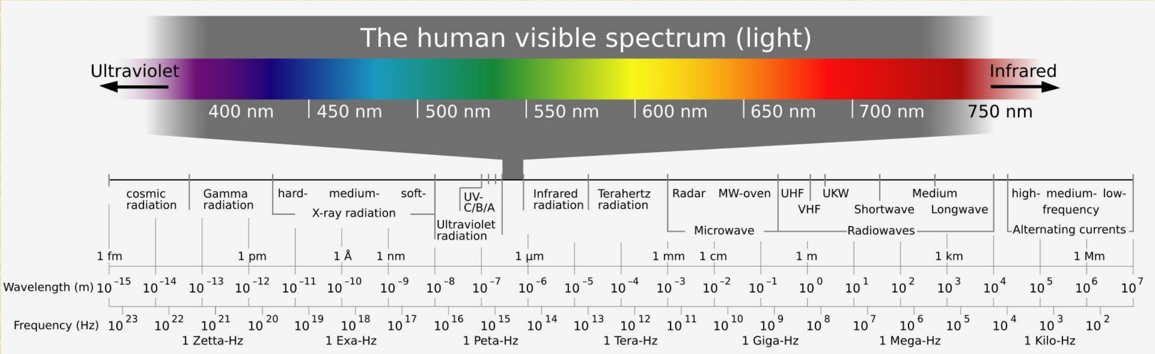


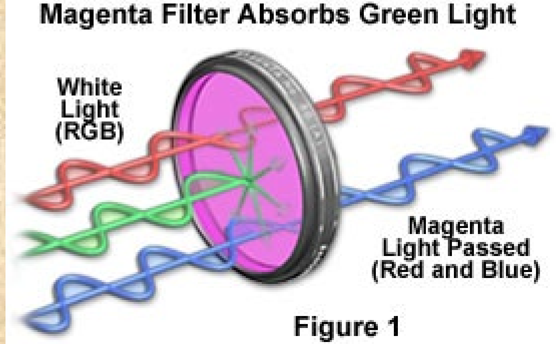
$$Z(f) = \frac{A\tau}{2} \operatorname{sinc}(f - f_c)\tau + \frac{A\tau}{2} \operatorname{sinc}(f + f_c)\tau.$$



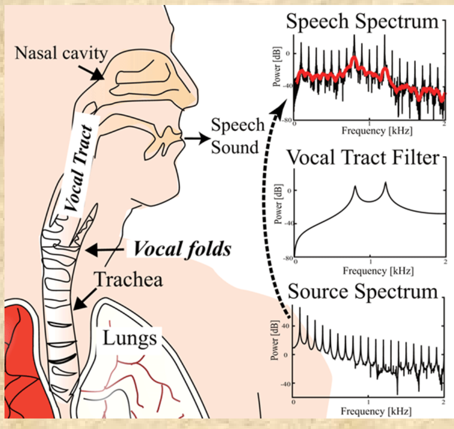
Filter examples







Filter examples



Statistics RMS -24.2 -24.1

Max Crest Factor 11.9 11.4

Clippings 0 0

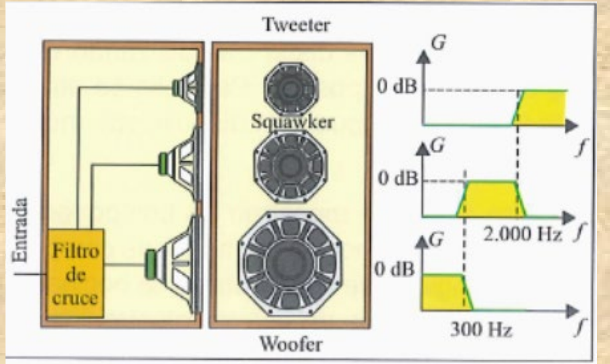
Metering DBFS

Peak -1.8 -0.8

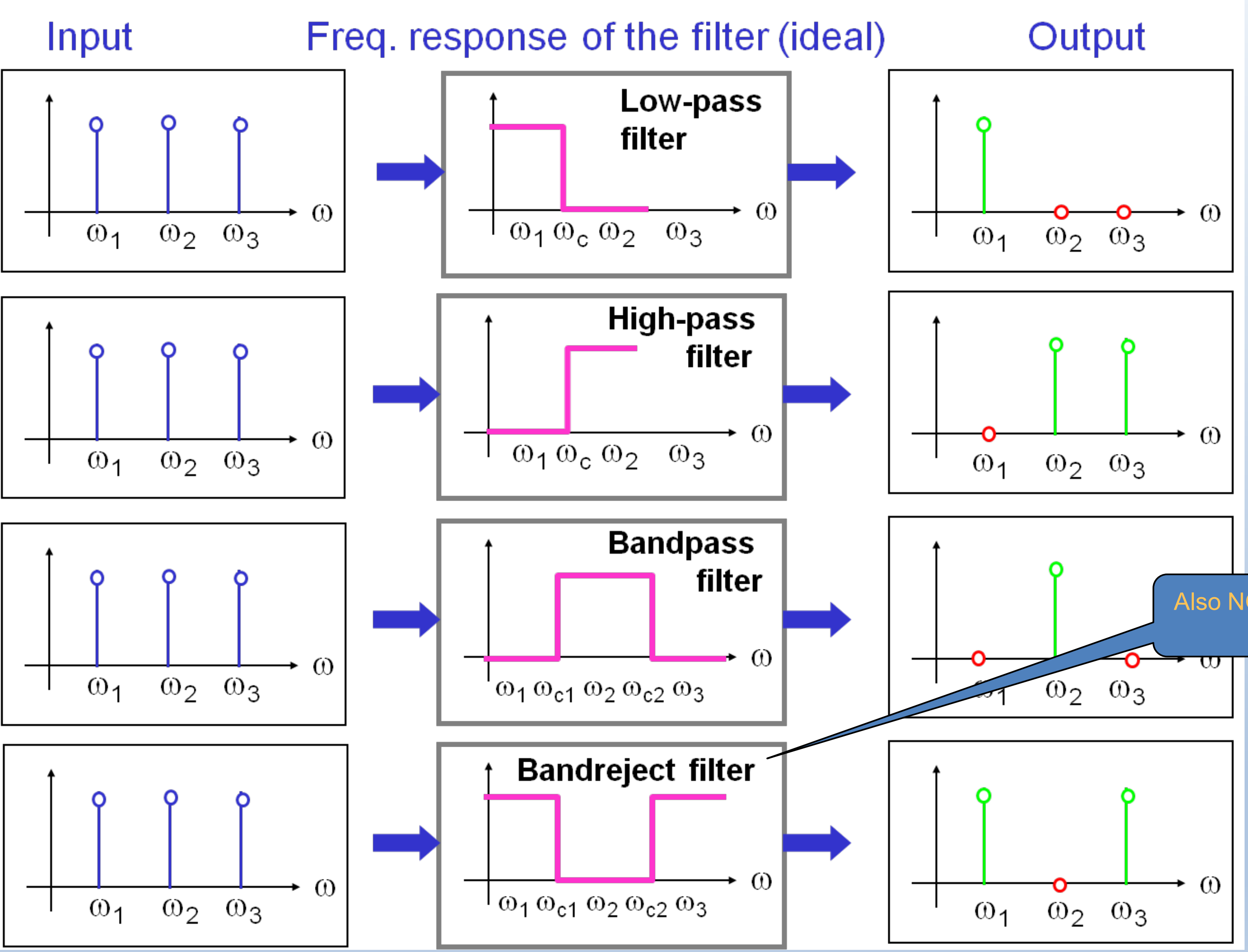
Correlation Meter R/L -0.5

FFT spectrum analyzer. Darker curve represents the secondary spectrum.

App: spectroid



Ideal & Real Filters ters



Input

Freq. response of the filter (ideal)

Output

Low-pass filter

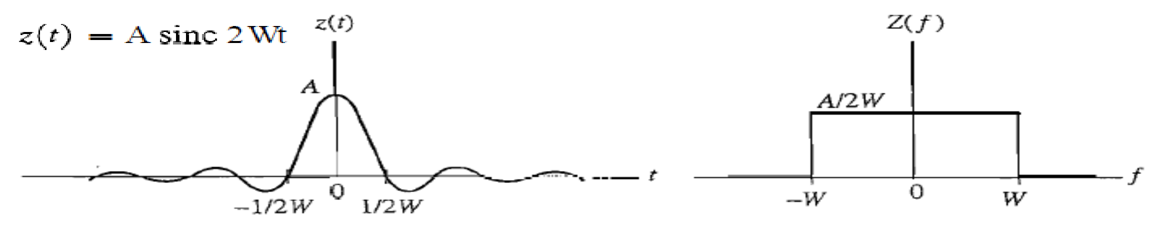
High-pass filter

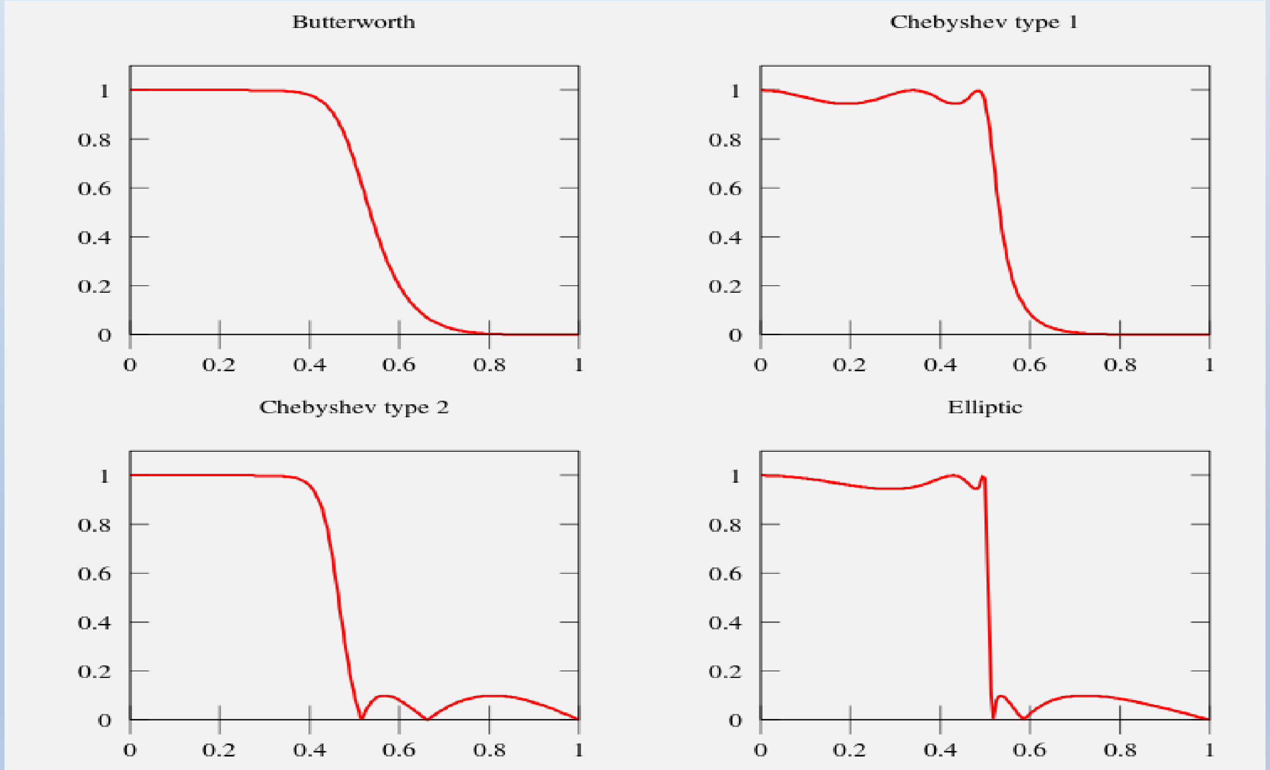
Bandpass filter

Bandreject filter

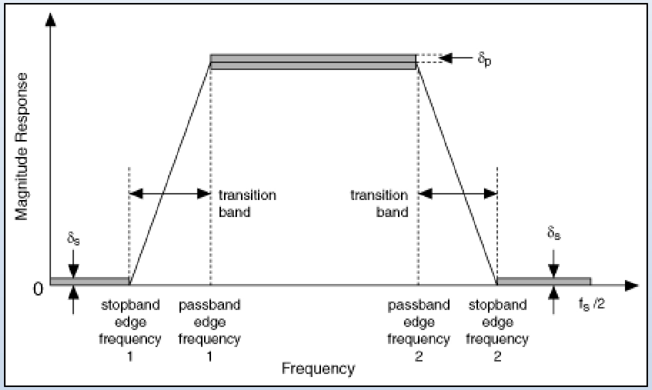
Also NOTCH filter

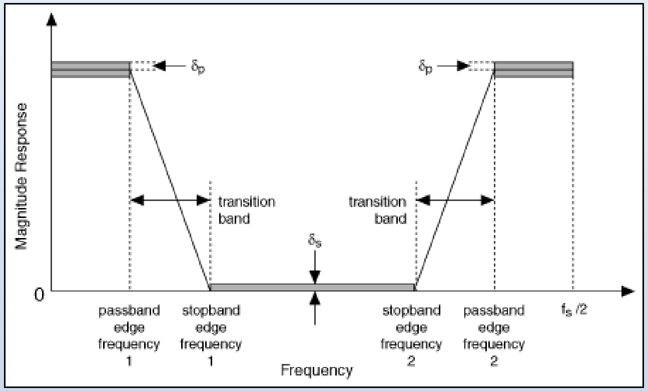
Ideal & Real Filters

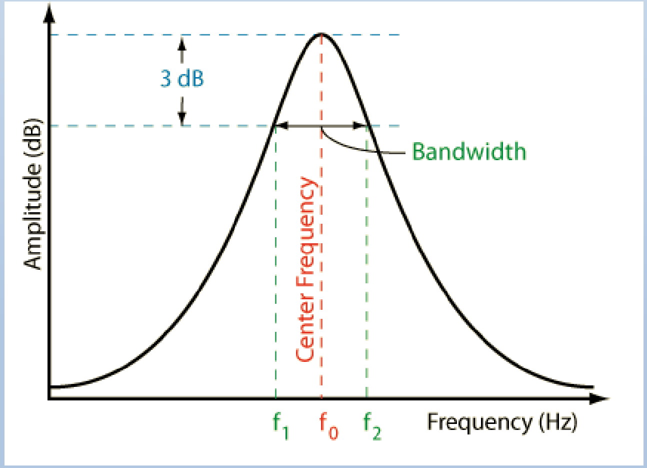




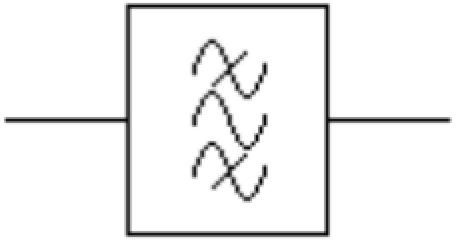
SPECIFICATIONS



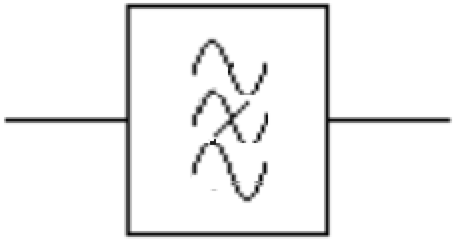




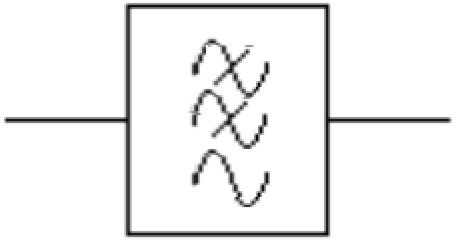
$$Q = \frac{f_0}{f_2 - f_1} = \frac{f_0}{\mathbf{BW}}$$



passa-banda

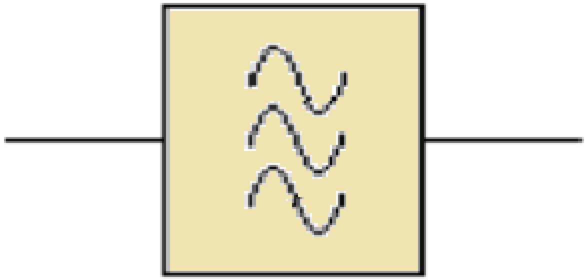


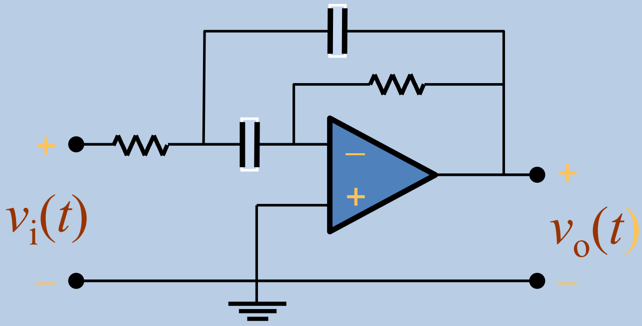
banda eliminada



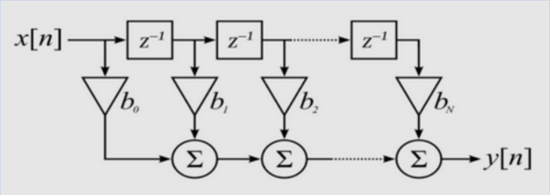
passa-baixes

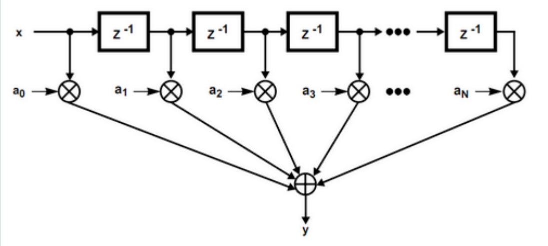
• • •





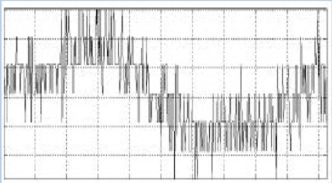
Active filter (analog)



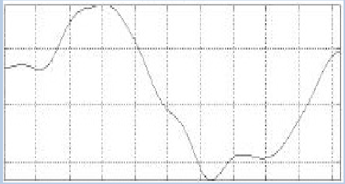


Digital Filter

Filter



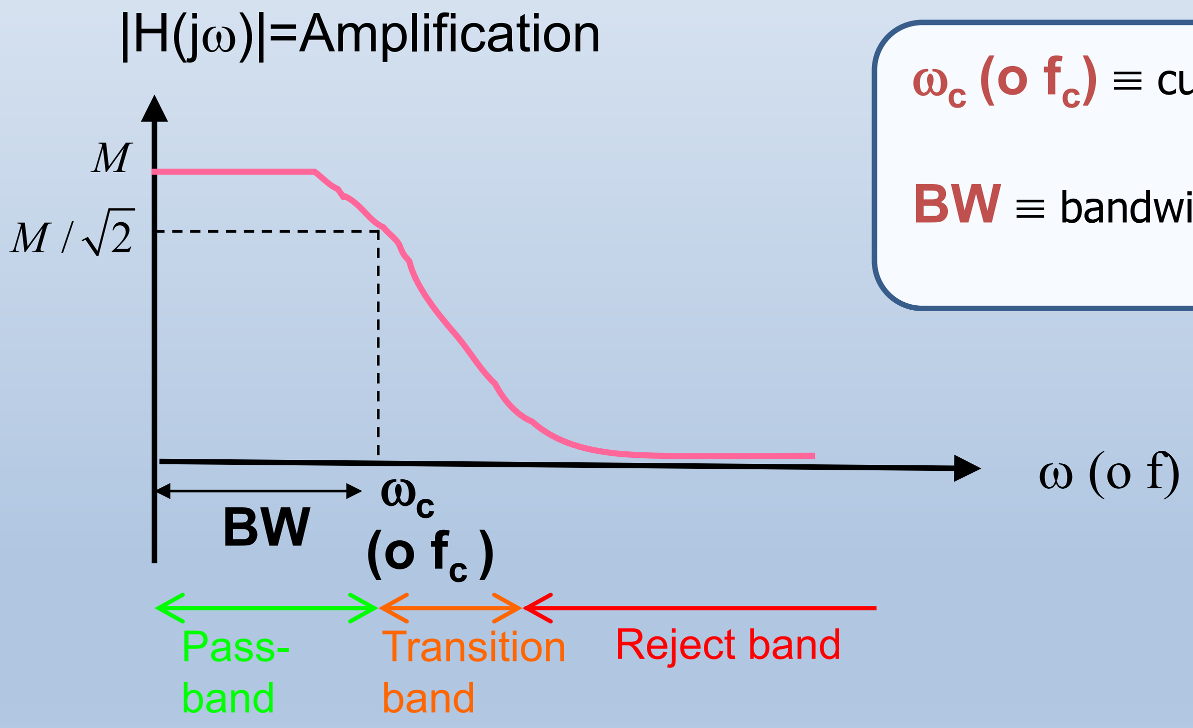
Noisy input]



Filtered output]

Filter parameters

In a real situation, the filters that can be built are approximations to the ideal response. Example for the low-pass filter:



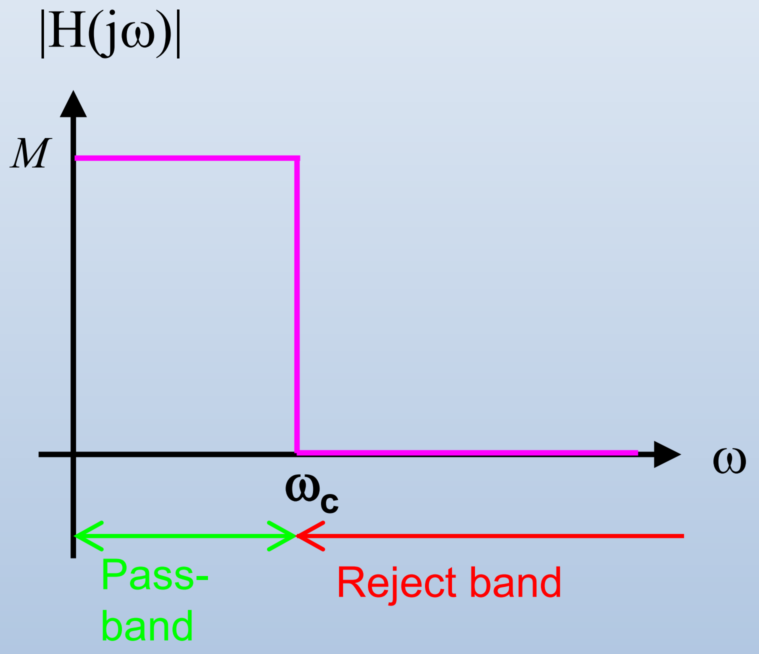
ω_c **(o f_c)** ≡ cutoff (cut-off) frequency

BW ≡ bandwidth

Analog Filtering

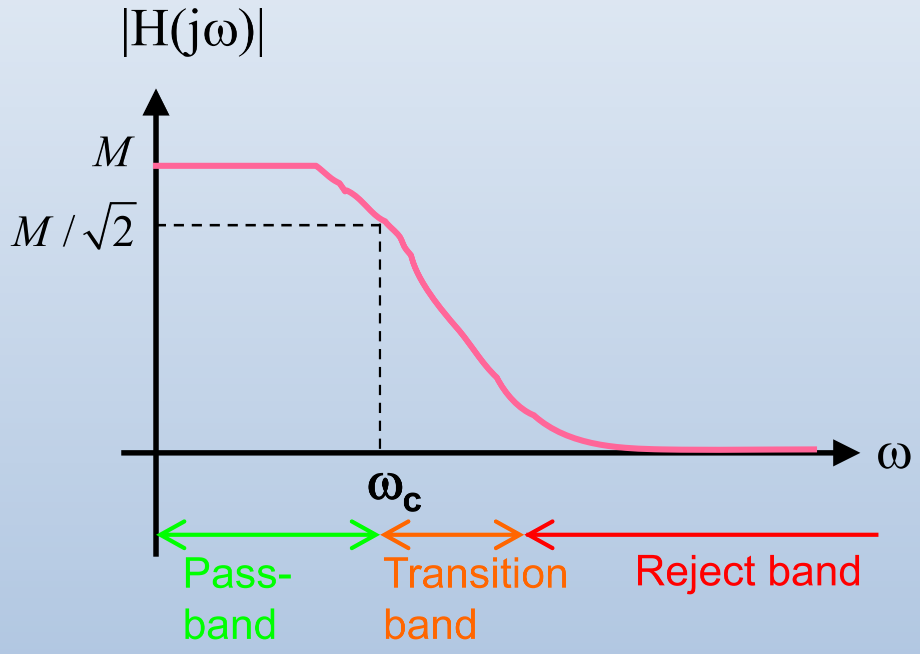
Filter parameters

Ideal filter



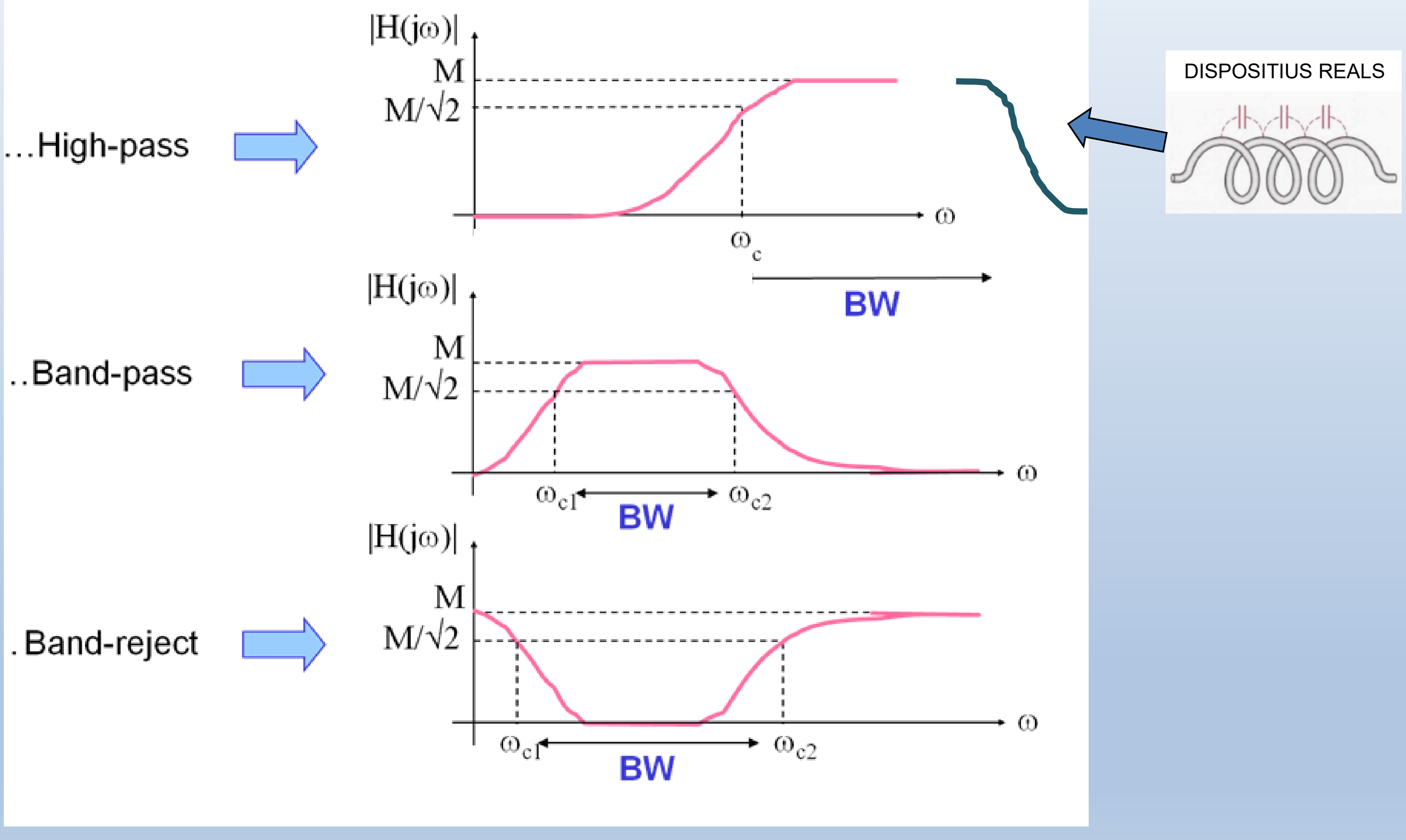
- There is no transition band.
- It cannot be built in analog (non-causal).

Real filter



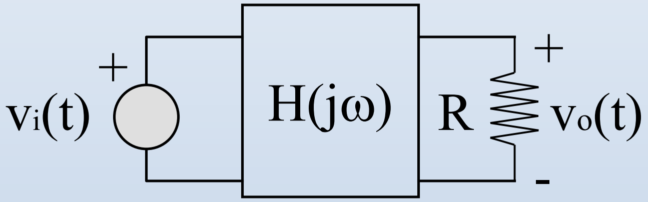
- There is transition band.
- By increasing the order the behaviour of the filter is closer to the ideal one.

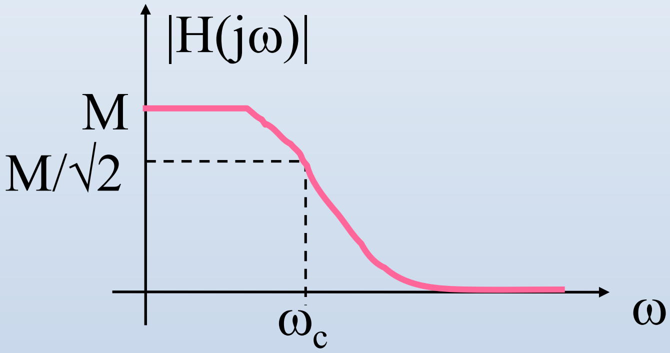
Filter parameters



Filter parameters

Which is the physical meaning of the cutoff frequency?





$v_i(t)=A\cos(\omega_1 t)$

$\omega_1 \ll \omega_c \Rightarrow v_o(t) = AM\cos(\omega_1 t + \angle H(j\omega_1))$

$P_R = (AM)^2/2R \equiv P_{RMAX}$

$\omega_1 = \omega_c \Rightarrow v_o(t) = AM/\sqrt{2}\cos(\omega_1 t + \angle H(j\omega_c))$

$P_R = (AM)^2/4R = P_{RMAX}/2$

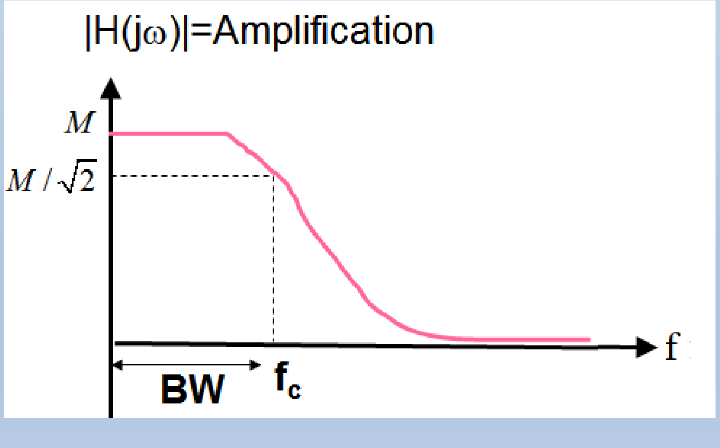
- ❑ The cutoff frequency is the frequency at which the power in the resistance is just the half of the one that would have been obtained with maximum amplification.

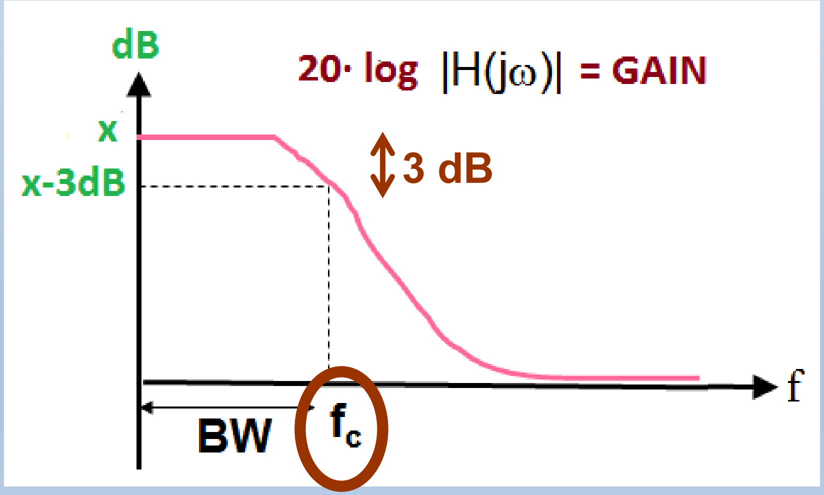
Logarithmic representation

$$G\ (\text{in dB}) = 10\cdot\log\left(\frac{P_2}{P_1}\right) dB = 10\cdot\log\left(\left|H(j\omega)\right|^2\right) = 20\cdot\log\left(\left|H(j\omega)\right|\right)$$

If $|(H(w)| = {}^{1}/_{\sqrt{2}} \quad \rightarrow \quad |(H(w)|^2 = {}^{1}/_{2} \quad \rightarrow \quad 10\log|(H(w)|^2$

$\rightarrow \quad 10\log(1) \; - 10\log(2) \;\; \cong \;\; -3\ dB$

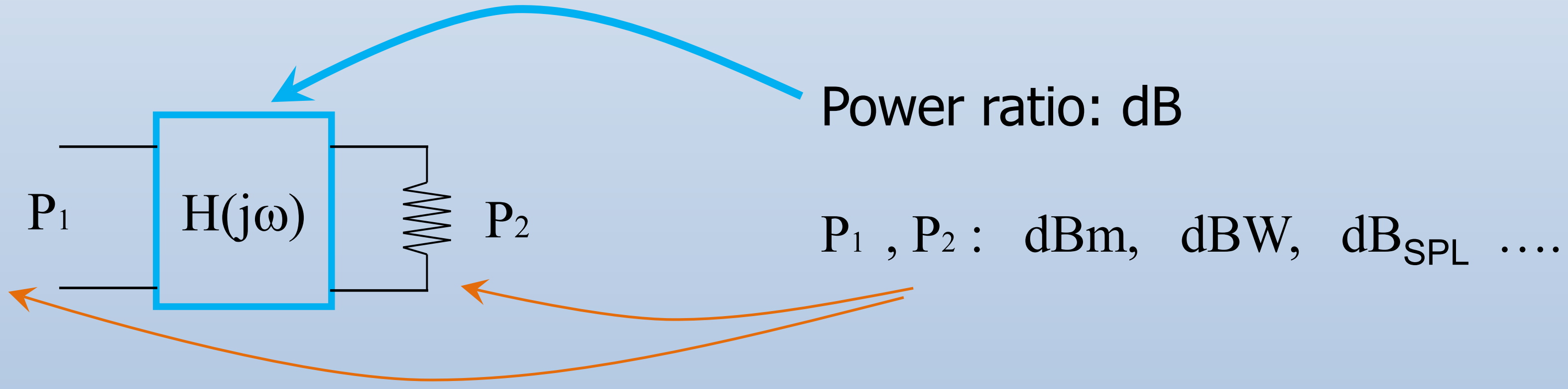




Logarithmic representation

dB: always referred to POWER

$$\text{G (in dB)} = 10\cdot\log\left(\frac{P_2}{P_1}\right) dB = 10\cdot\log\left(\left|H(j\omega)\right|^2\right) = 20\cdot\log\left(\left|H(j\omega)\right|\right)$$



Power ratio: dB

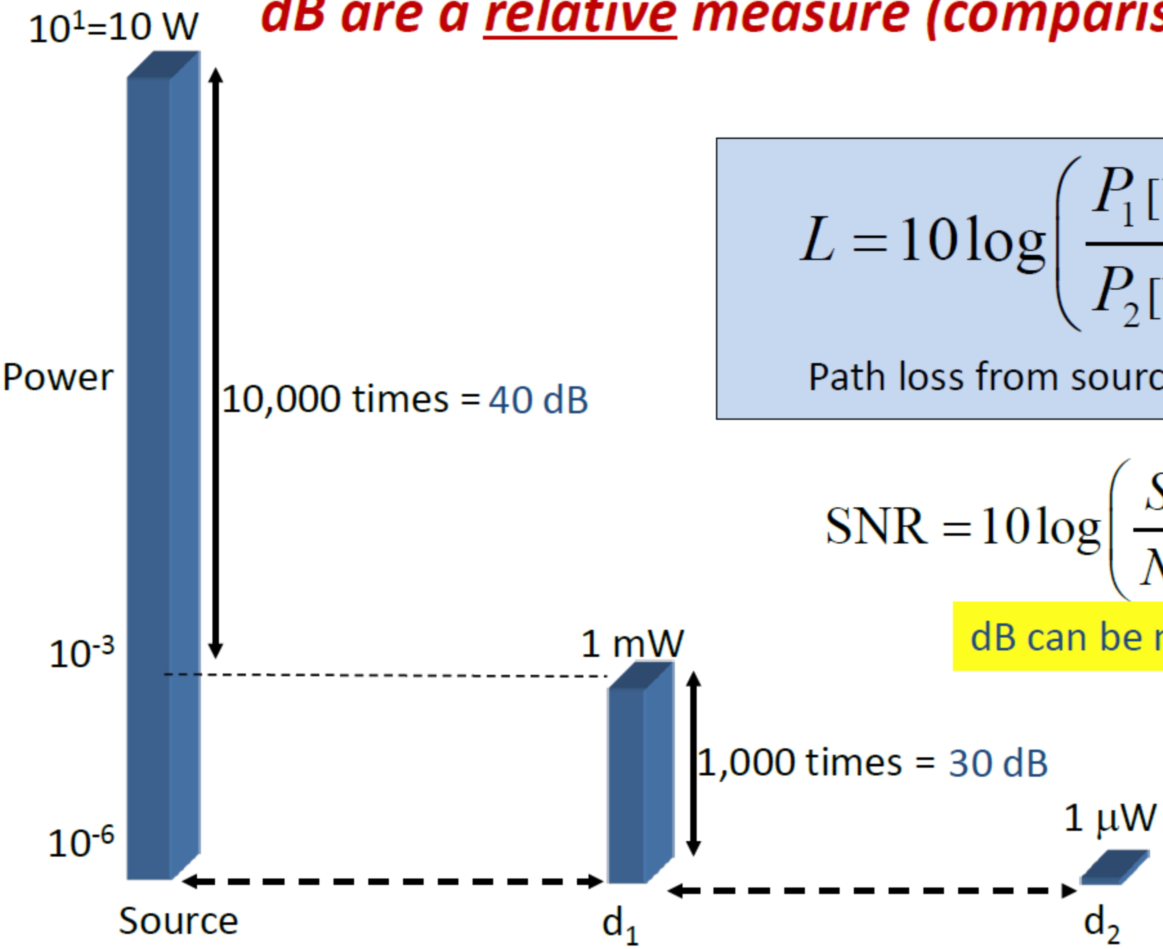
P_1 , P_2 : dBm, dBW, dB_{SPL} ….

V_2 *(in volts)* = V_1 *(in volts)* · A (*Amplification: dimensionless*)

P_2 (in dBxxx) = P_1 (in dBxxx) + G (in dB)

Unitats logarítmiques

dB are a relative measure (comparison) of powers:



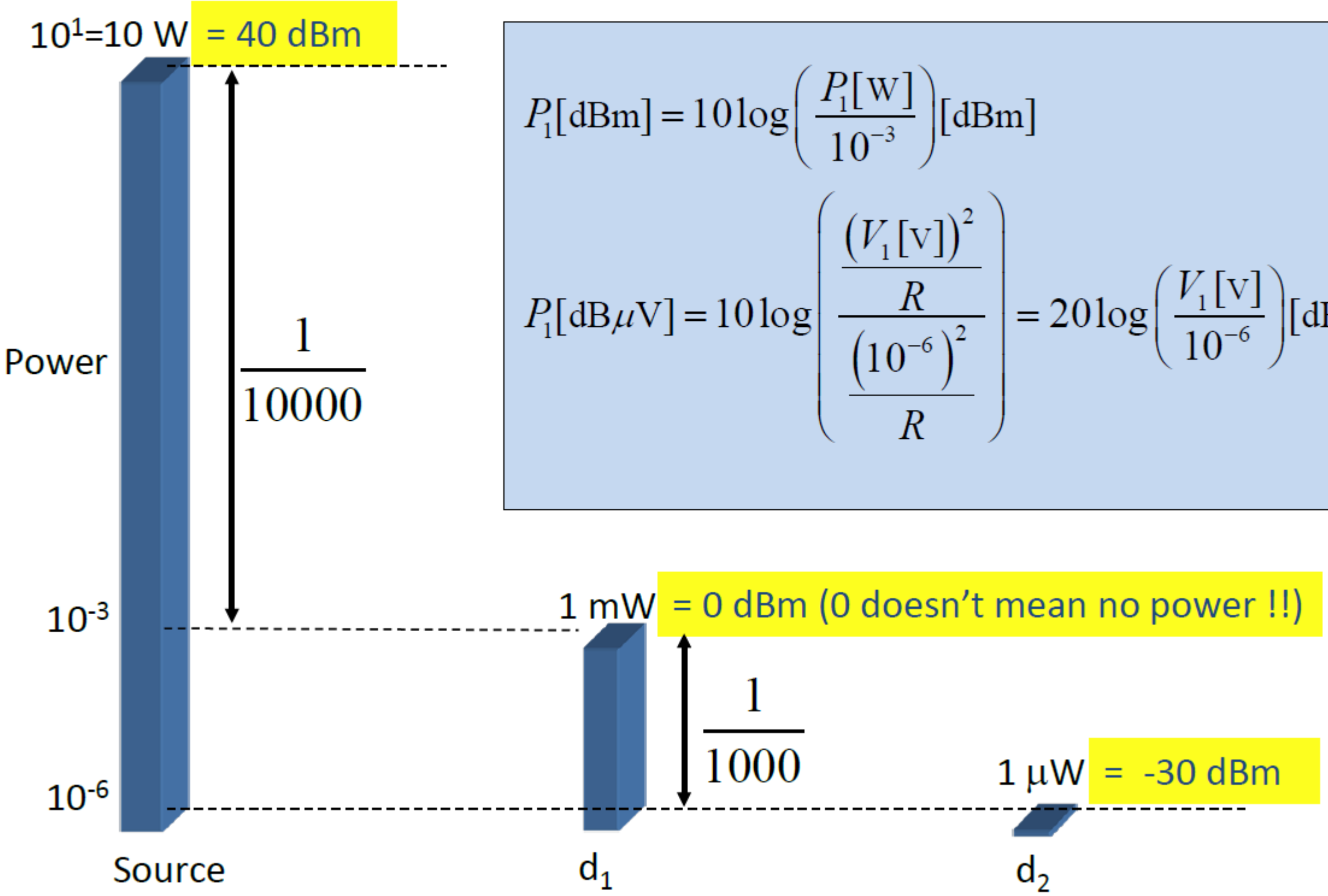
$$L = 10\log\left(\frac{P_1[\mathrm{W}]}{P_2[\mathrm{W}]}\right)[\mathrm{dB}]$$

Path loss from source to d_2 = 70dB

$$\mathrm{SNR} = 10\log\left(\frac{S[\mathrm{w}]}{N[\mathrm{w}]}\right)[\mathrm{dB}]$$

dB can be negative !!)

dBm, dBW, dbµV, dbV… (absolute measure of power)

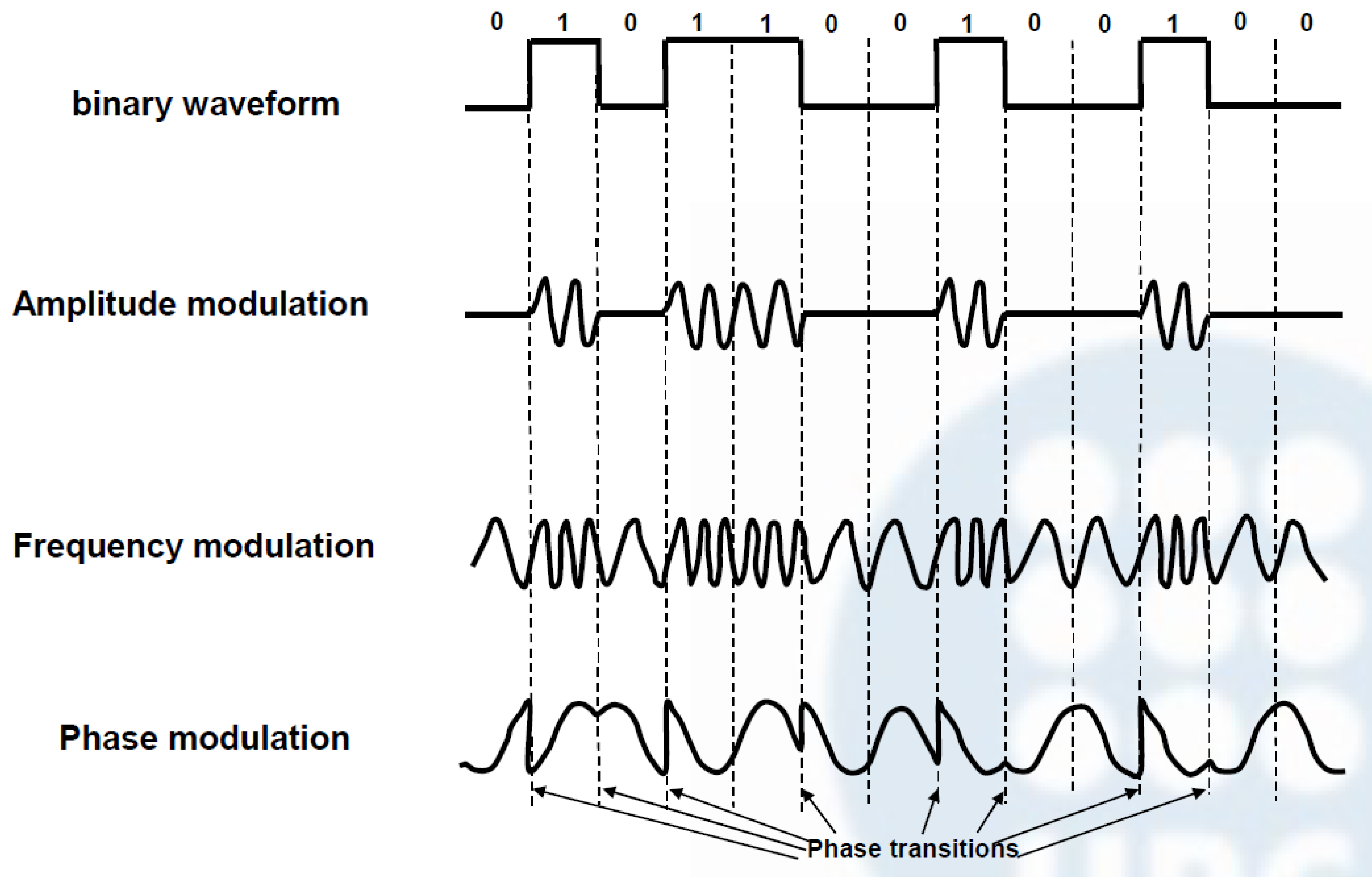


$$P_1[\text{dBm}] = 10\log\left(\frac{P_1[\text{W}]}{10^{-3}}\right)[\text{dBm}]$$

$$P_1[\text{dB}\mu\text{V}] = 10\log\left(\frac{\dfrac{(V_1[\text{V}])^2}{R}}{\dfrac{(10^{-6})^2}{R}}\right) = 20\log\left(\frac{V_1[\text{V}]}{10^{-6}}\right)[\text{dB}\mu\text{V}]$$

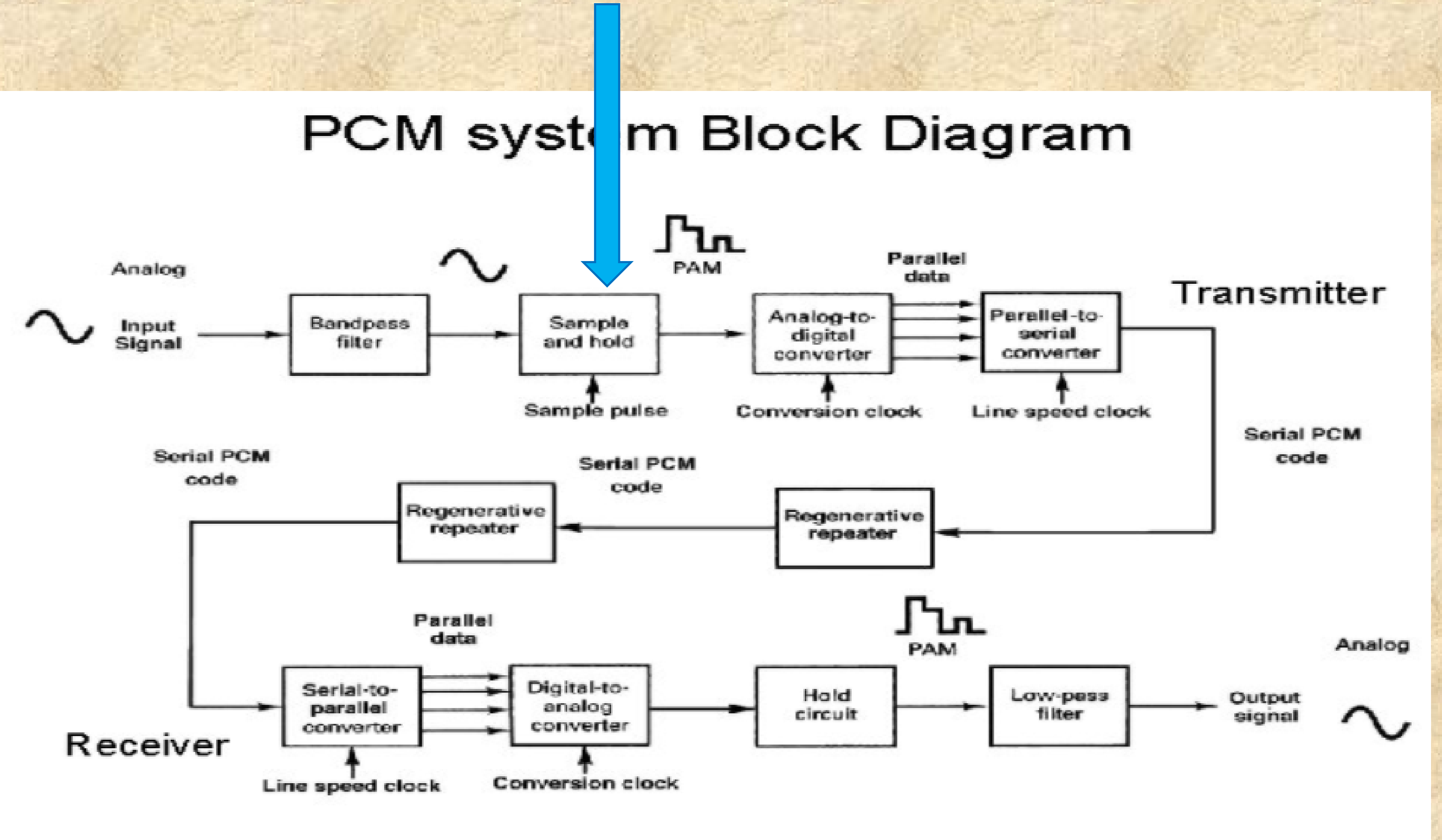
MODULE 4.2: FUNDAMENTALS

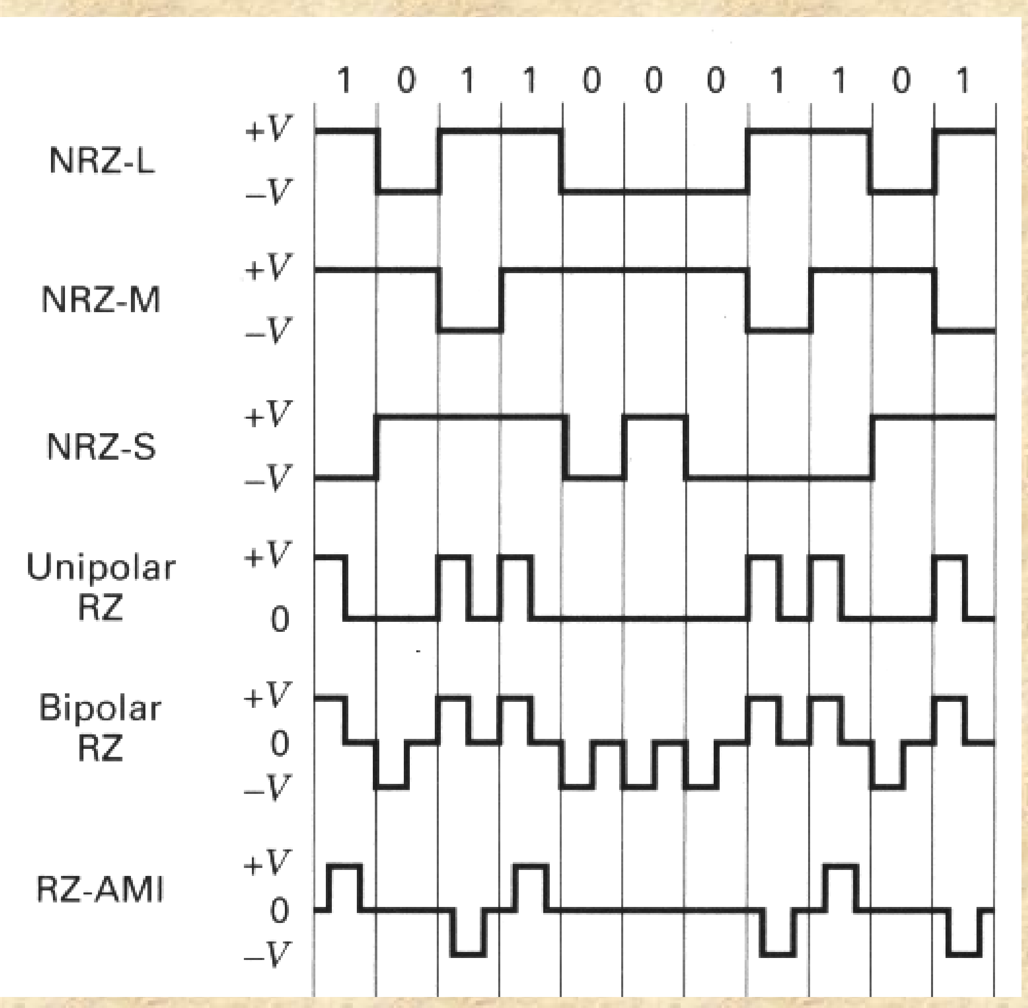
(BASEBAND TRANSMISSION. BUSES)



PCM . Pulse Code Modulation

Nyquist sampling condition:: fs ≥ 2 fmax





L : Level

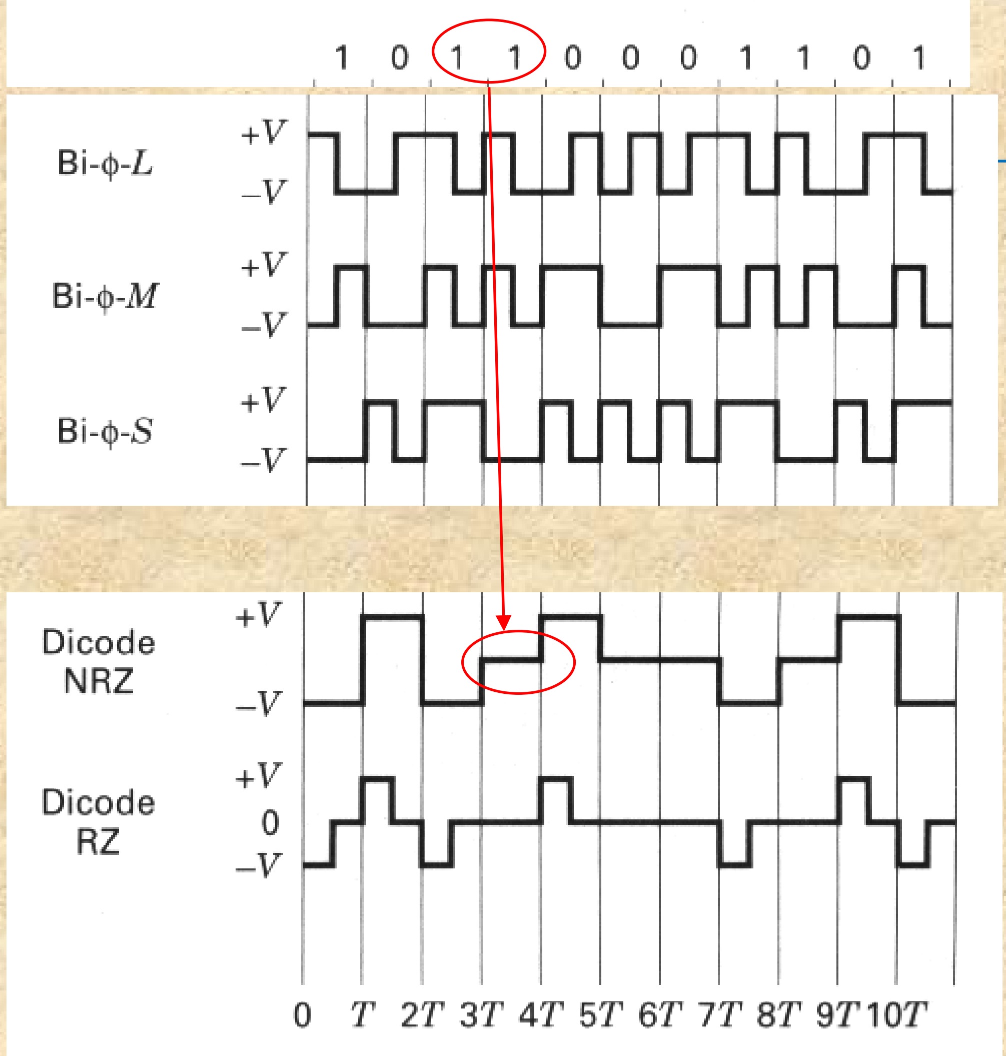
Changes in level:
M: Mark (“1”)
S: Space (“0”)

Only pulses for “1”

Opposite levels for “1” and “0”

Only pulses for “1”, but alternating level (AMI: Alternate Mask Inversion)

Phase encoded:



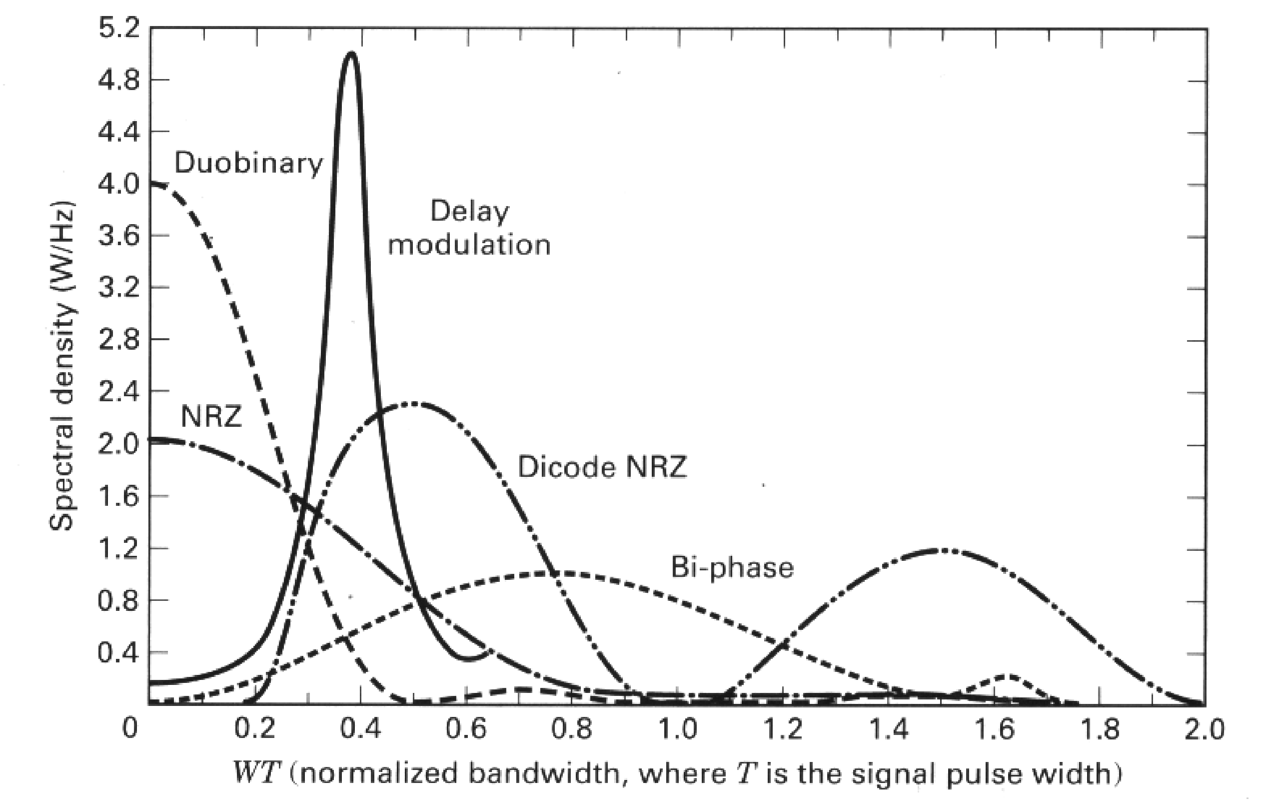
Manchester

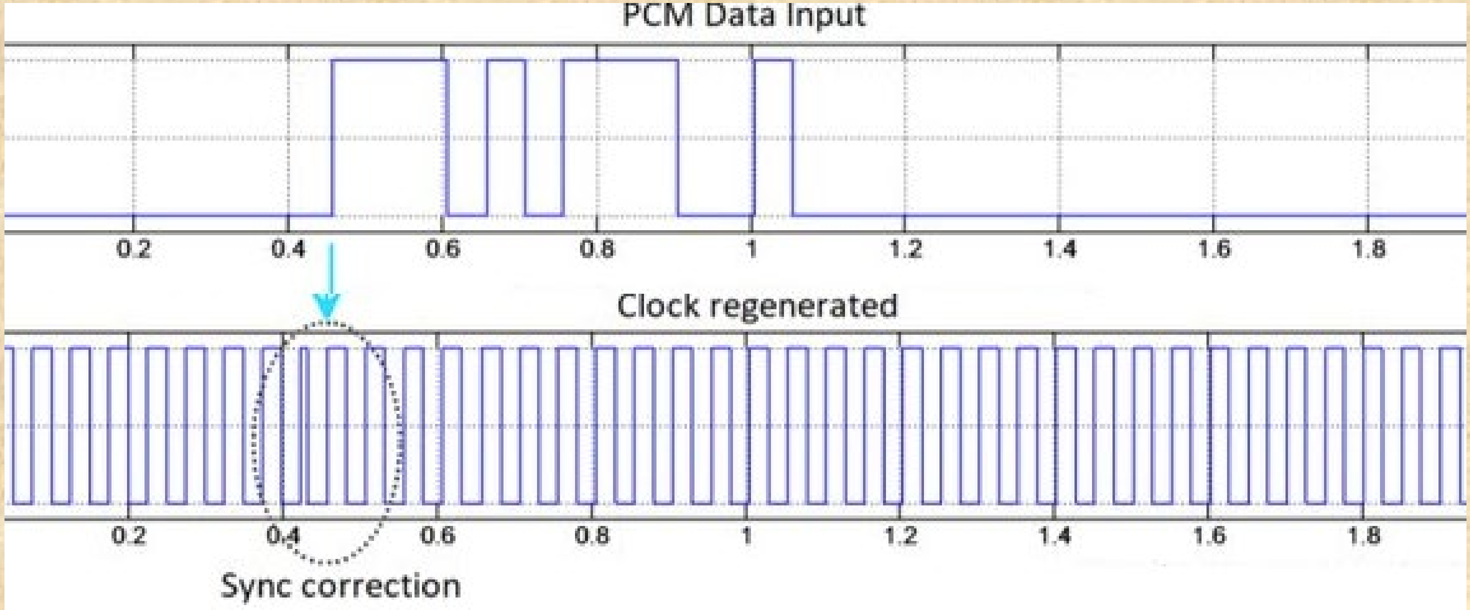
M and S: Always a transition at the beginning of each bit interval. The presence of second transition denotes M or S.

Dicode = Duobinary:
Some advantages in presence of ISI (Intersymbol Interference)

To choose a PCM waveform:

- DC component
- Clock synchronization
- Channels capable to invert signal polarity (differential encoding)
- Noise immunity
- Bandwidth occupancy

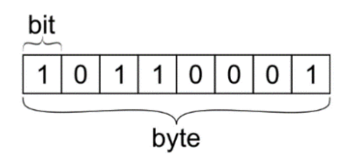


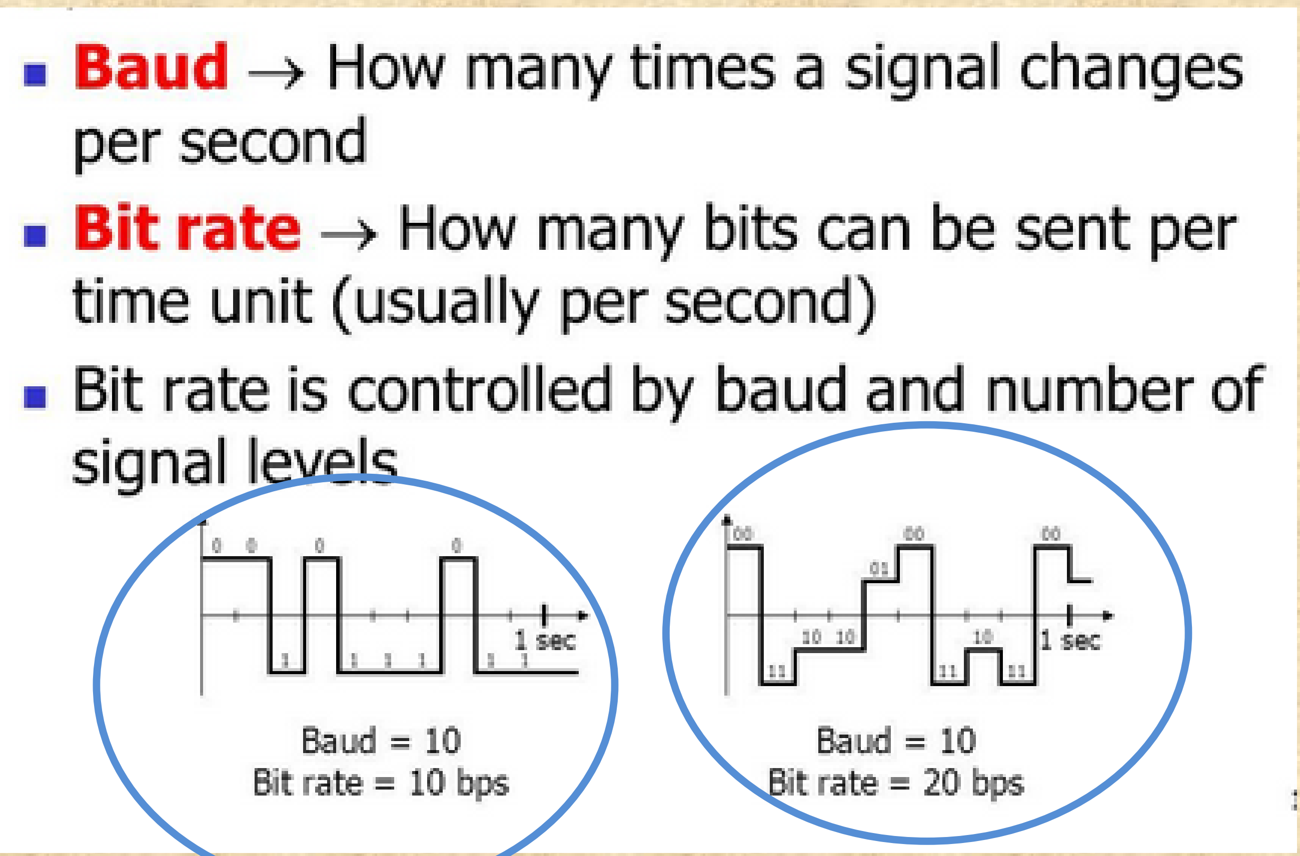

PCM Data Input
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Clock regenerated
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Sync correction

Baud: Number of ~~bytes~~ per second

words

✓





- **Baud** → How many times a signal changes per second
- **Bit rate** → How many bits can be sent per time unit (usually per second)
- Bit rate is controlled by baud and number of signal levels

Baud = 10
Bit rate = 10 bps

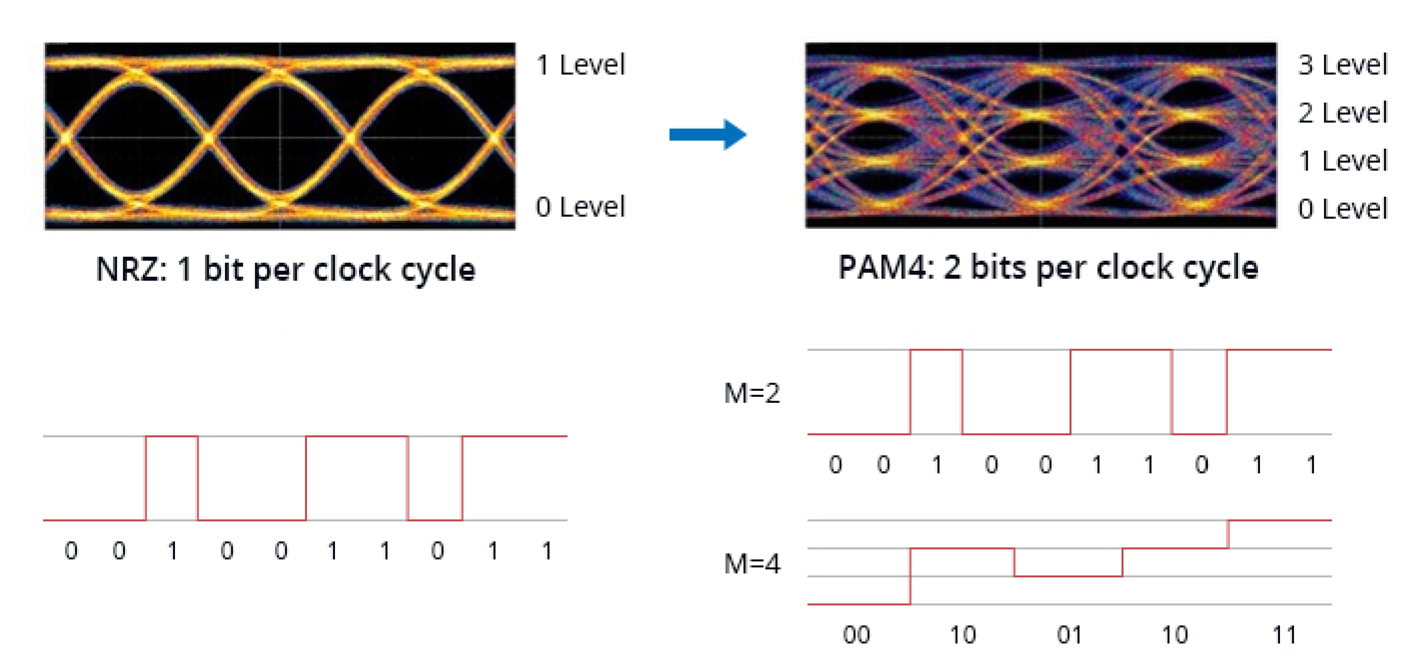
Baud = 10
Bit rate = 20 bps

✓

Number of symbols (conveying simultaneously multiple bits) per second

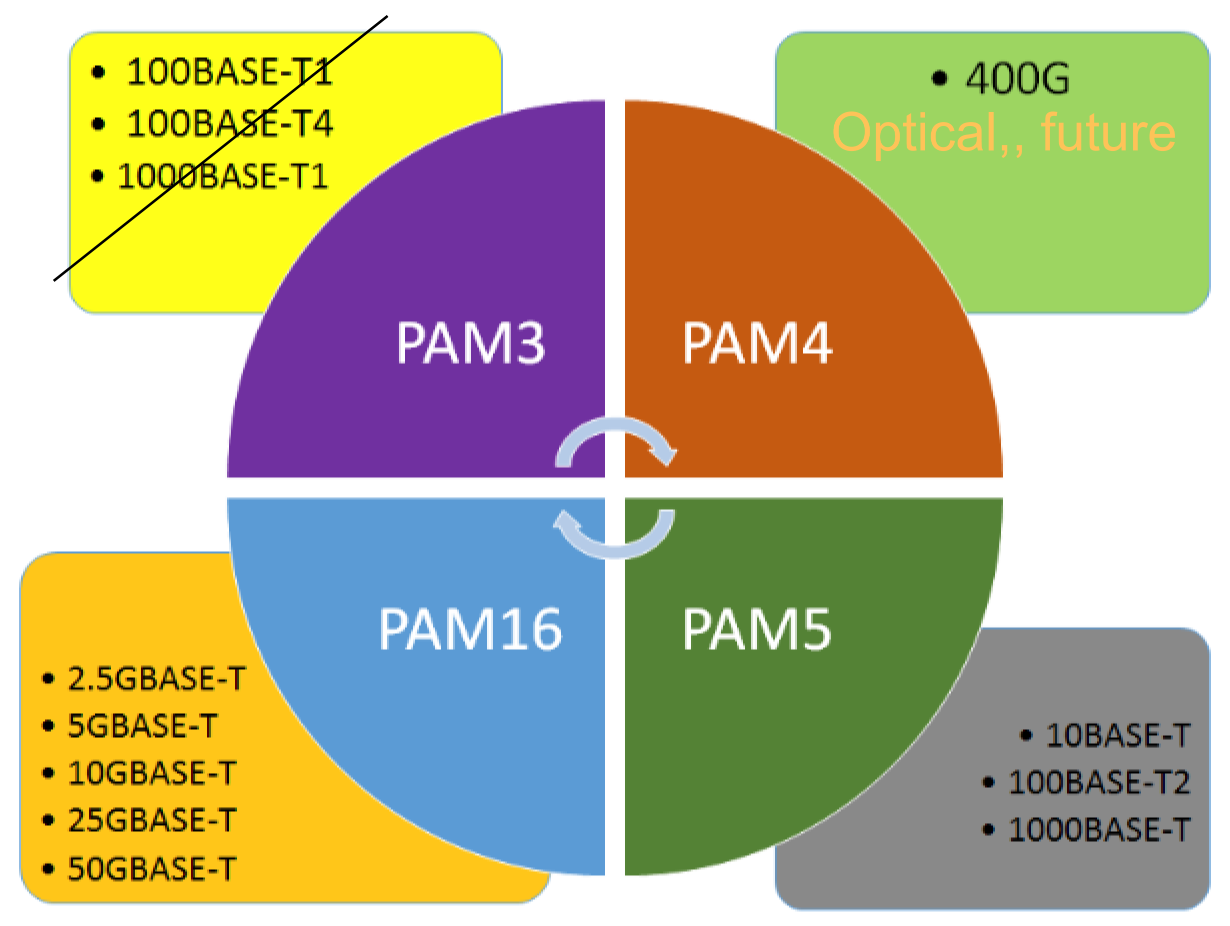
False, but often used, specially for network deployers

IEEE 802.3 : **ETHERNET**. **(Pulse amplitude modulation = PAM)**



PAM4 vs. NRZ

IEEE 802.3 : **ETHERNET**. **(PAM and network wiring (or cabling))**



- ~~100BASE-T1~~
- ~~100BASE-T4~~
- ~~1000BASE-T1~~

- 400G

Optical,, future

- 2.5GBASE-T
- 5GBASE-T
- 10GBASE-T
- 25GBASE-T
- 50GBASE-T

- 10BASE-T
- 100BASE-T2
- 1000BASE-T

100base T4 ,Cat 3 : obsolete
100base T2, Cat3, replaced by 100 base TX (Cat 5)
Etc….

Base "F": fiber, Base "?X" double couples of (?) : wires or fiber),….

MESSAGES, CHARACTERS, AND SYMBOLS

Character: sequence of bits (bit stream)

Symbol: : combinations of k-bits

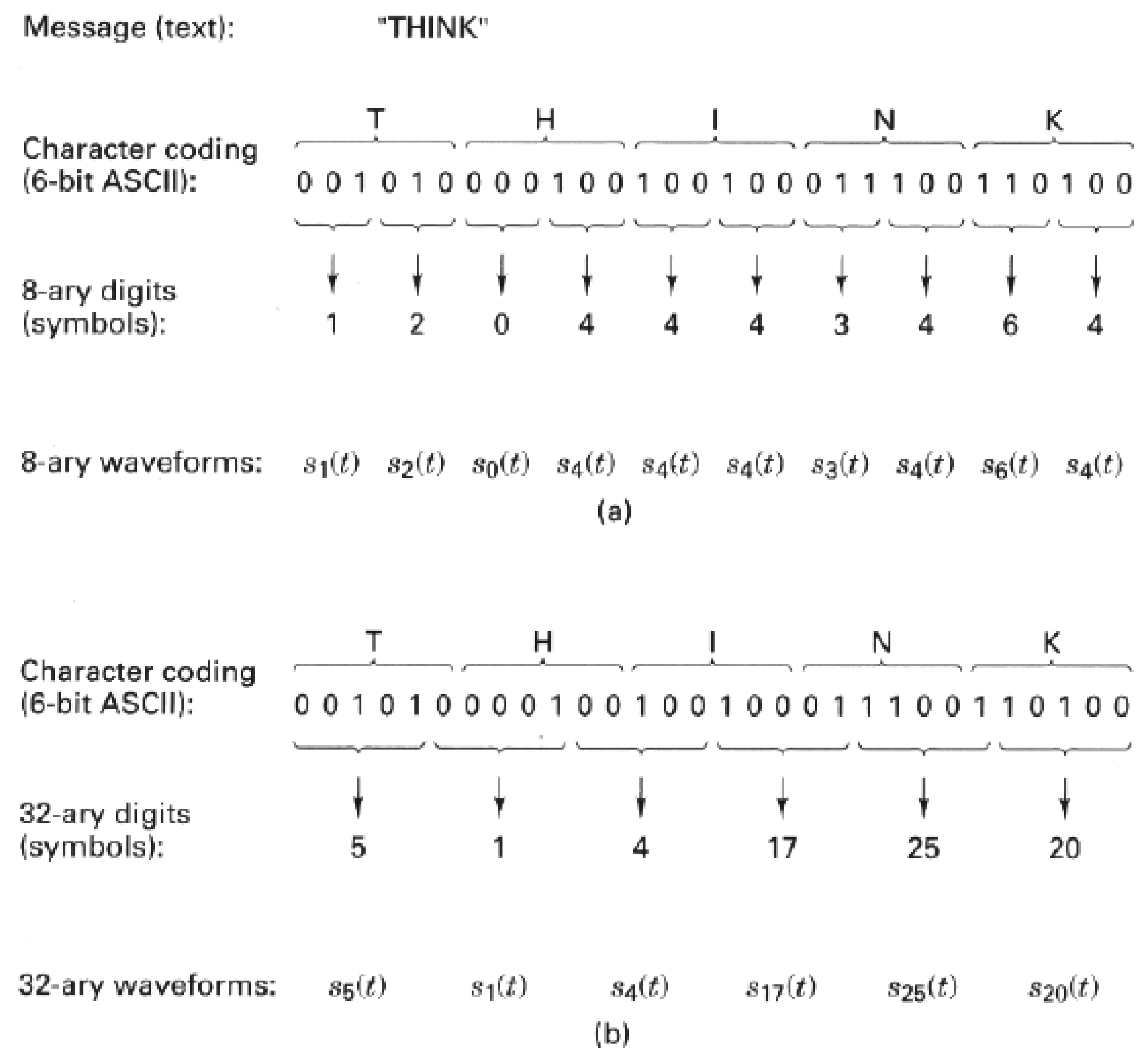


Figure 2.5 Messages, characters, and symbols. (a) 8-ary example. (b) 32-ary example.

BUSES

Fieldbus
Profibus,
CAN
IEEE 1394
Industrial Internet / Ethernet
…

… and manufacturer's "variations"

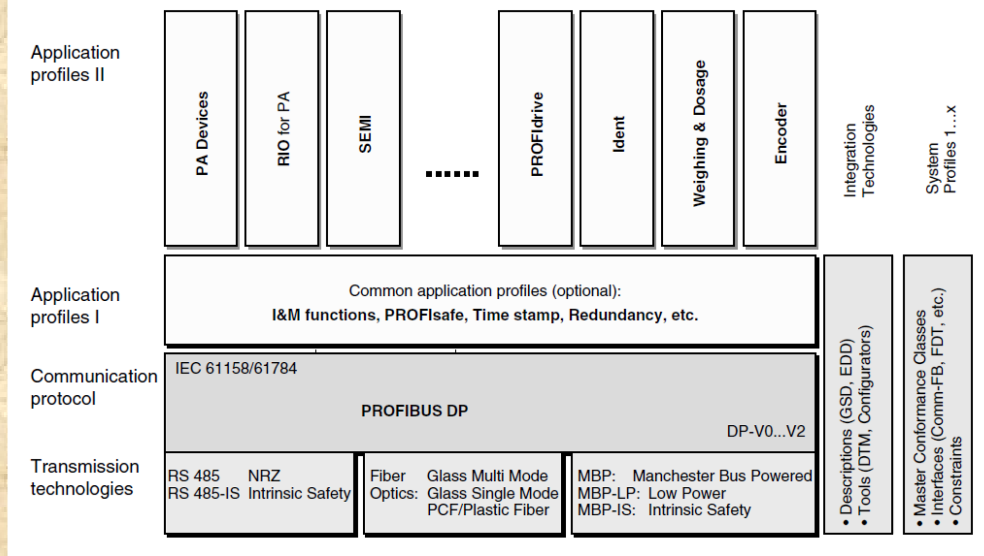
Criteria:

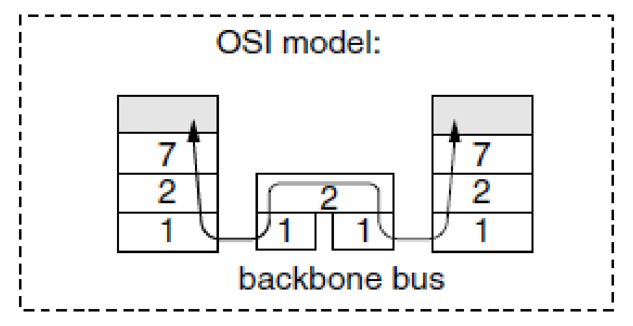
Safety,
Velocity,
Access method,
Number of nodes,
Length of the wires (if wired)
Error detection/correction,
Latency
…

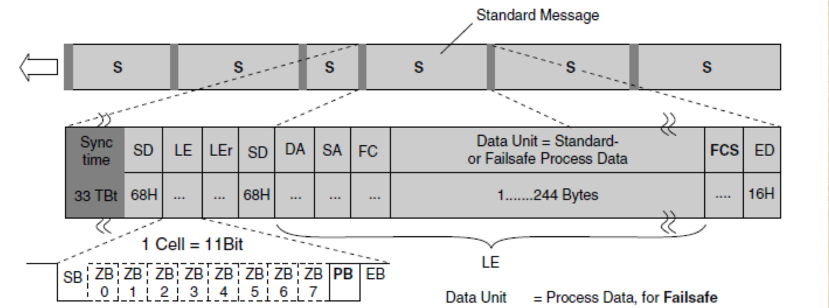
Often, the engineer is slave to choose the bus: pre-existing equipment (and manufacturers) is critical

PROFIBUS (PROcess FIeld BUS)

May be line, star or tree topology. Master-Slave
Token passing (Masters share the channel).
May be synchronous or asynchronous,
NRZ or Manchester encoding,…
(depends on the **PHY layer,** as
well as impedances and velocity **- kbps**)

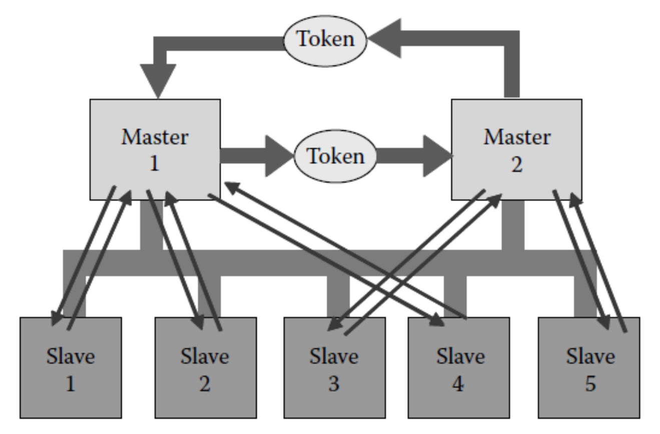


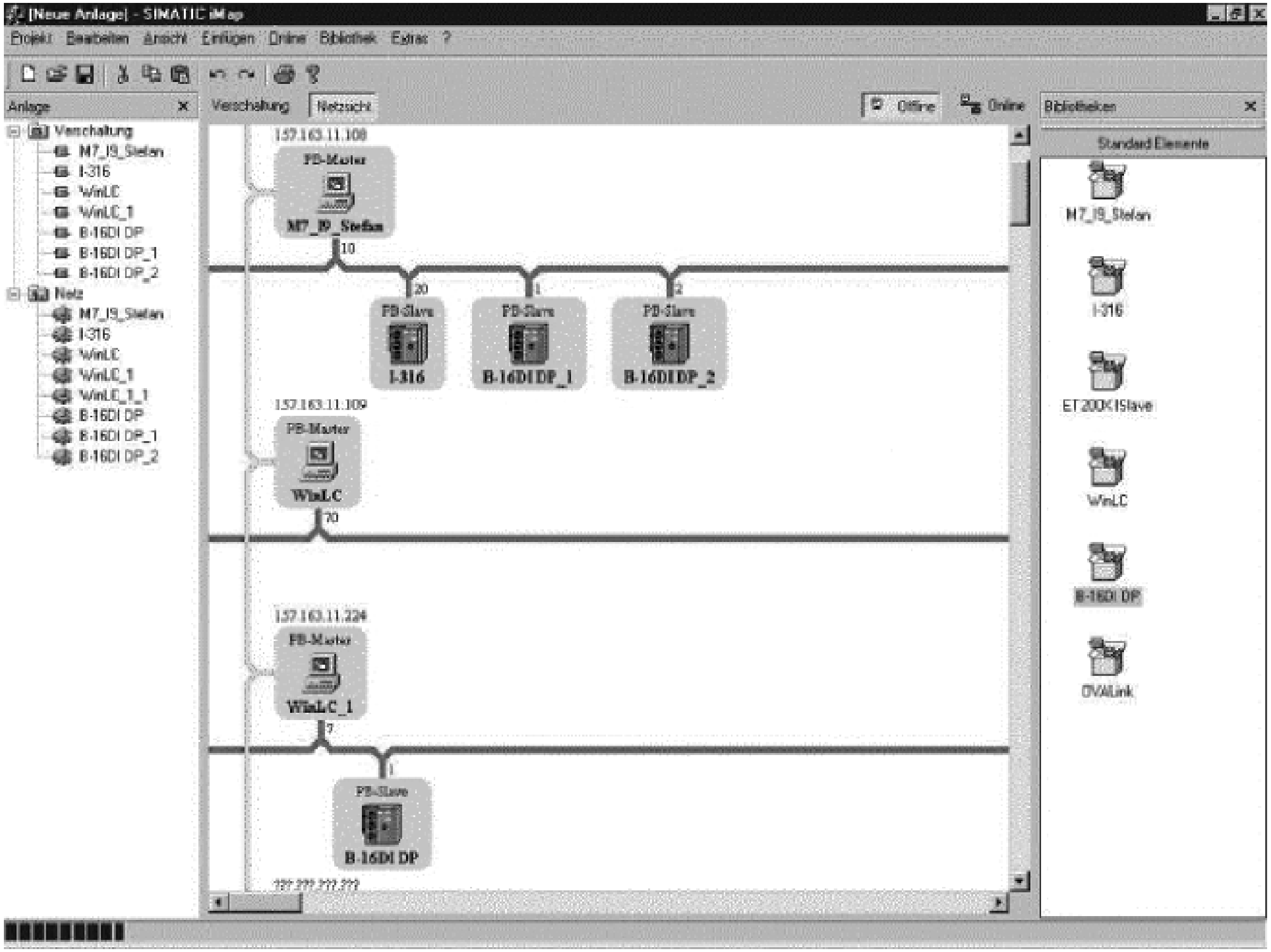




TBit = Clock-Bit = 1/Baudrate
SD = Start Delimiter (here SD2, var. data length)
LE = Length of Process Data
LEr = Repetion of Length; no Check in FCS
DA = Destination Address
SA = Source Address
FC = Function Code (Message type)

Data Unit = Process Data, for **Failsafe Process Data** also, max. 244 Bytes
FCS = Frame Checking Sequence (across data within LE)
ED = End Delimiter
SB = Start-Bit
ZBO...7 = Character-Bit
PB = (even) Parity Bit
EB = Stop-Bit




[Neue Anlage] - SIMATIC iMap
Projekt
Bearbeiten
Ansicht
Einfügen
Online
Bibliothek
Extras
?
Anlage
Verschaltung
M7_I9_Stefan
I-316
WinLC
WinLC_1
B-16DI DP
B-16DI DP_1
B-16DI DP_2
Netz
M7_I9_Stefan
I-316
WinLC
WinLC_1
WinLC_1_1
B-16DI DP
B-16DI DP_1
B-16DI DP_2
Verschaltung
Netzsicht
Offline
Online
157.163.11.108
PB-Master
M7_I9_Stefan
10
20
1
2
PB-Slave
I-316
PB-Slave
B-16DI DP_1
PB-Slave
B-16DI DP_2
157.163.11.109
PB-Master
WinLC
70
157.163.11.224
PB-Master
WinLC_1
7
1
PB-Slave
B-16DI DP
???.???.???.???
Bibliotheken
Standard Elemente
M7_I9_Stefan
I-316
ET 200X ISlave
WinLC
B-16DI DP
DVALink

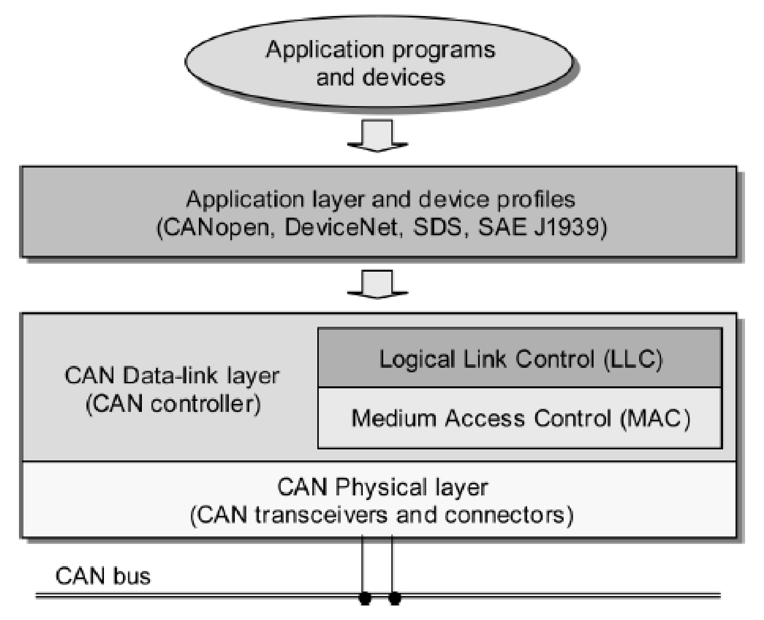
CONTROLLER AREA NETWORK (CAN)

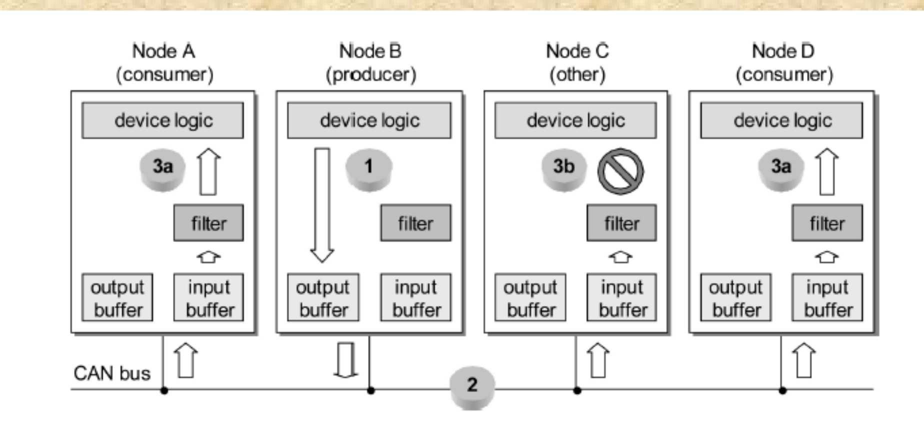
Robert Bosch GmbH,

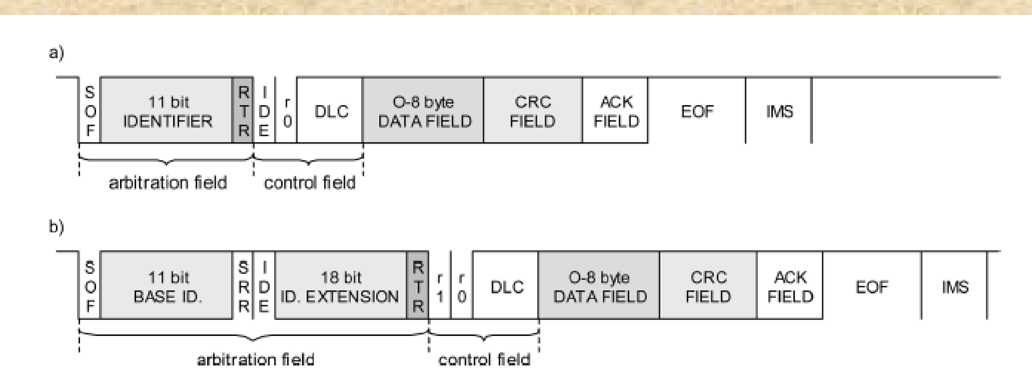
BUS, CSMA/BA (Collision Sense Multiple Access/Bitwise Arbitration): A simultaneous access of two nodes is stopped, and according to the destination address it is selected the first to transmit.

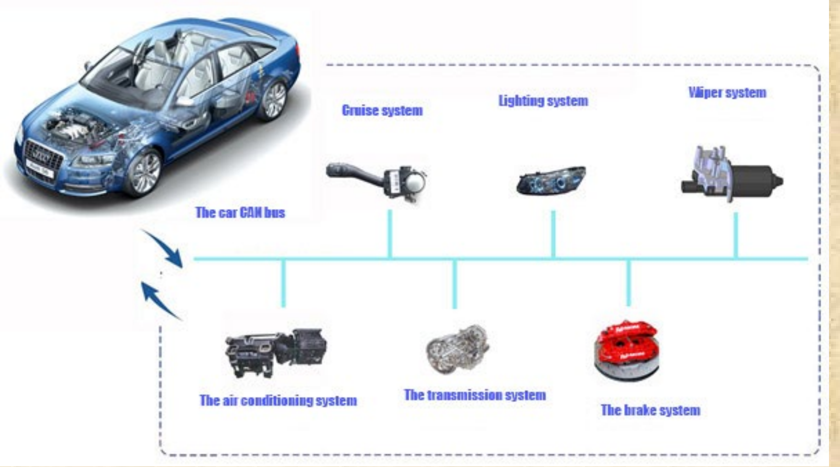
ISO 11898-3: 125 kbps, 10 kbps (5 km).

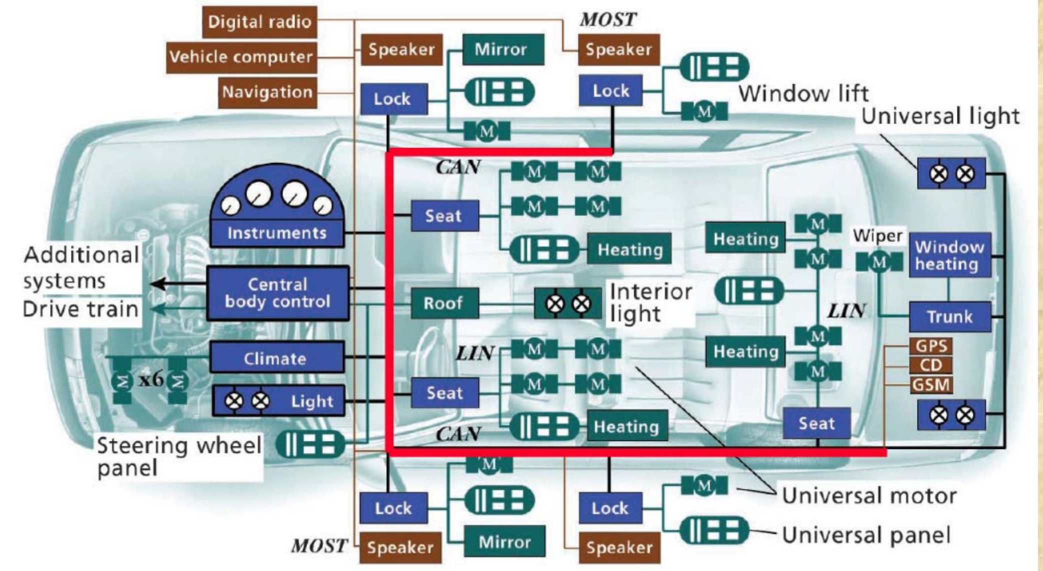
ISO 11898-2: High velocity CAN: 120 Ω. Up to 1 Mbps (30m), 5 Mbit/s on CAN-FD








Cruise system
Lighting system
Wiper system
The car CAN bus
The air conditioning system
The transmission system
The brake system


Digital radio
Vehicle computer
Navigation
MOST
Speaker
Mirror
Speaker
Lock
Lock
Window lift
Universal light
CAN
Seat
Instruments
Heating
Heating
Wiper
Window heating
Additional systems
Drive train
Central body control
Roof
Interior light
LIN
Trunk
Climate
LIN
Heating
GPS
CD
GSM
x6
Light
Seat
Heating
Seat
CAN
Steering wheel panel
M
Lock
Lock
Universal motor
Mirror
Universal panel
MOST
Speaker
Speaker

Modelo: **NI-9881**

Número de Parte: 781673-02

Ficha Técnica y Especificaciones

€ 987,00

1

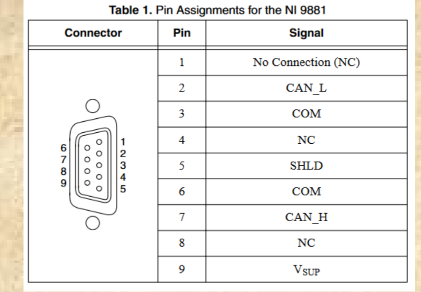
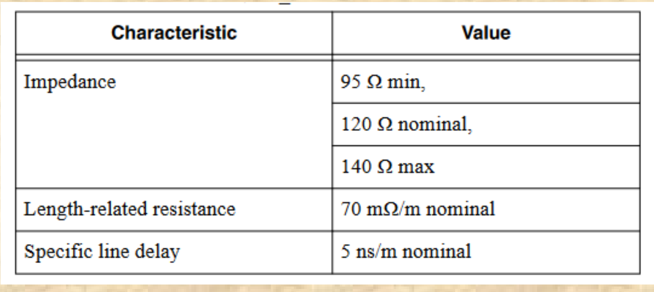


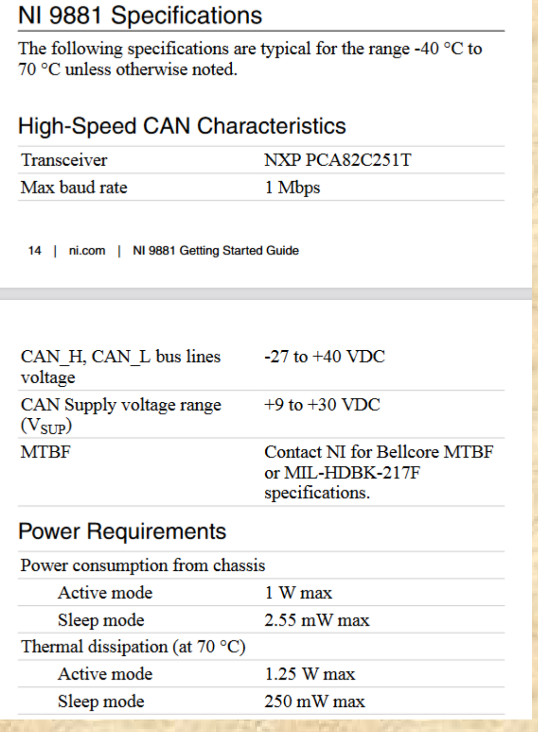
Table 1. Pin Assignments for the NI 9881

Connector	Pin	Signal
	1	No Connection (NC)
	2	CAN_L
	3	COM
	4	NC
	5	SHLD
	6	COM
	7	CAN_H
	8	NC
	9	V_{SUP}



Characteristic	Value
Impedance	95 Ω min, 120 Ω nominal, 140 Ω max
Length-related resistance	70 mΩ/m nominal
Specific line delay	5 ns/m nominal

I(n this case, the R is not for impedance matching –power transfer)



NI 9881 Specifications

The following specifications are typical for the range -40 °C to 70 °C unless otherwise noted.

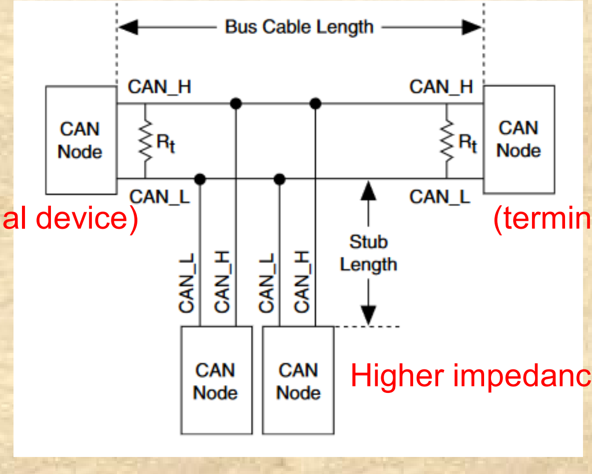
High-Speed CAN Characteristics

Transceiver	NXP PCA82C251T
Max baud rate	1 Mbps

CAN_H, CAN_L bus lines voltage	-27 to +40 VDC
CAN Supply voltage range (V_{SUP})	+9 to +30 VDC
MTBF	Contact NI for Bellcore MTBF or MIL-HDBK-217F specifications.

Power Requirements

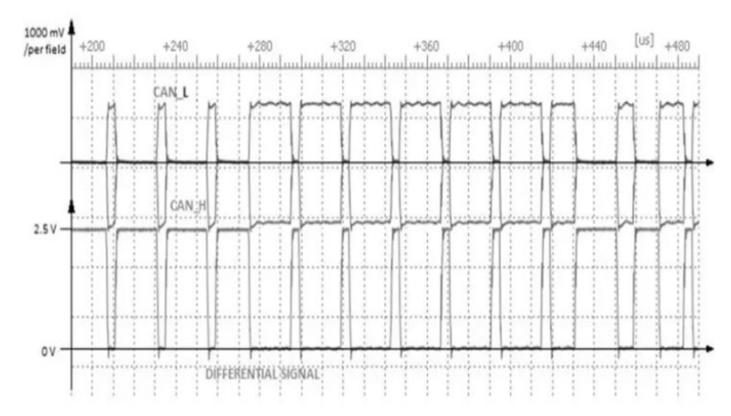
Power consumption from chassis	
Active mode	1 W max
Sleep mode	2.55 mW max
Thermal dissipation (at 70 °C)	
Active mode	1.25 W max
Sleep mode	250 mW max

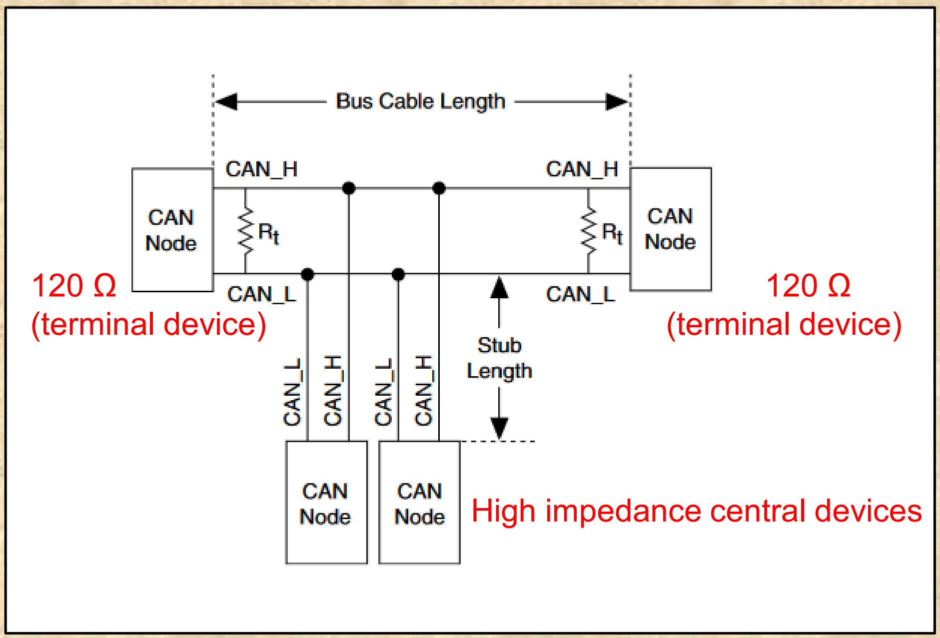


120 Ω
(terminal device)

120 Ω
(terminal device)

Higher impedance central devices

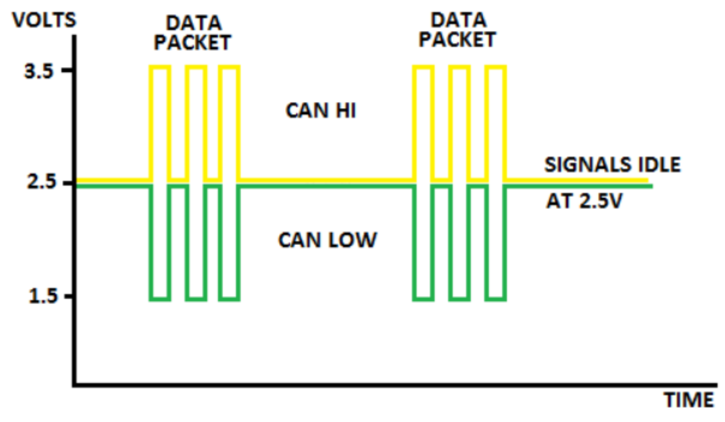


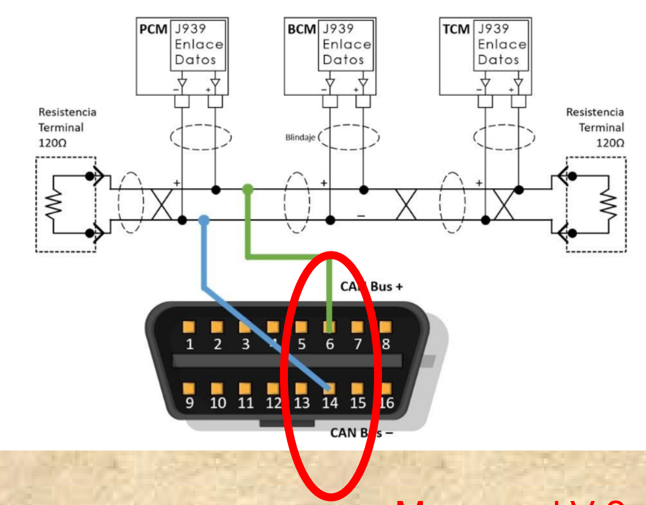


120 Ω
(terminal device)

120 Ω
(terminal device)

High impedance central devices

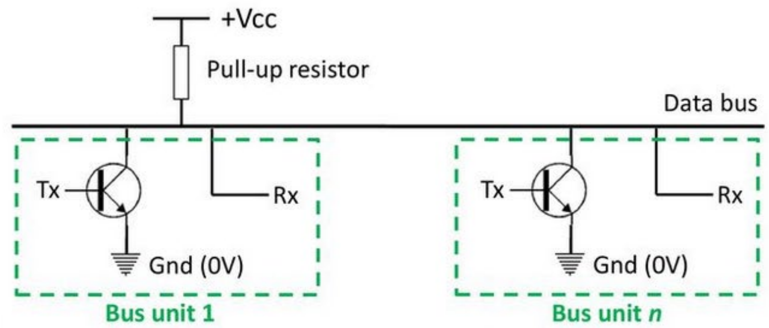




Measured V ?

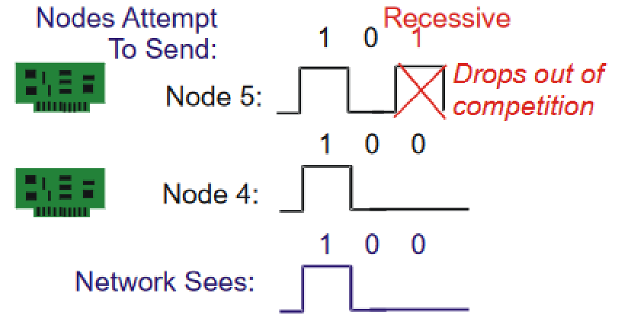
Bitwise Arbitration

Bus states: Recessive: when no nodes are communicating (Dominant overrides it)



Truth table

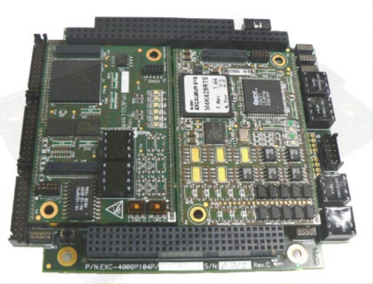
Station		**Bus value**
1	2	
0	0	**0**
0	1	**0**
1	0	**0**
1	1	**1**

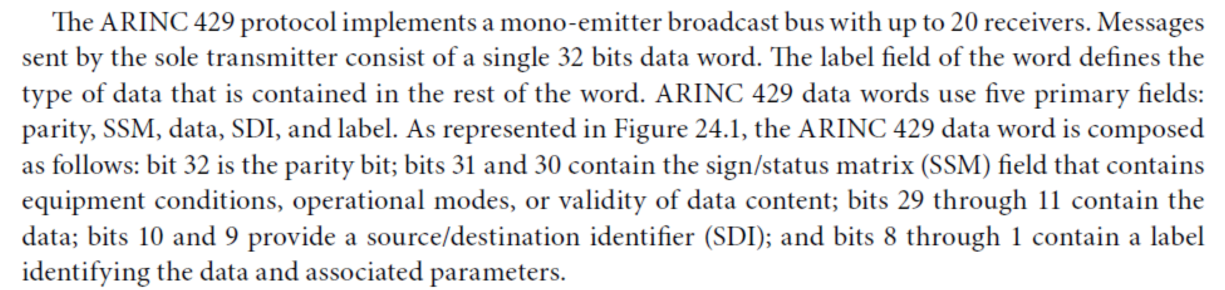


- **Operation**
  - Each node is assigned a unique identification number
  - All nodes wishing to transmit compete for the channel by transmitting a binary signal based on their identification value
  - A node drops out the competition if it detects a dominant state while transmitting a passive state
  - Thus, the node with the lowest identification value wins

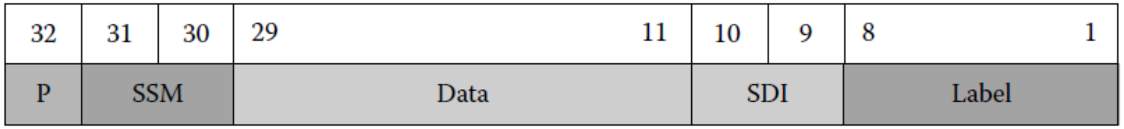
Aeronautical Radio, Inc. (ARINC). Private corporation

Single transmitter, 1-20 receivers (BUS)
Low speed: 12,5 kHz, High Speed: 100 kHz
Bipolar RZ
Message sending: FIFO or SCHEDULED
C/ C++; LabVIEW, MATLAB,,…





The ARINC 429 protocol implements a mono-emitter broadcast bus with up to 20 receivers. Messages sent by the sole transmitter consist of a single 32 bits data word. The label field of the word defines the type of data that is contained in the rest of the word. ARINC 429 data words use five primary fields: parity, SSM, data, SDI, and label. As represented in Figure 24.1, the ARINC 429 data word is composed as follows: bit 32 is the parity bit; bits 31 and 30 contain the sign/status matrix (SSM) field that contains equipment conditions, operational modes, or validity of data content; bits 29 through 11 contain the data; bits 10 and 9 provide a source/destination identifier (SDI); and bits 8 through 1 contain a label identifying the data and associated parameters.



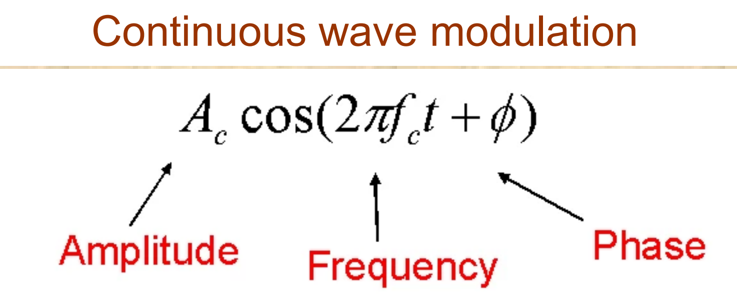
32	31	30	29 … 11	10	9	8 … 1
P	SSM		Data	SDI		Label

FIGURE 24.1 ARINC 429 data word.

MODULE 4.3: FUNDAMENTALS

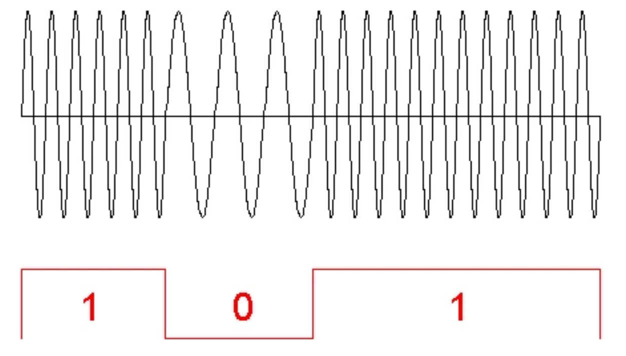
(MODULATIONS)

CW MODULATIONS: ANALOG and DIGITAL



$$A_c \cos(2\pi f_c t + \phi)$$

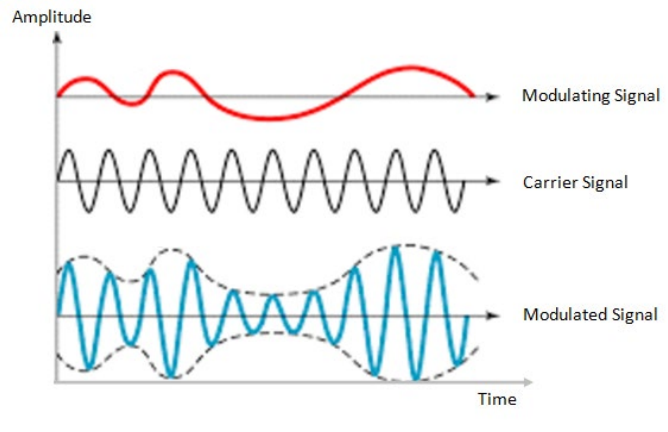
- **ANALOG:**
  - **Amplitude modulation (AM)**
    - DSB
    - SSB
    - VSB
    - QAM (…)
  - **Angle Modulation** (nonlinear – or exponential- modulation)
    - FM
    - PM



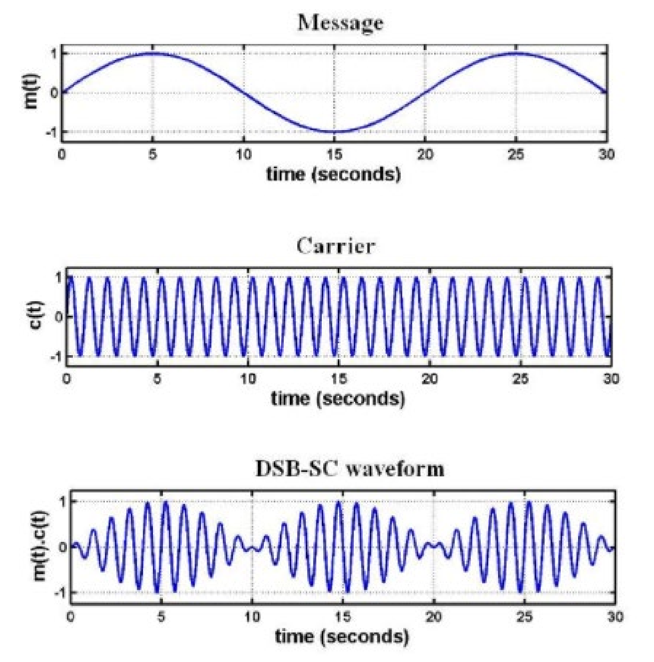
- **DIGITAL**
  - ASK
  - FSK (MSK) –nonlinear-
  - PSK
  - QAM

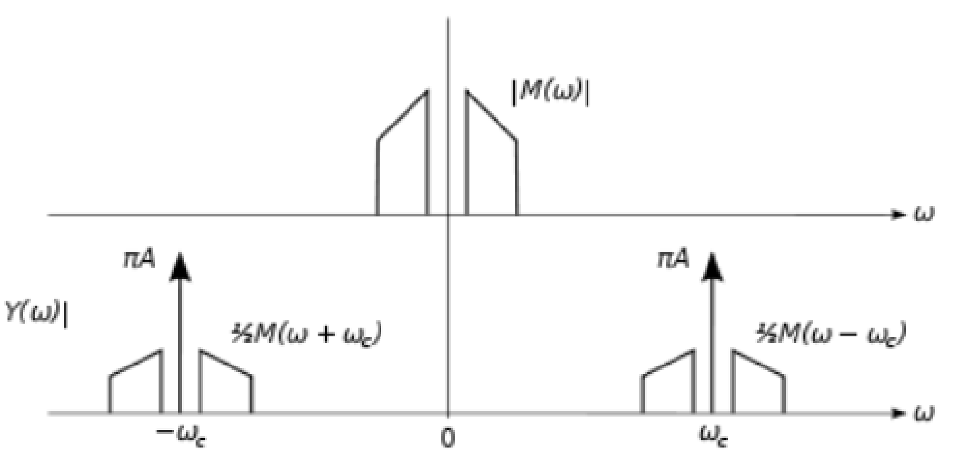
Amplitude modulation

DSB Double side-band



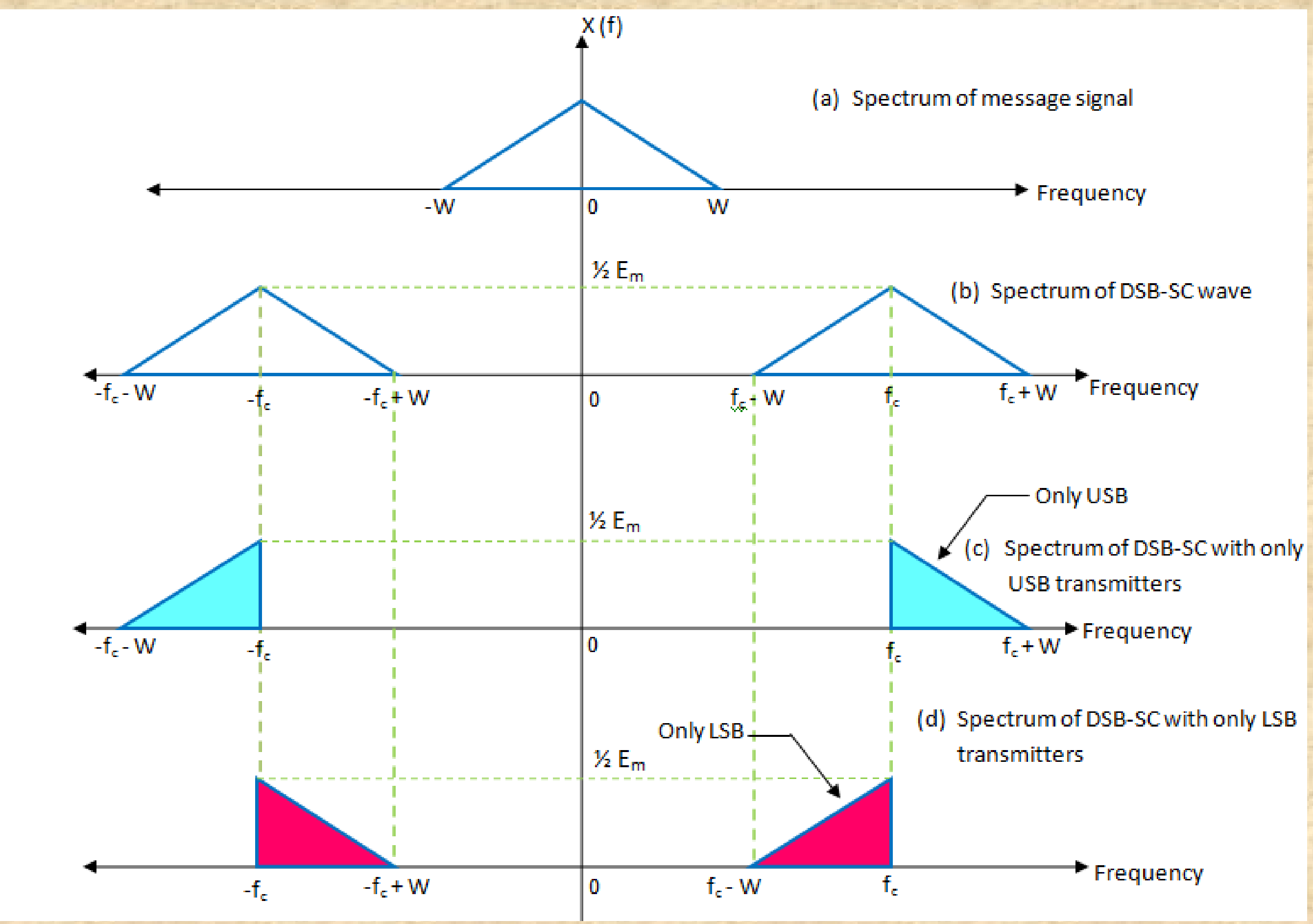
DSB-SC (suppressed-carrier)



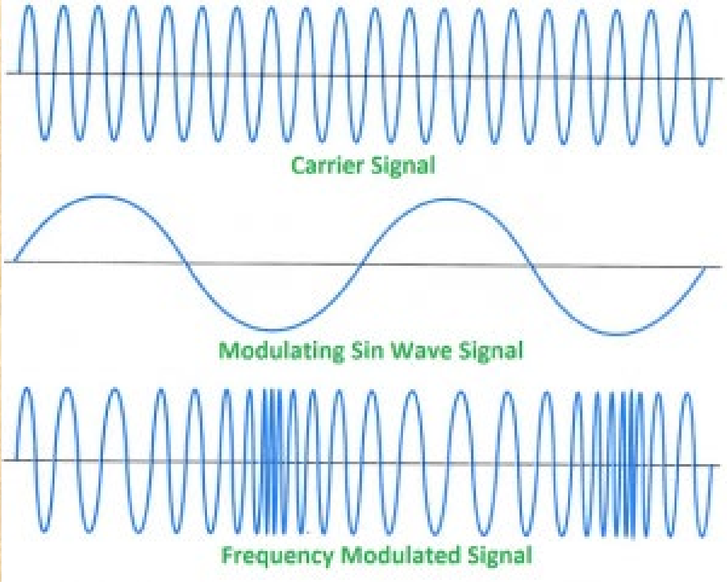


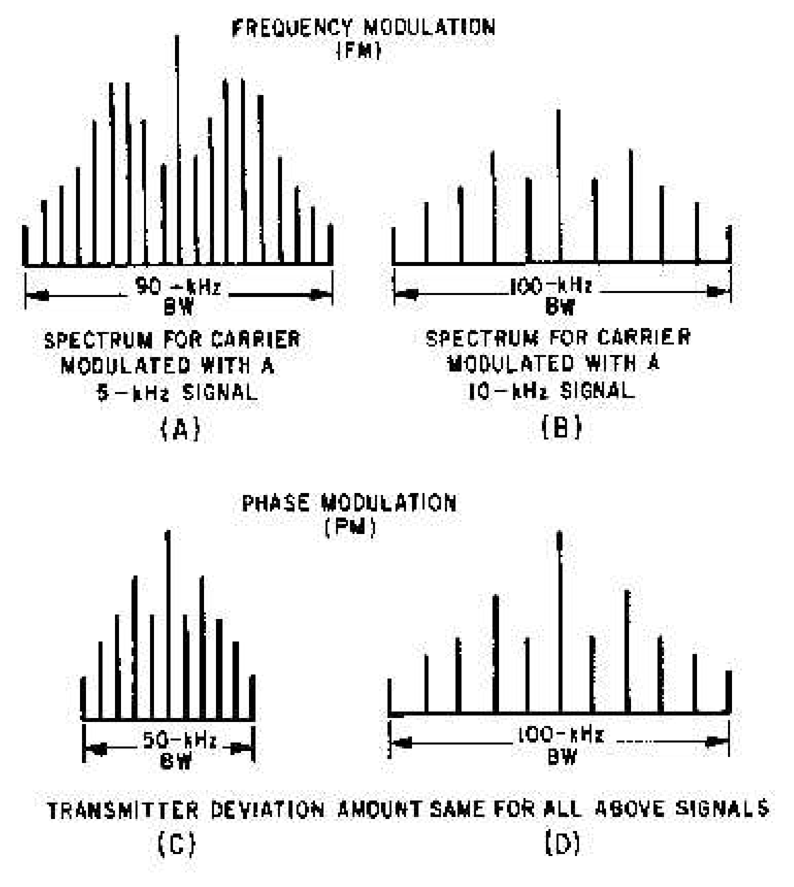
Amplitude modulation

SSB Single sideband (upper or lower)



FM : Frequency Modulation

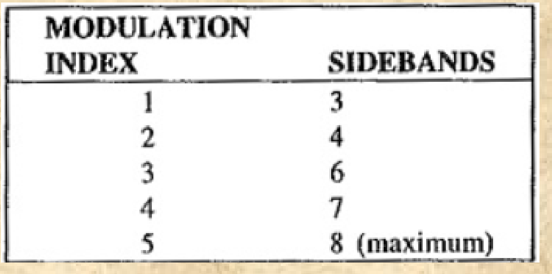




modulation index for FM,

$$v = A \sin(\omega_c t + m_f \sin \omega_m t)$$

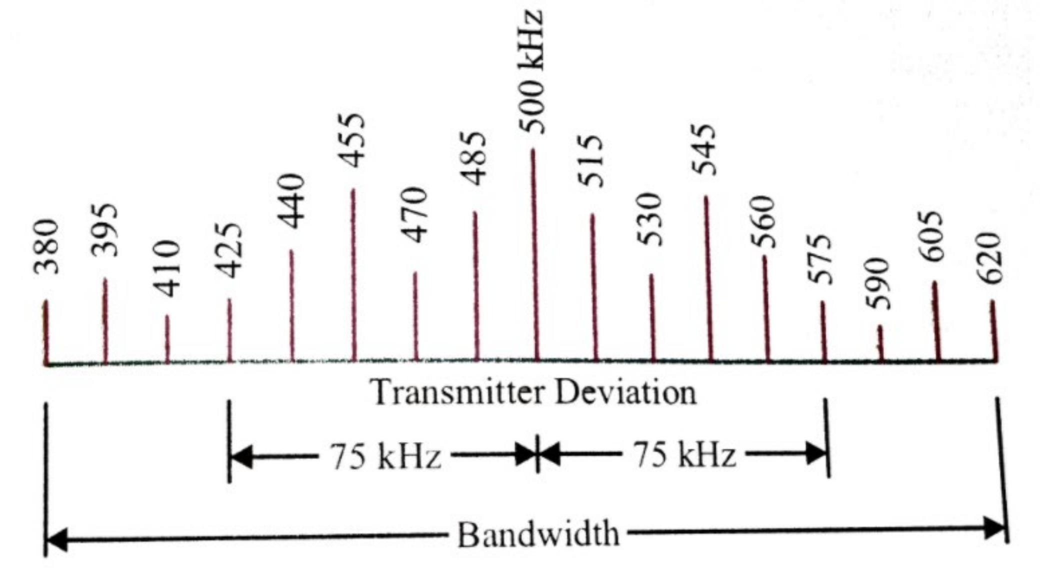
$$m_f = \frac{\text{(maximum) frequency deviation}}{\text{modulating frequency}}$$



MODULATION INDEX	SIDEBANDS
1	3
2	4
3	6
4	7
5	8 (maximum)

Commercial FM: The modulating frequency is 15 kHz and the deviation frequency is 75 kHz

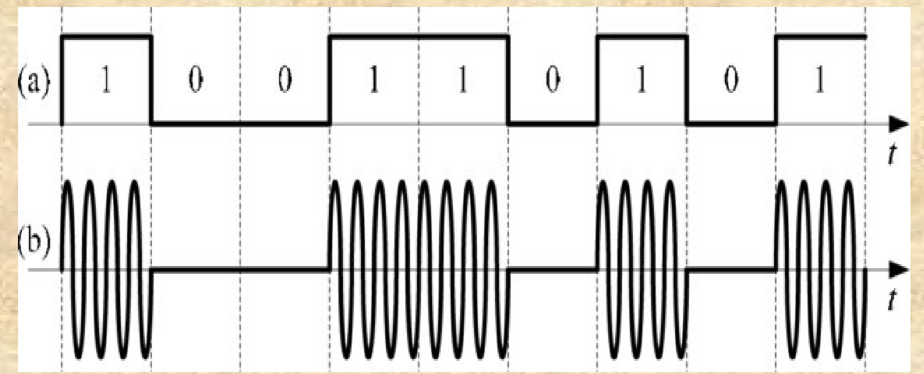
$$MI = \frac{\Delta f}{f_m} = 5$$

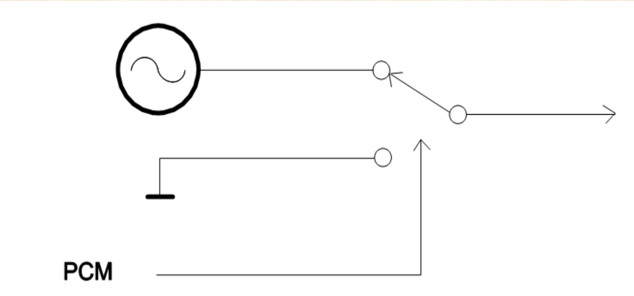


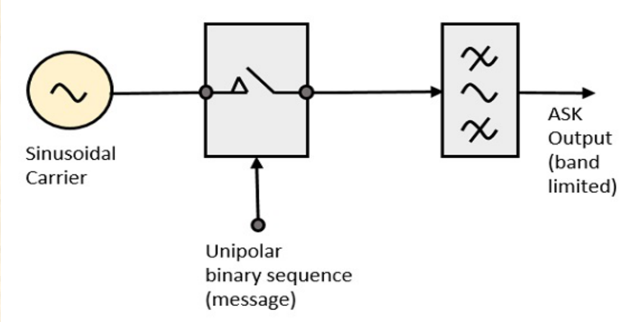
If the carrier frequency is 500kHz

Digital CW modulations (bandpass digital transmission)

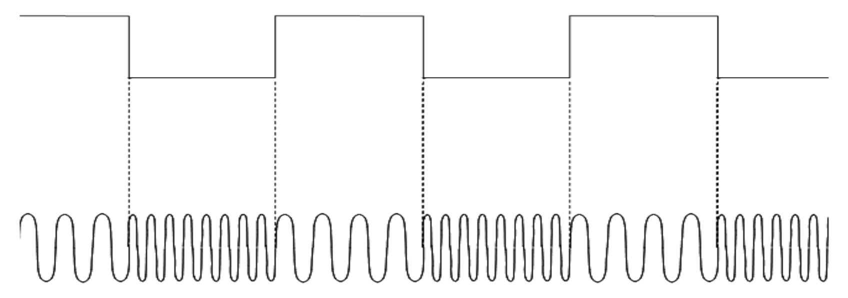
ASK (Amplitude-Shift Keying) – Case of **OOK (On-Off Keying)**

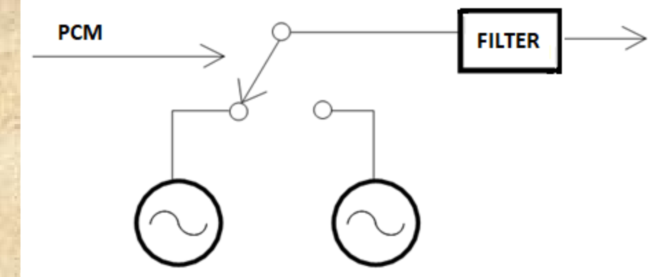


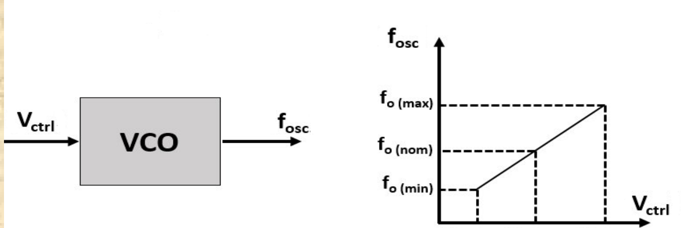




FSK (Frequency-Shift Keying)



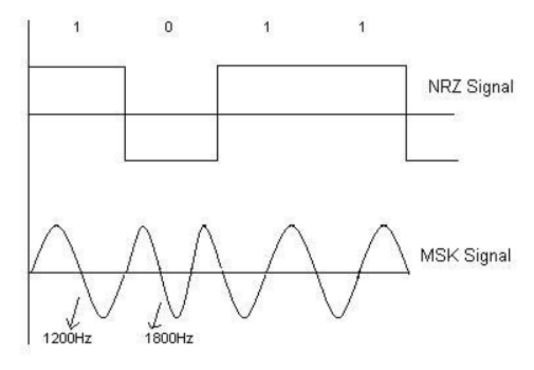




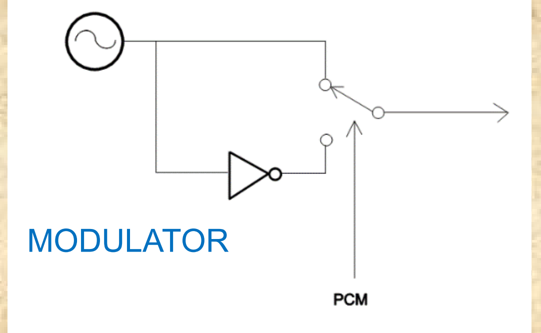
Voltage controlled oscillator

MSK: Minimum Shift Keying (for digital comms, smallest FSK modulation index)

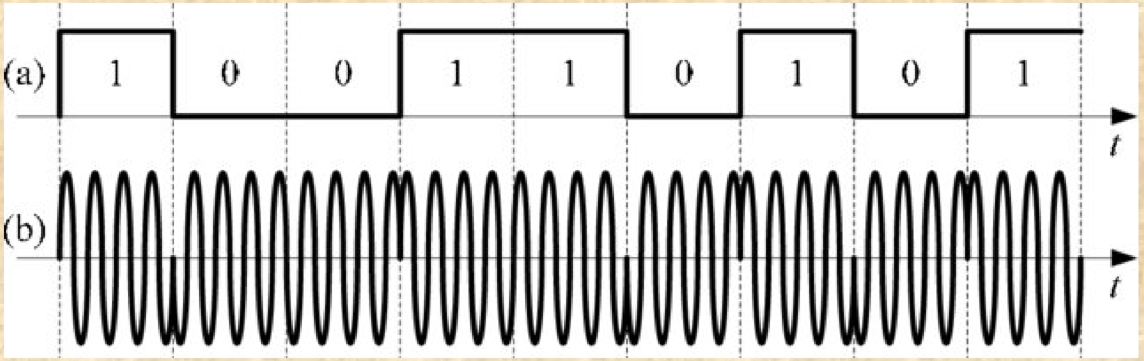
PSK Phase-Shift Keying ….

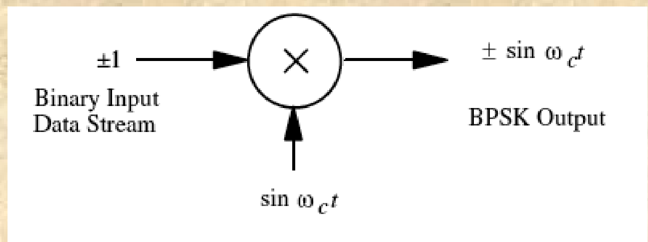


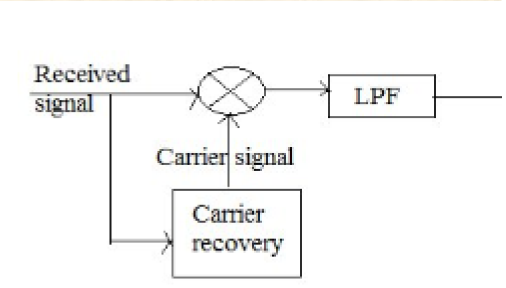
BPSK (Binary Phase-Shift Keying)

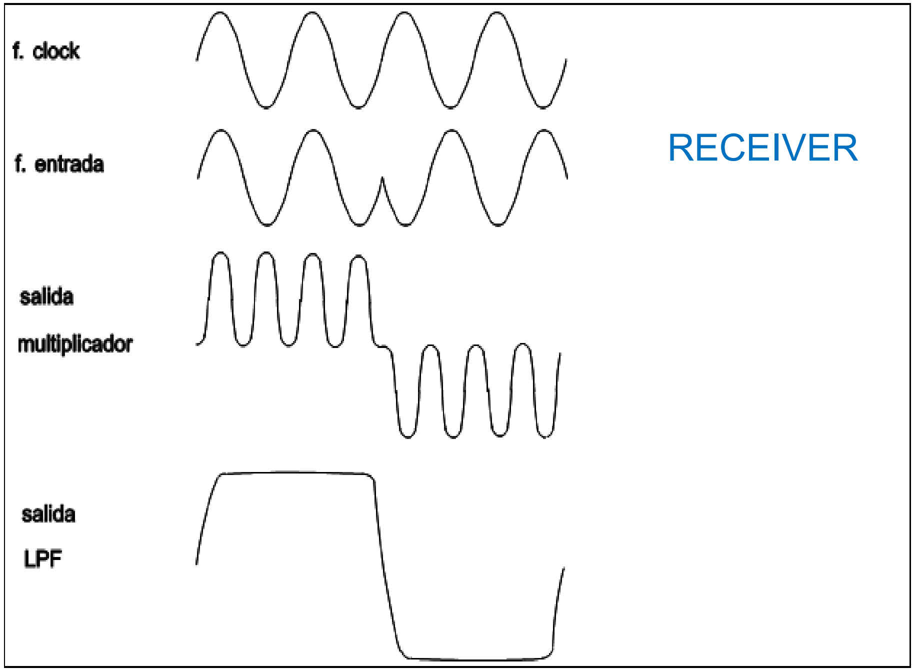


MODULATOR





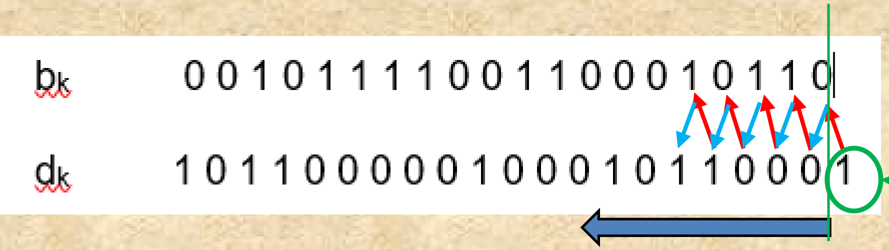




RECEIVER

DPSK (Differential Phase-Shift Keying) : BPSK is ambiguous, only a jump of 180º is sure, but it is necessary a reference of the carrier in the receiver (carrier recovering) to compare phases. DPSK overcomes that by using a differential coding (each bit is compared with the previous result)

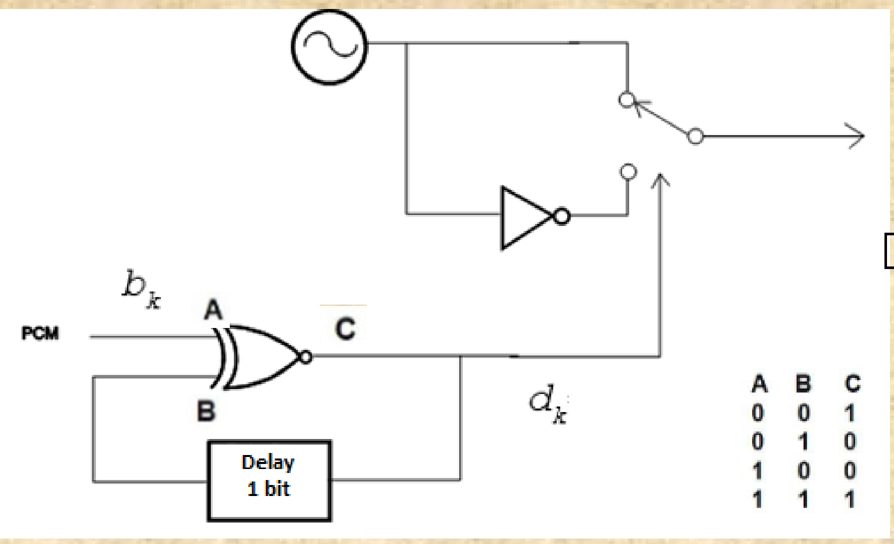
$$d_k = \overline{b_k \oplus d_{k-1}}$$



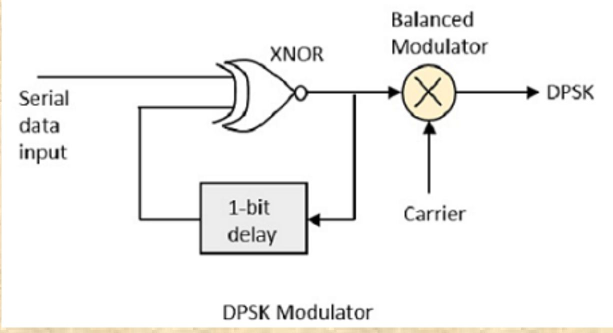
b_k 0 0 1 0 1 1 1 1 0 0 1 1 0 0 0 1 0 1 1 0

d_k 1 0 1 1 0 0 0 0 0 1 0 0 0 1 0 1 1 0 0 0 1

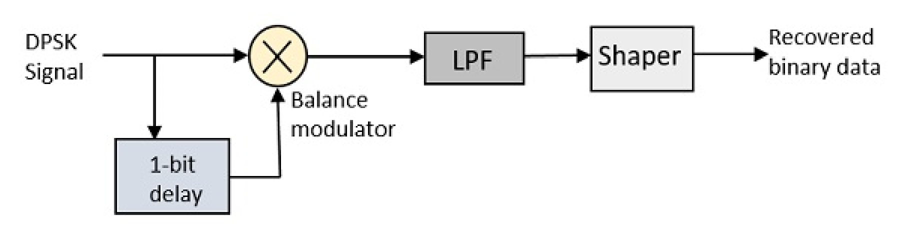
Initial bit (known)



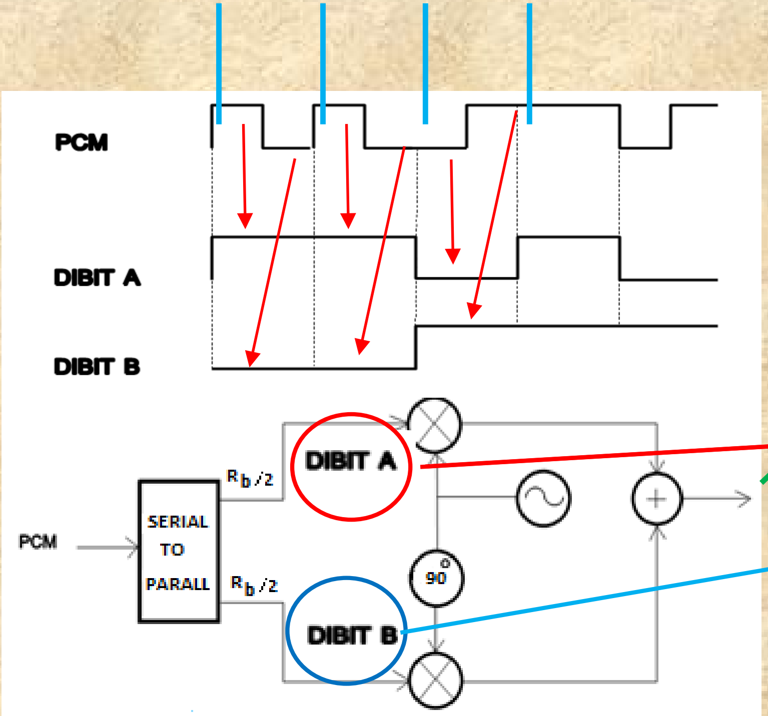
A	B	C
0	0	1
0	1	0
1	0	0
1	1	1



DPSK Modulator



QPSK (Quaternary Phase-Shift Keying)



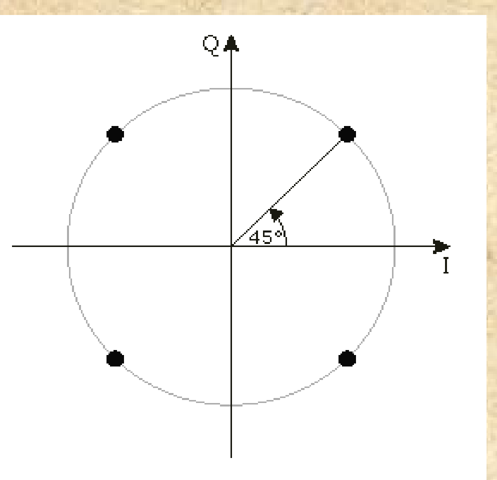
$$s(t) = A\cos\left(2\pi f_c t + \theta(t)\right)$$

$$s(t) = A\cos\left(2\pi f_c t + \theta(t)\right)$$

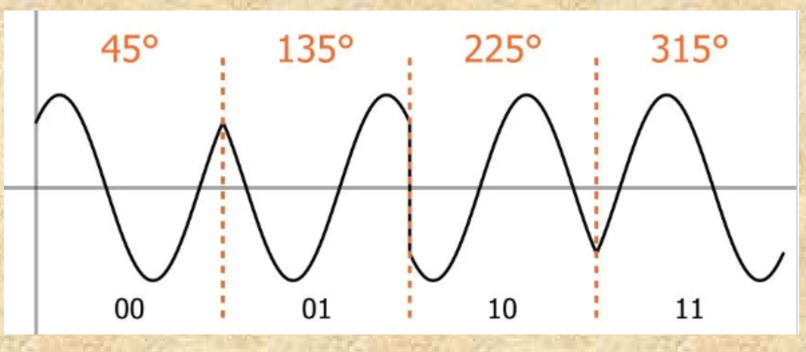
$$= A\cos\left(\theta(t)\right)\cos(2\pi f_c t) - A\sin\left(\theta(t)\right)\sin(2\pi f_c t) =$$

$$\mathrm{I}(t)\cos(2\pi f_c t) - Q(t)\sin(2\pi f_c t)$$

A_k	B_k	I	Q	PHASE
1	1	-1	-1	-135°
0	1	1	-1	-45°
0	0	1	1	45°
1	0	-1	1	135°

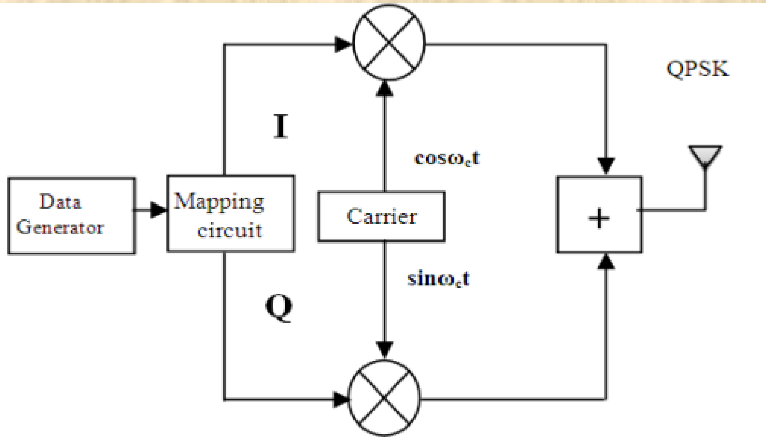


QPSK constellation



one SYMBOL → two BITS

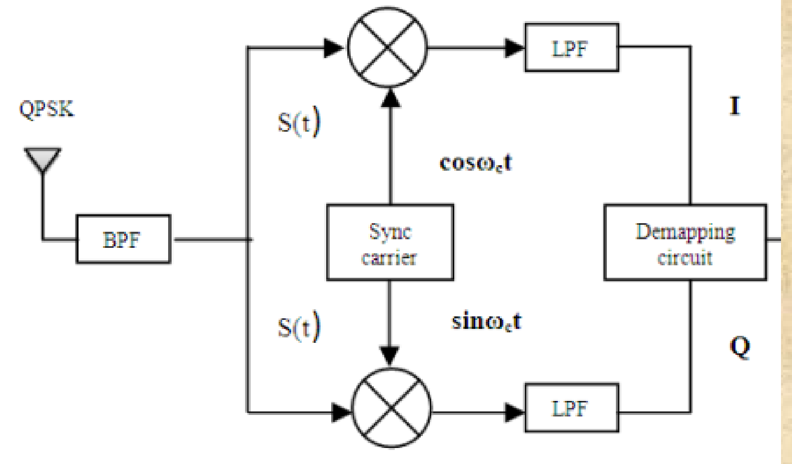
QPSK (Quaternary Phase-Shift Keying)



$$s(t) = A\cos\left(2\pi f_c t + \theta(t)\right)$$

$$= A\cos\left(\theta(t)\right)\cos(2\pi f_c t) - A\sin\left(\theta(t)\right)\sin(2\pi f_c t) =$$

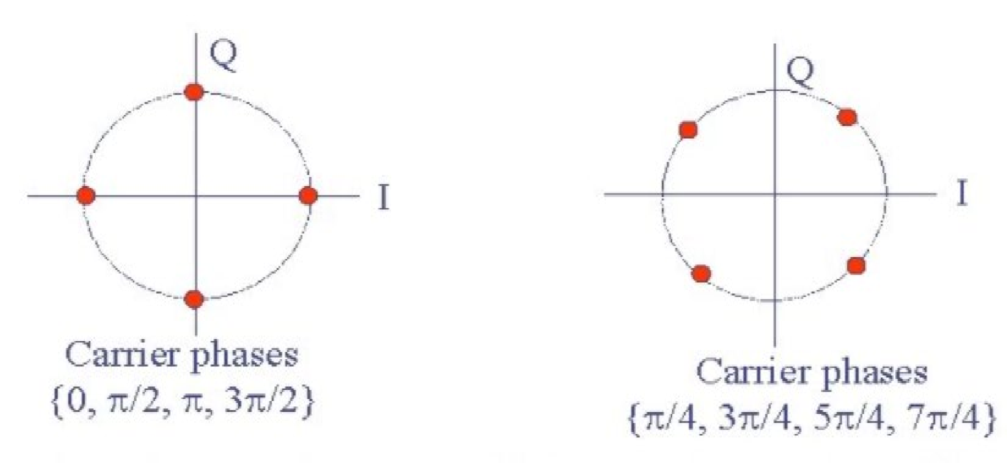
$$\mathrm{I(t)}\cos(2\pi f_c t) - Q(t)\sin(2\pi f_c t)$$



$$s(t)\cdot\cos(2\pi f_c\, t) = I(t)\cdot\, cos^2(2\pi f_c\, t) - Q(t)\cos(2\pi f_c\, t)\sin(2\pi f_c\, t) =$$

$$= I(t)\cdot\, \frac{1}{2}(1+\cos(4\pi f_c\, t)) - Q(t)\,(\sin(4\pi f_c\, t) + \sin 0)\ = I(t)/2$$

Other angles are possible



Carrier phases $\{0, \pi/2, \pi, 3\pi/2\}$

Carrier phases $\{\pi/4, 3\pi/4, 5\pi/4, 7\pi/4\}$

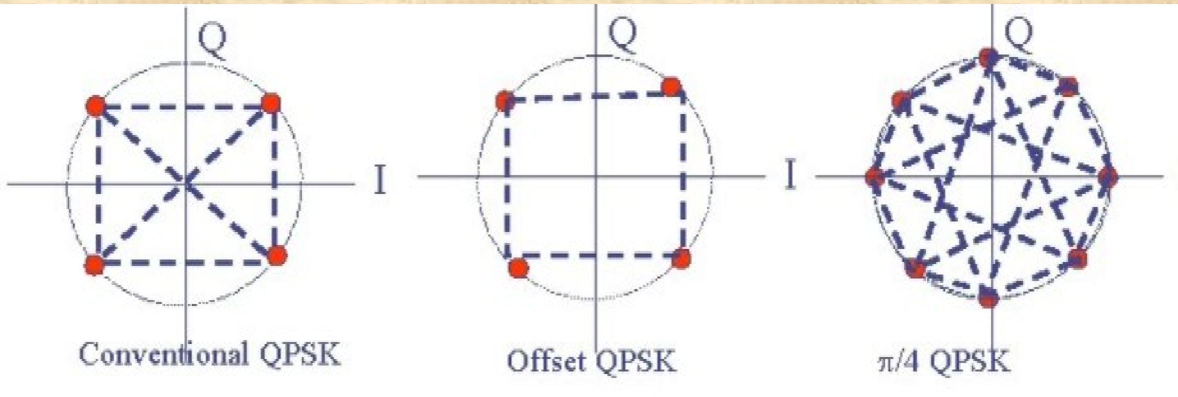
QPSK variations

DQPSK (Differential Quaternary Phase-Shift Keying)

$$I_k = \overline{(A_k \oplus B_K)}\,(A_k \oplus I_{k-1}) + (A_k \oplus B_k)(B_k \oplus Q_{k-1})$$

$$Q_k = \overline{(A_k \oplus B_k)}\,(B_k \oplus Q_{k-1}) + (A_k \oplus B_k)(A_k \oplus I_{k-1})$$

QPSK variations …



Conventional QPSK

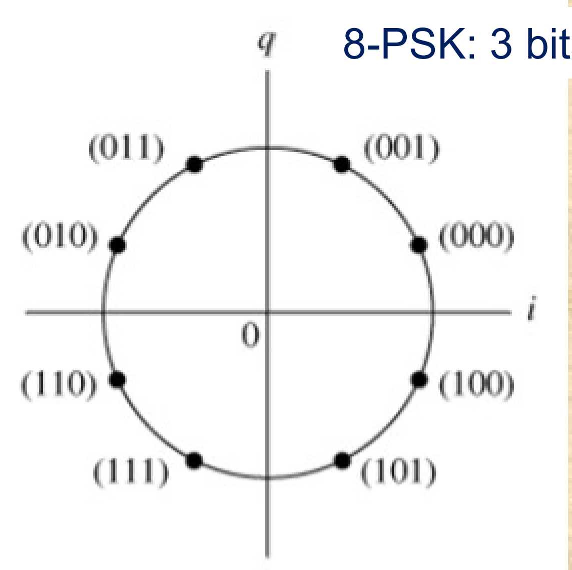
Offset QPSK

π/4 QPSK

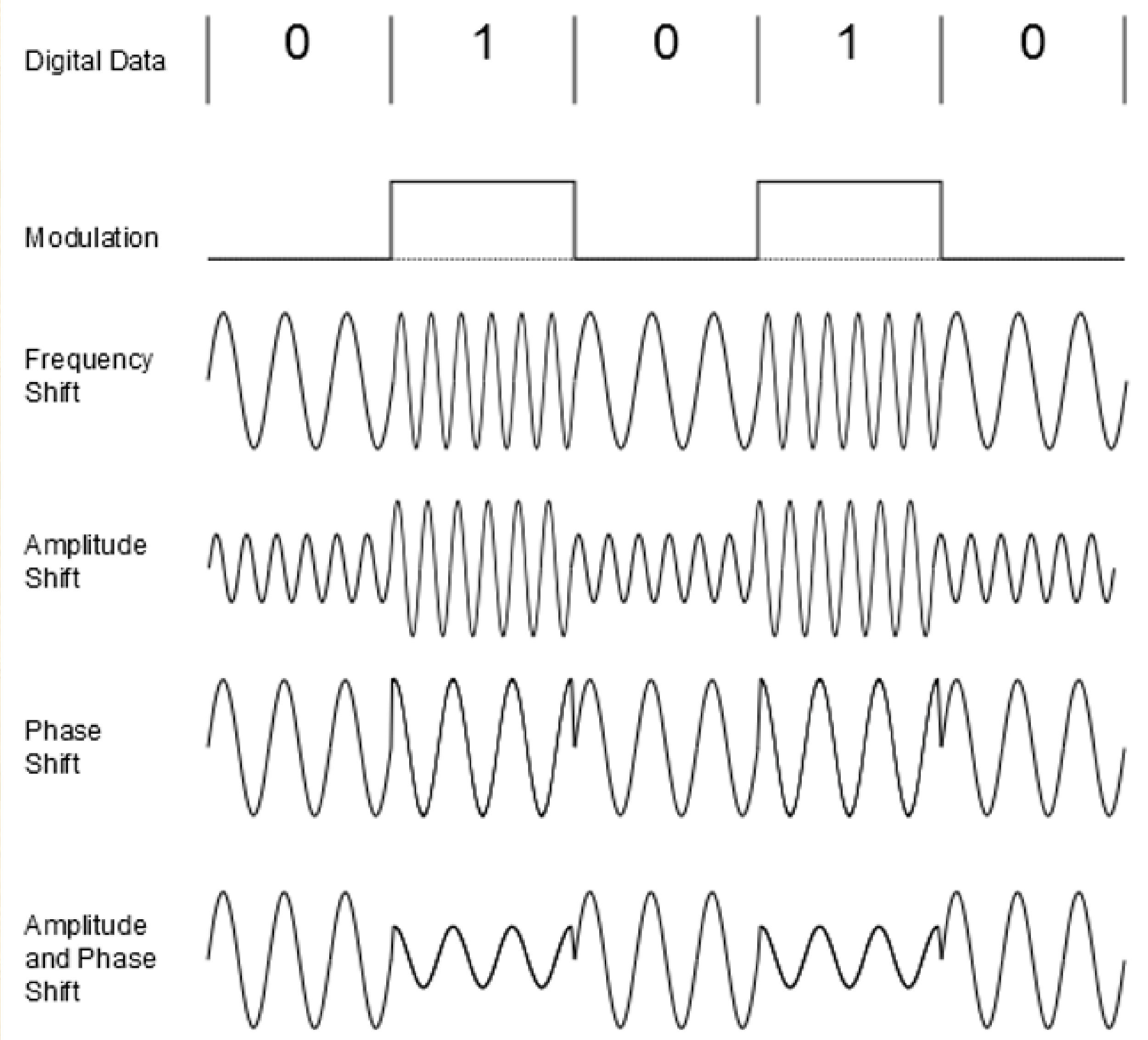
M-PSK

$$M = 2^n \rightarrow n = log_2 M$$

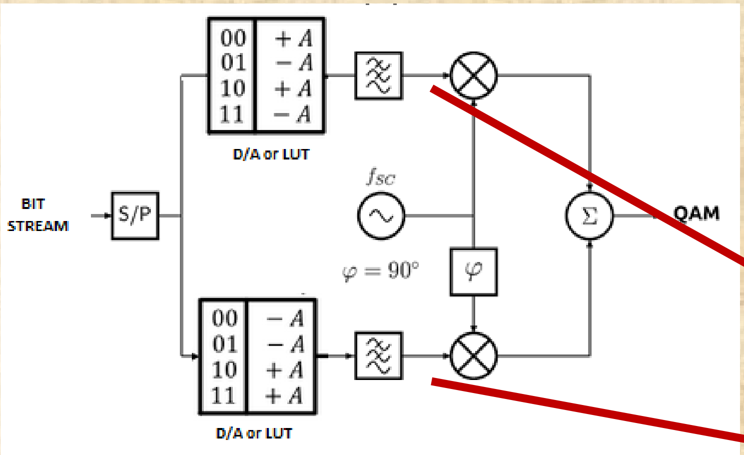
M: Symbols (size of the modulation)
N: bits



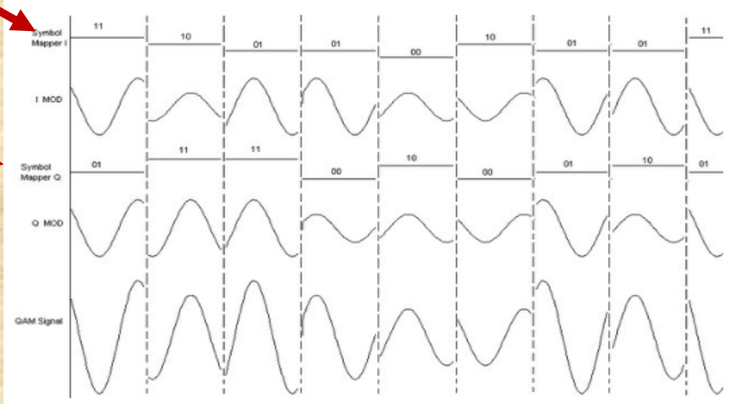
8-PSK: 3 bits/symbol

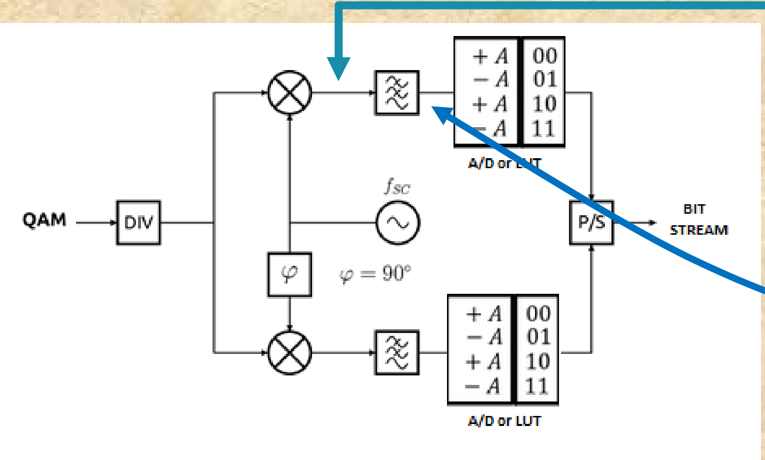

Digital Data
0
1
0
1
0
Modulation
Frequency Shift
Amplitude Shift
Phase Shift
Amplitude and Phase Shift

QAM (Quadrature Amplitude Modulation)



$$s_c(t) = I(t)\cos(2\pi f_0 t) - Q(t)\sin(2\pi f_0 t)$$



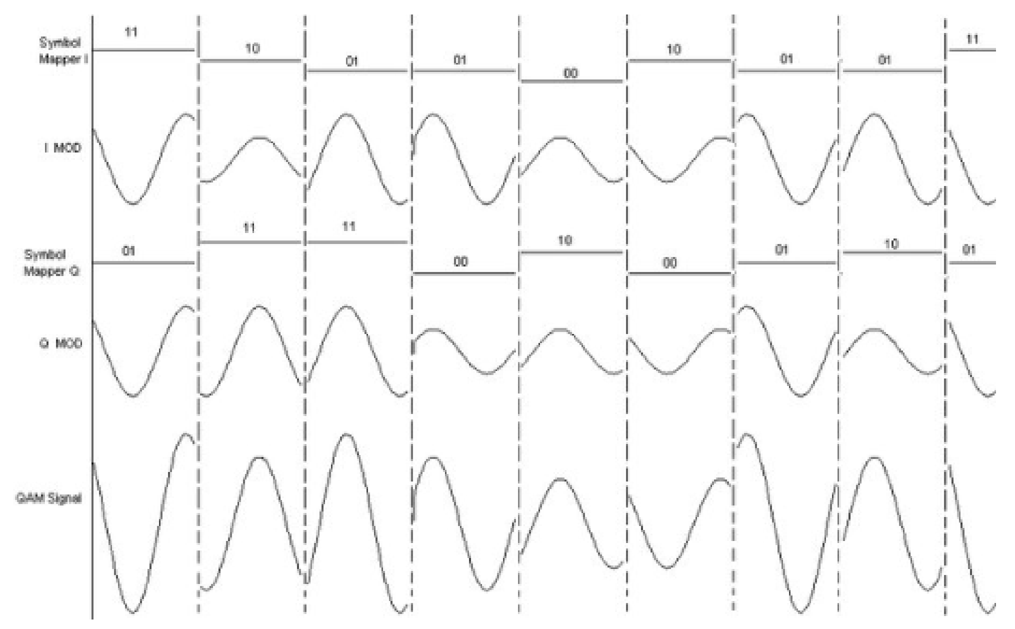


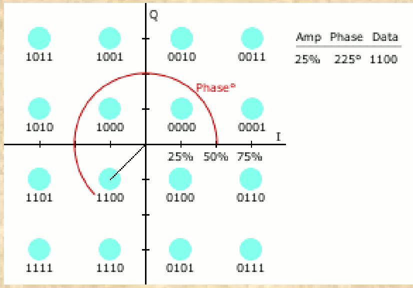
$$r(t) = s_c(t)\cos(2\pi f_c t) =$$

$$= I(t)\cos(2\pi f_c t)\cos(2\pi f_c t) - Q(t)\sin(2\pi f_c t)\cos(2\pi f_c t)$$

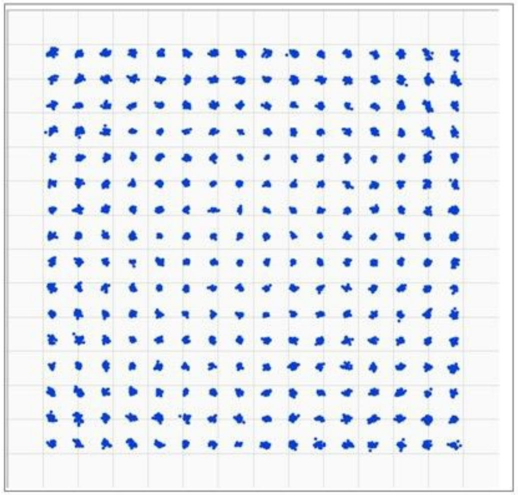
$$= \frac{1}{2}I(t) + \frac{1}{2}\left[I(t)\cos(4\pi f_c t) - Q(t)\sin(4\pi f_c t)\right]$$

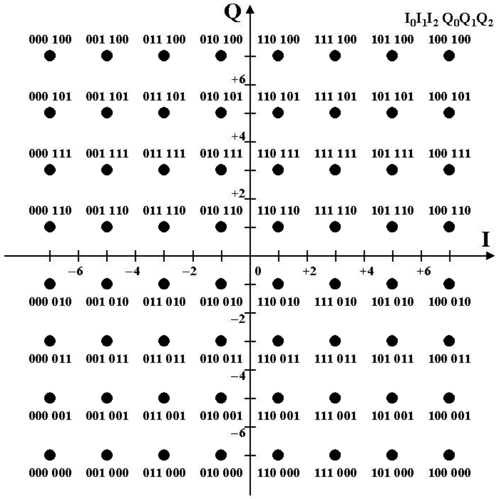
$$= \frac{1}{2}I(t)$$



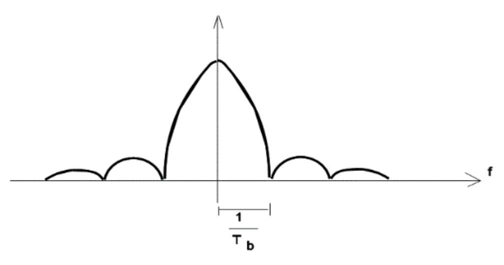


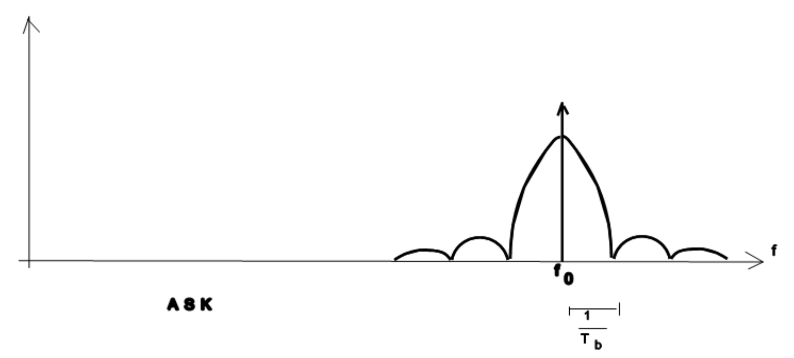
256-QAM Constellation

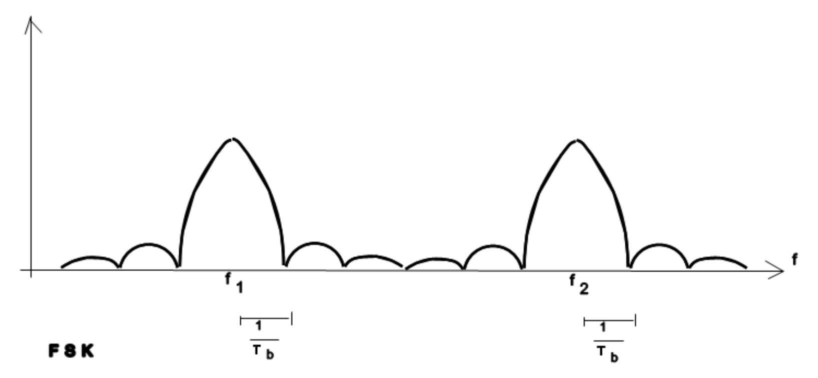


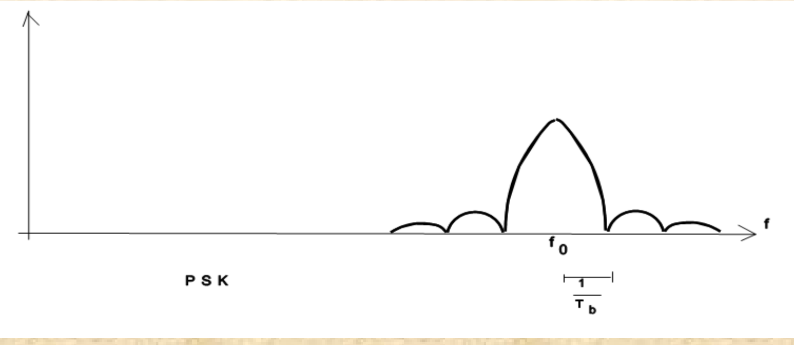


SPECTRA OF DIGITAL MODULATIONS





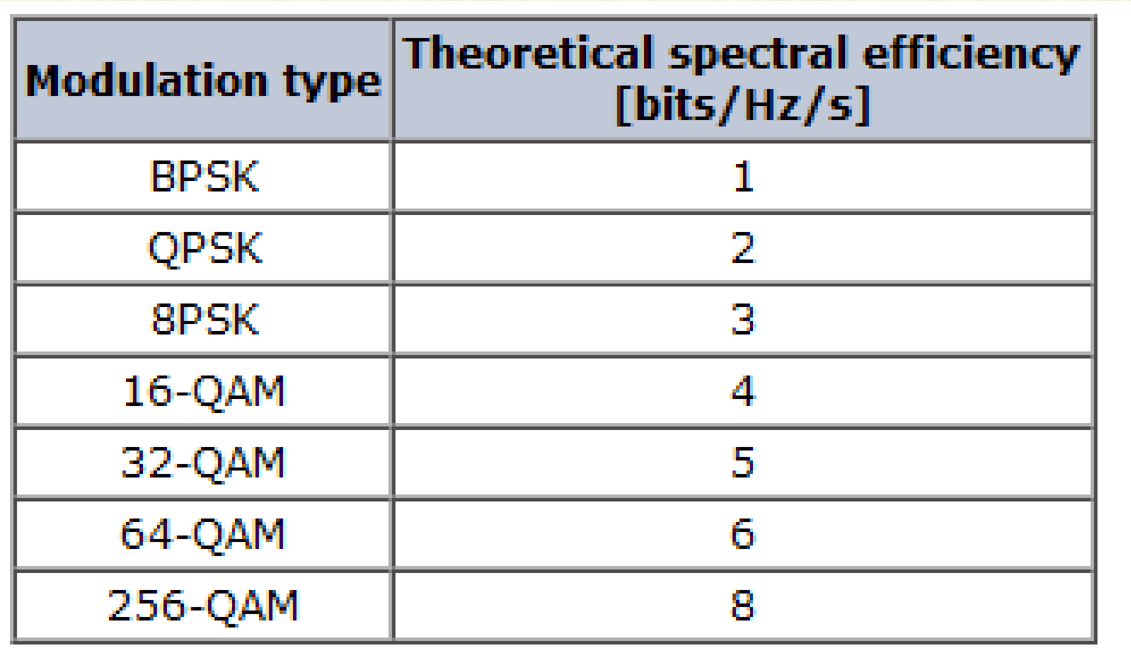




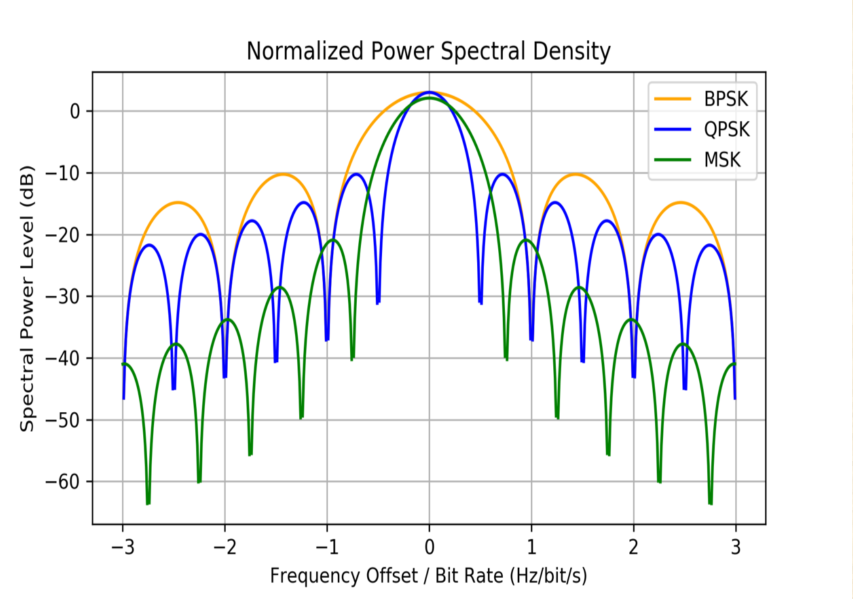
Spectral efficiency (bandwidth efficiency)
bits/s/Hz

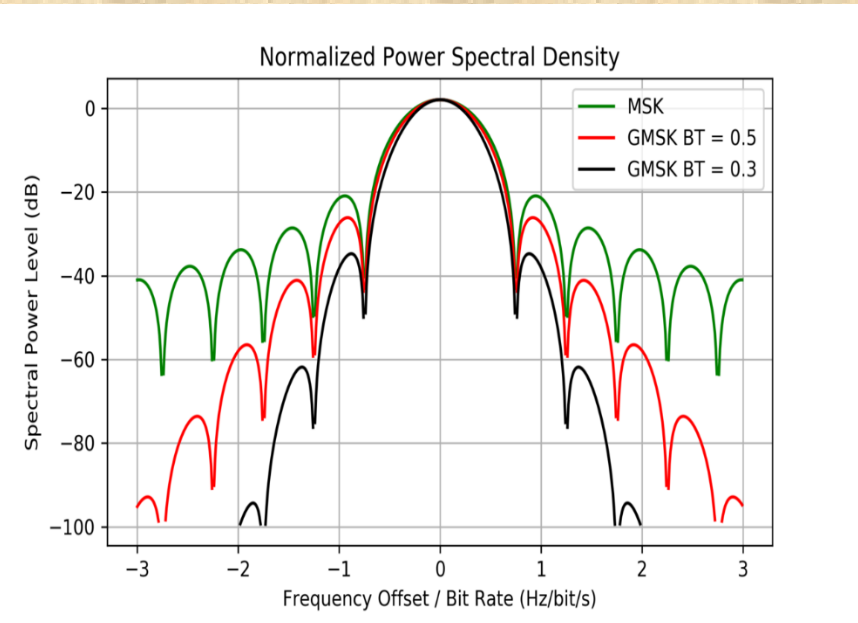
Spectral efficiency (bandwidth efficiency)

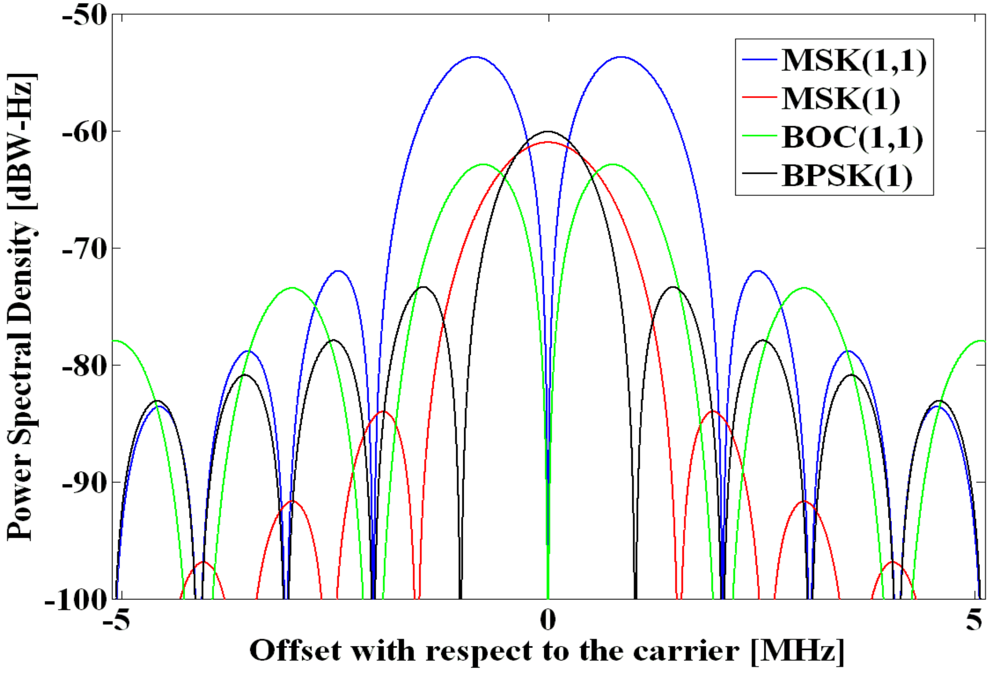
bits/s/Hz



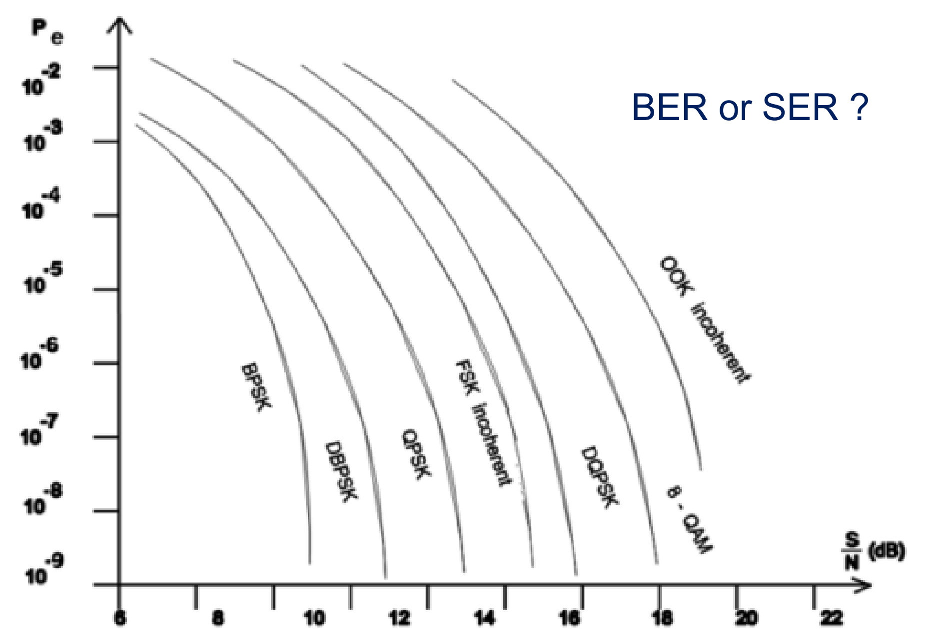
Modulation type	Theoretical spectral efficiency [bits/Hz/s]
BPSK	1
QPSK	2
8PSK	3
16-QAM	4
32-QAM	5
64-QAM	6
256-QAM	8


Normalized Power Spectral Density
BPSK
QPSK
MSK
Spectral Power Level (dB)
0
−10
−20
−30
−40
−50
−60
−3
−2
−1
0
1
2
3
Frequency Offset / Bit Rate (Hz/bit/s)

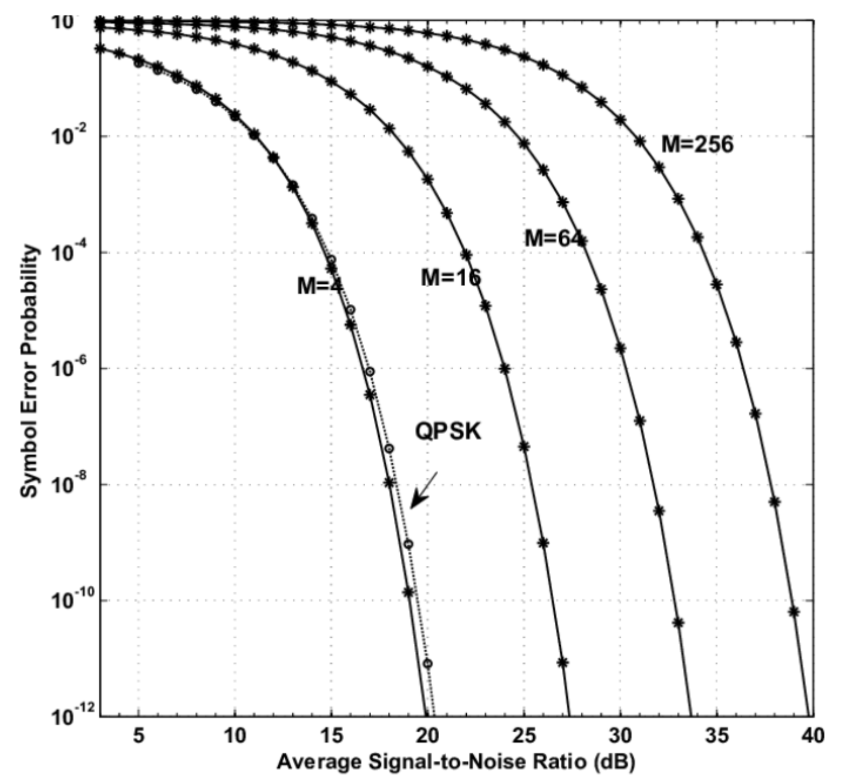

Normalized Power Spectral Density
MSK
GMSK BT = 0.5
GMSK BT = 0.3
Spectral Power Level (dB)
0
−20
−40
−60
−80
−100
−3
−2
−1
0
1
2
3
Frequency Offset / Bit Rate (Hz/bit/s)

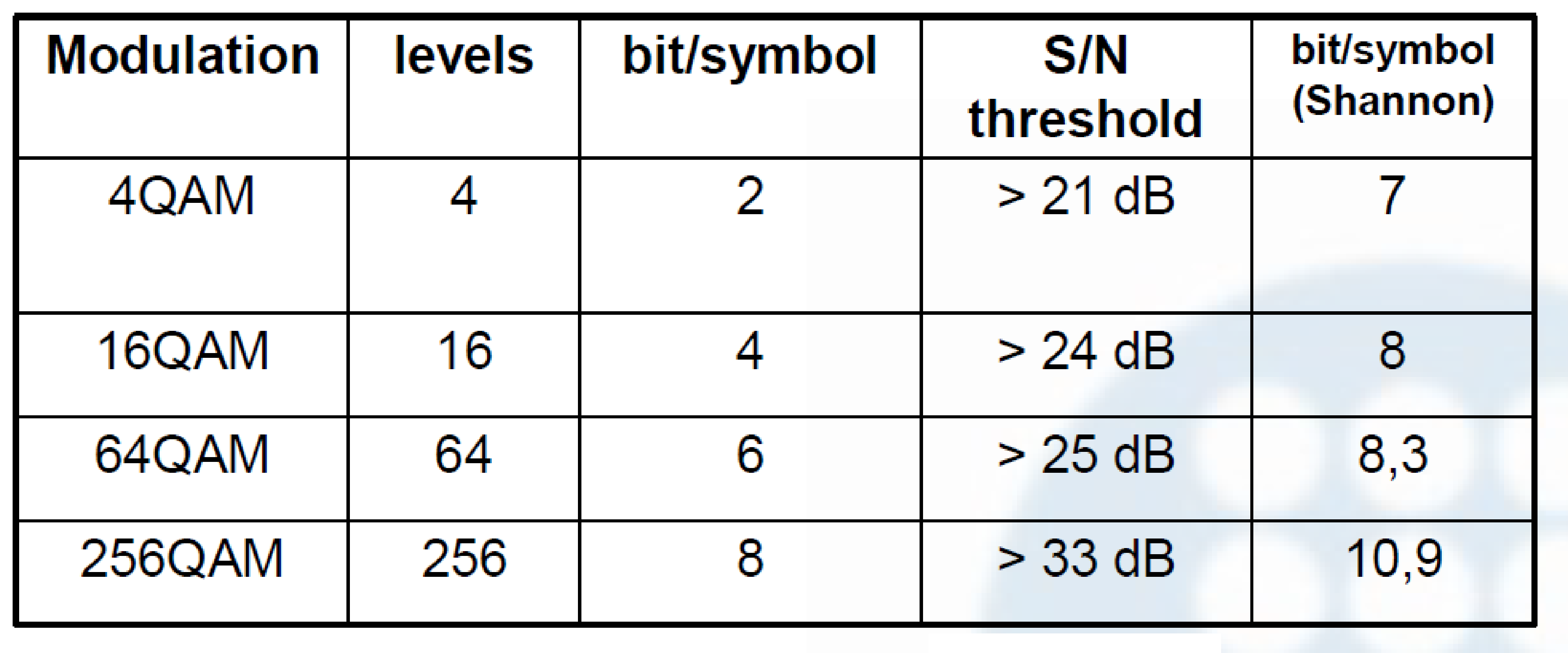

MSK(1,1)
MSK(1)
BOC(1,1)
BPSK(1)
Power Spectral Density [dBW-Hz]
-50
-60
-70
-80
-90
-100
-5
0
5
Offset with respect to the carrier [MHz]

Error Probability



BER or SER ?

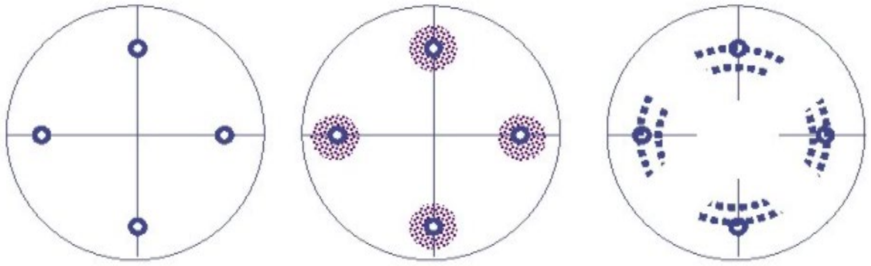




Modulation	levels	bit/symbol	S/N threshold	bit/symbol (Shannon)
4QAM	4	2	> 21 dB	7
16QAM	16	4	> 24 dB	8
64QAM	64	6	> 25 dB	8,3
256QAM	256	8	> 33 dB	10,9

cable TV

Distortions

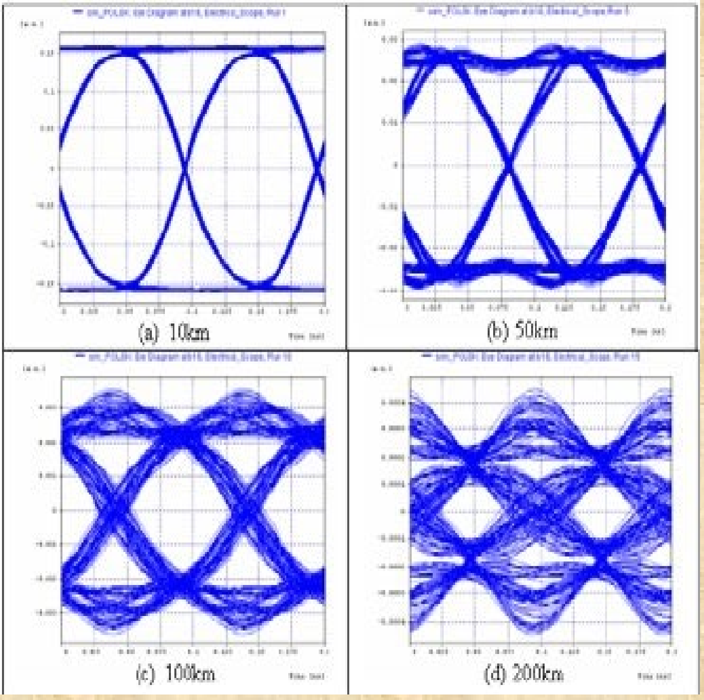


Perfect channel

White noise

Phase jitter

EYE diagrams

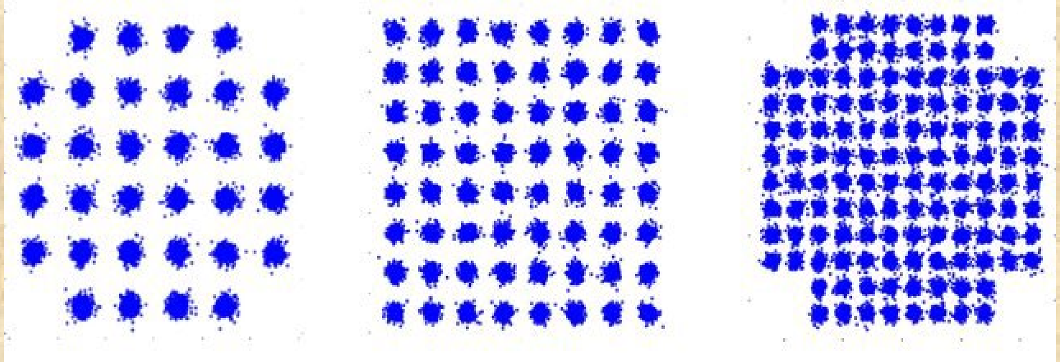


(a) 10km

(b) 50km

(c) 100km

(d) 200km



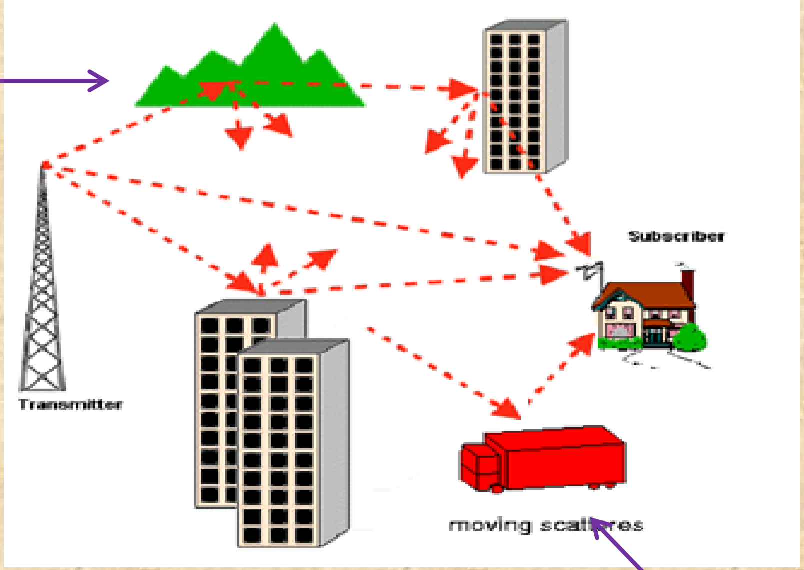
(a) 32- QAM

(b) 64-QAM

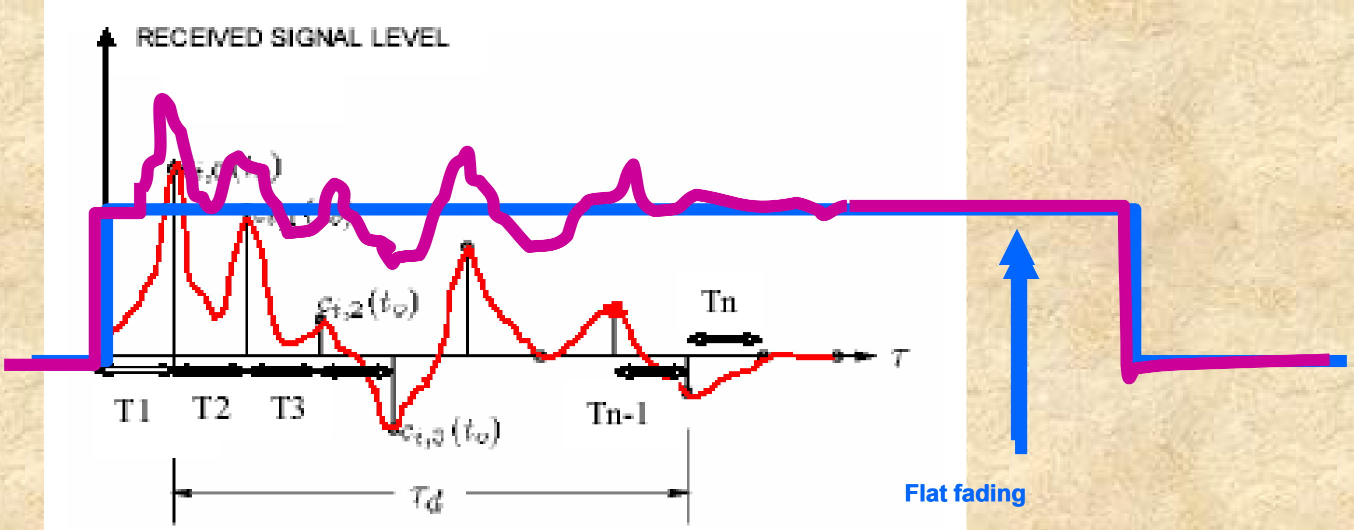
(c) 128-QAM

MULTIPATH DISTORTION

SLOW FADING



FAST FADING



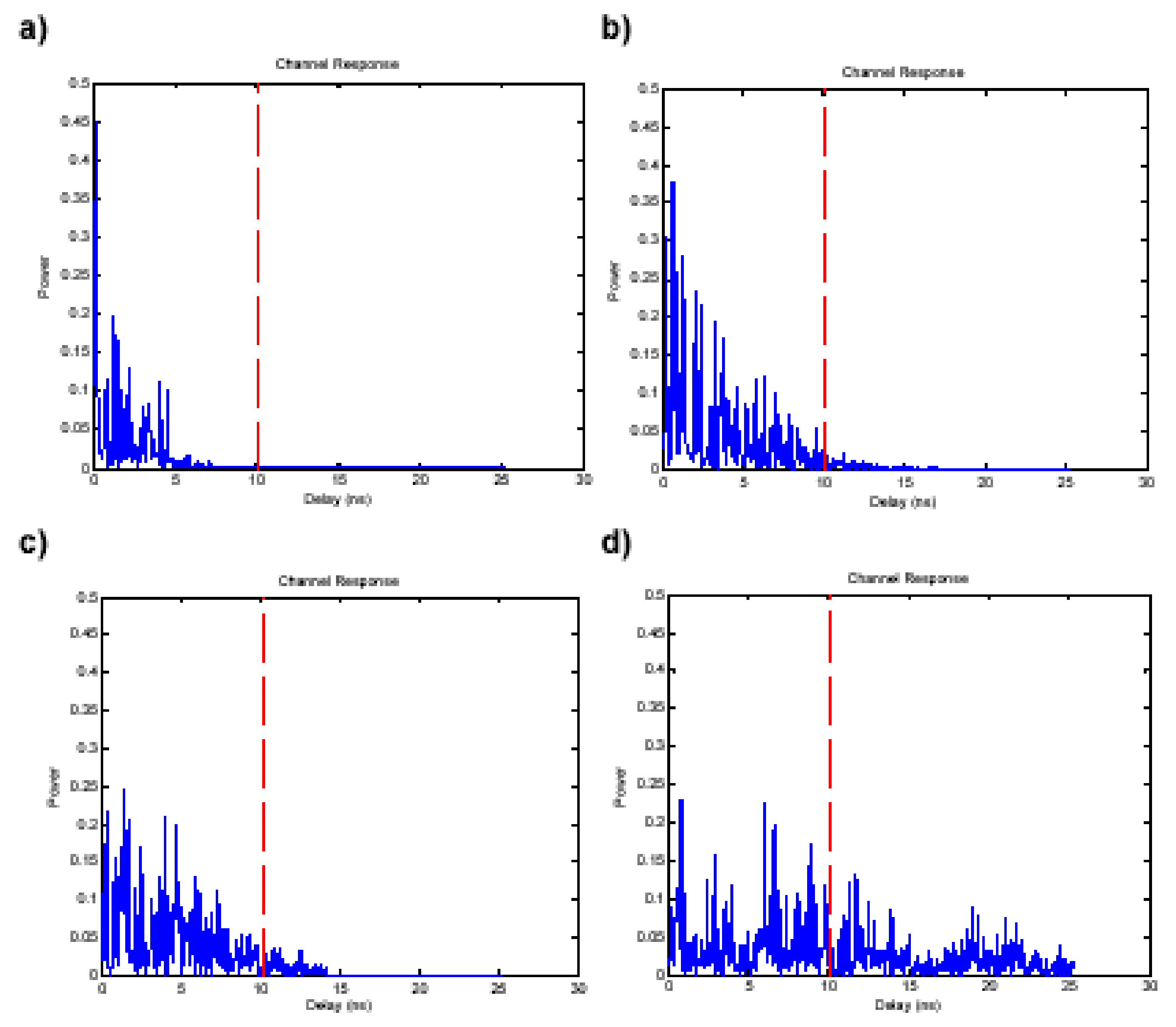
Delay spread (proportional to its inverse: Coherence bandwidth)

Flat fadding: signal BW < coherence BW

MULTIPATH

IEEE802.15.3a: Channel conditions (multipath)

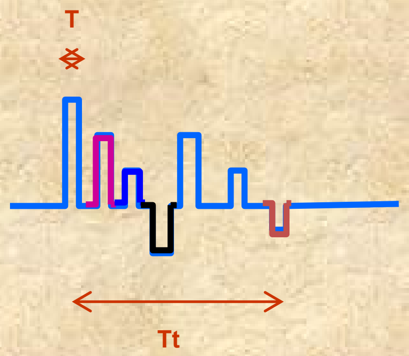
a) Line-of-sight channel, distance 0-4m.
b) Non-line-of-sight channel, distance 0-4m
c) Non-line-of-sight channel, distance 4-10m
d) Extreme non-line-of-sight channel.

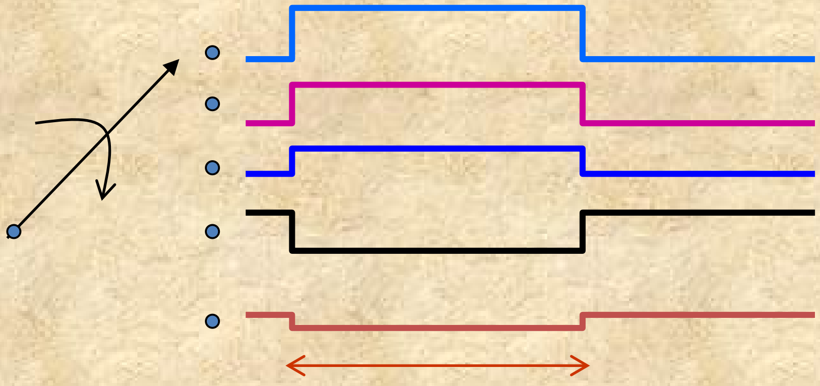


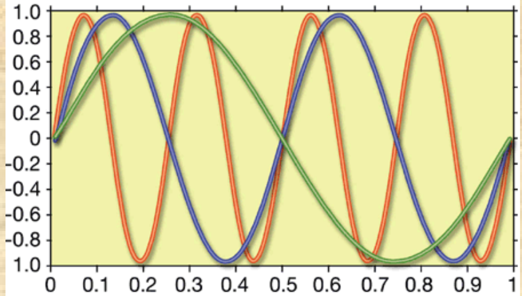
MULTIPATH

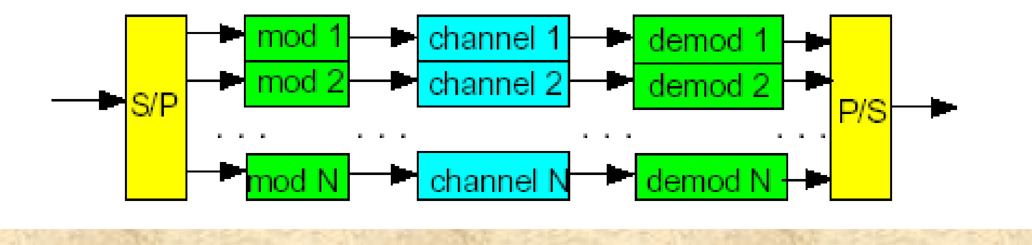
- ☐ Receiver diversity
  - Time
  - Frequency
  - Spatial (several antennas, diverse polarization)
- ☐ Beamforming
- ☐ OFDM
- ☐ Direct Sequence Spread Spectrum (DSSS)
- ☐ Frequency hopping spread spectrum (FHSS)

OFDM (multipath mitigation)









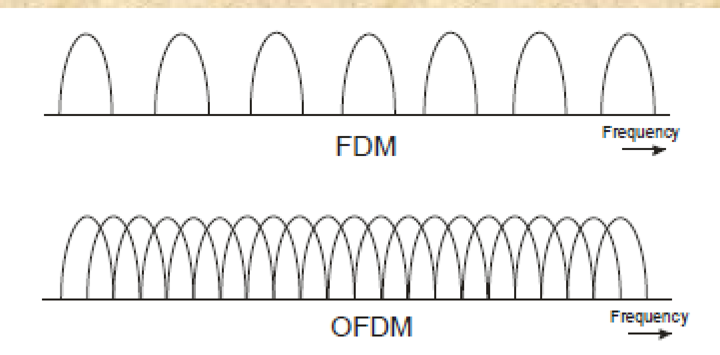
S/P

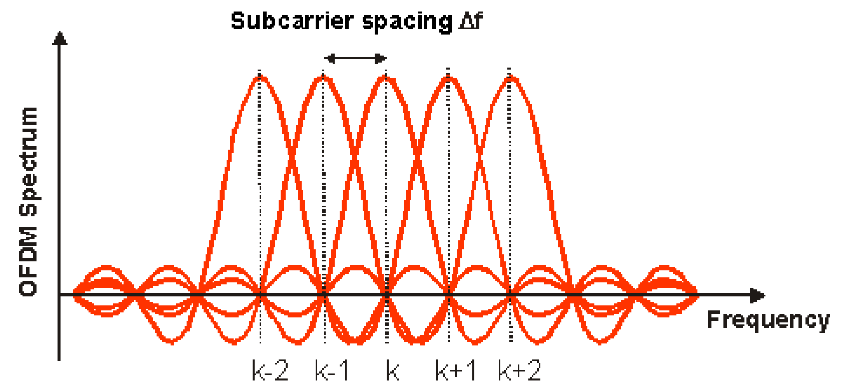
mod 1
mod 2
. . . .
mod N

channel 1
channel 2
. . . .
channel N

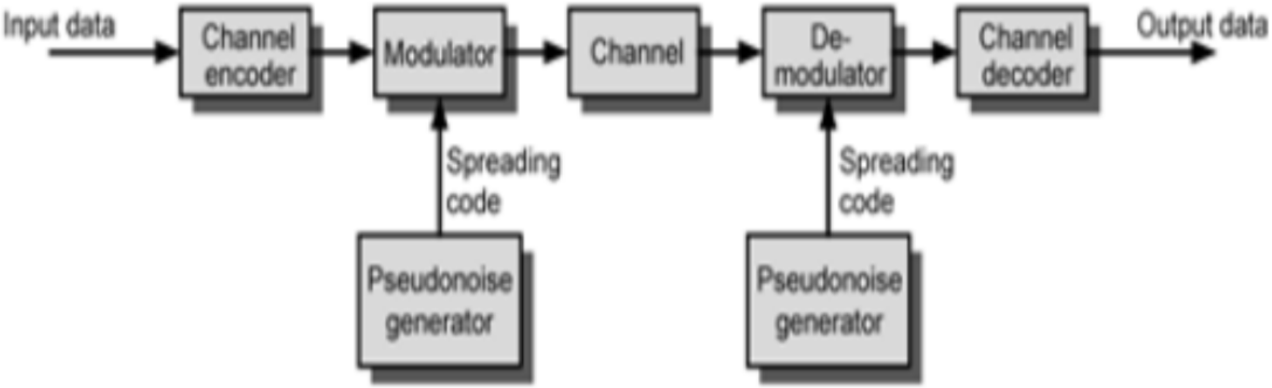
demod 1
demod 2
. . . .
demod N

P/S



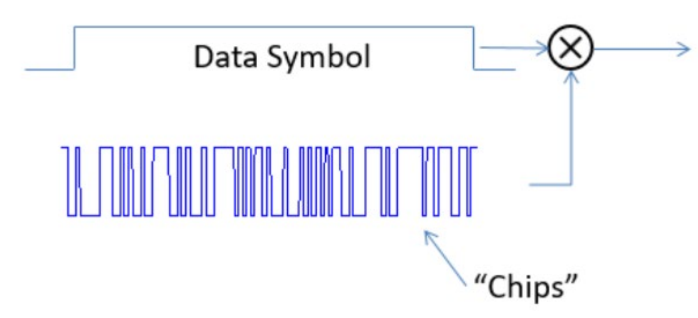


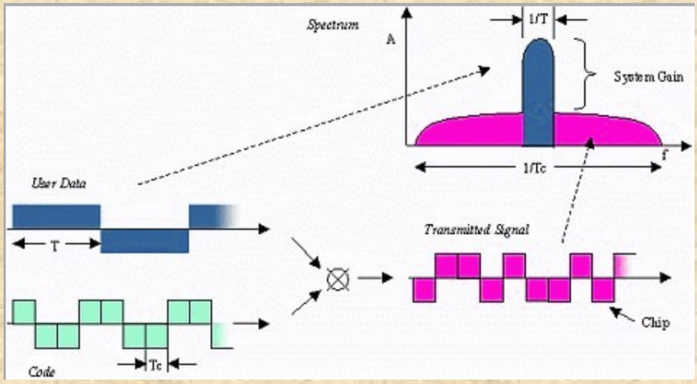
❑ Spread spectrum (SS) : General idea

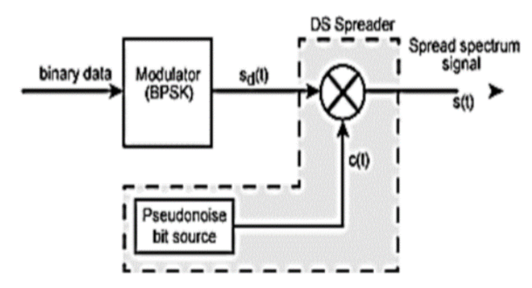


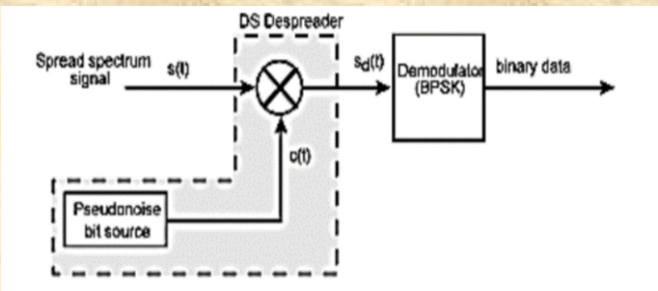
General Model of a Spread Spectrum system

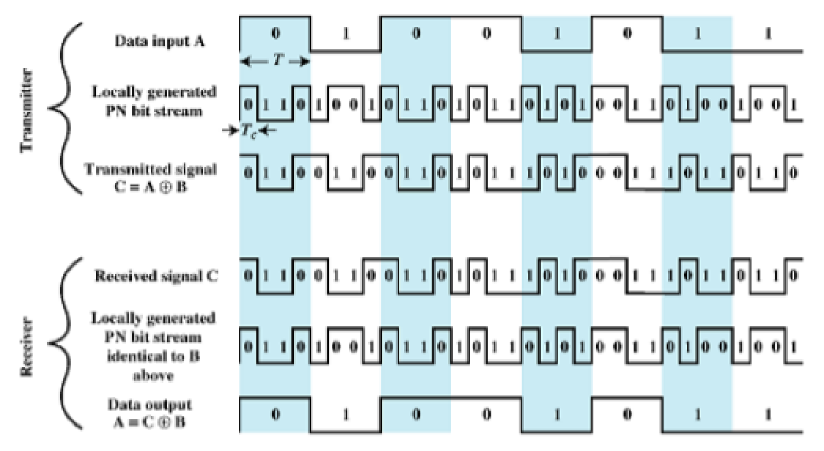
❑ Direct Sequence Spread Spectrum (DSSS)





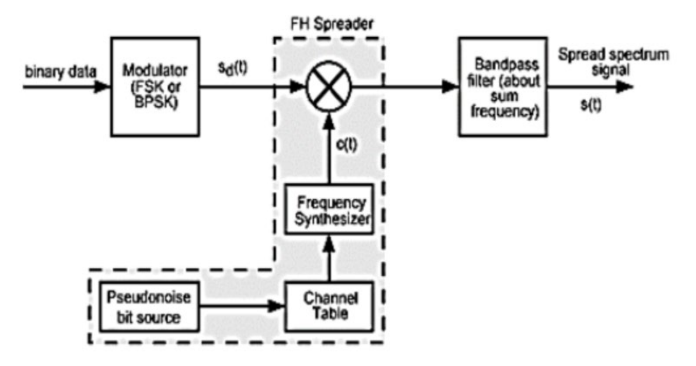


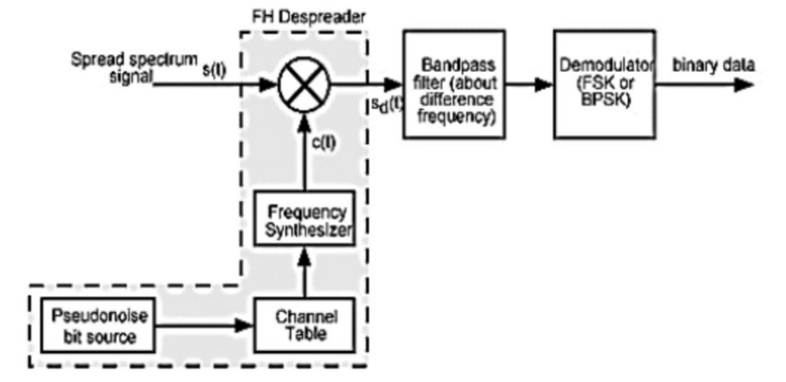


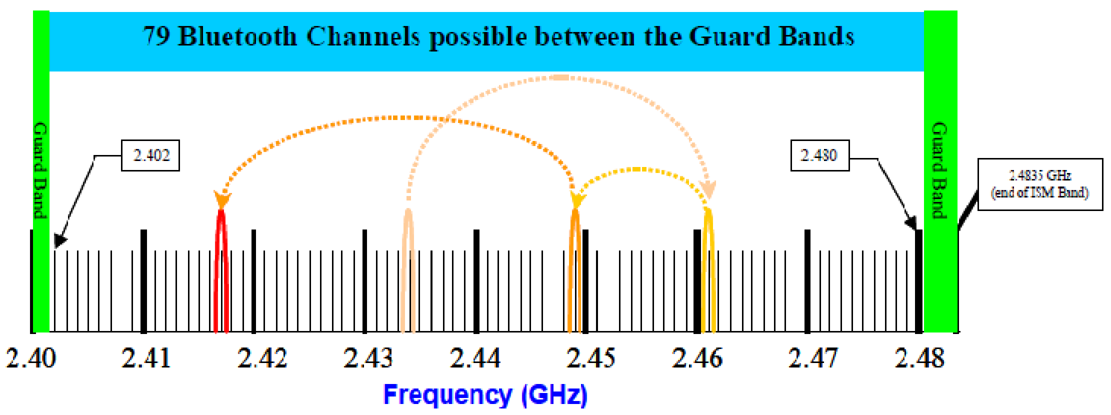


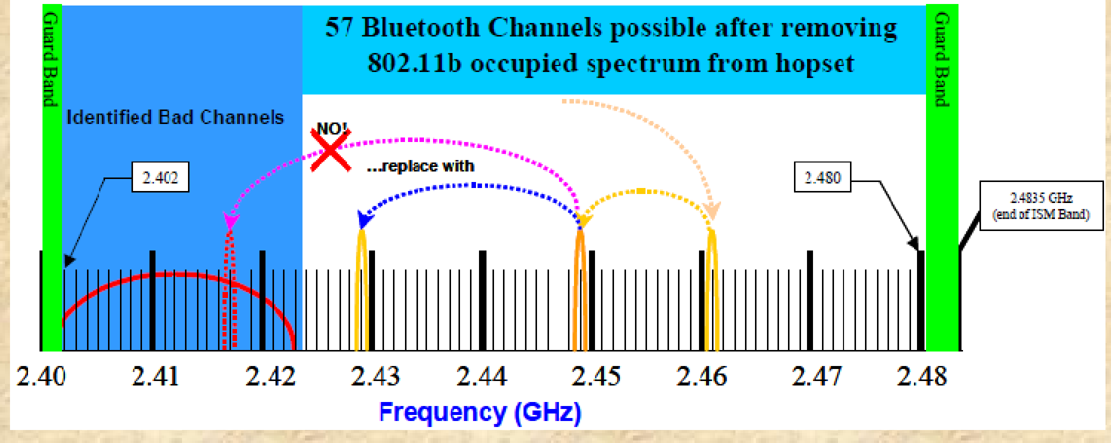
Example of DSSS

❑ Frequency hopping spread spectrum (FHSS)

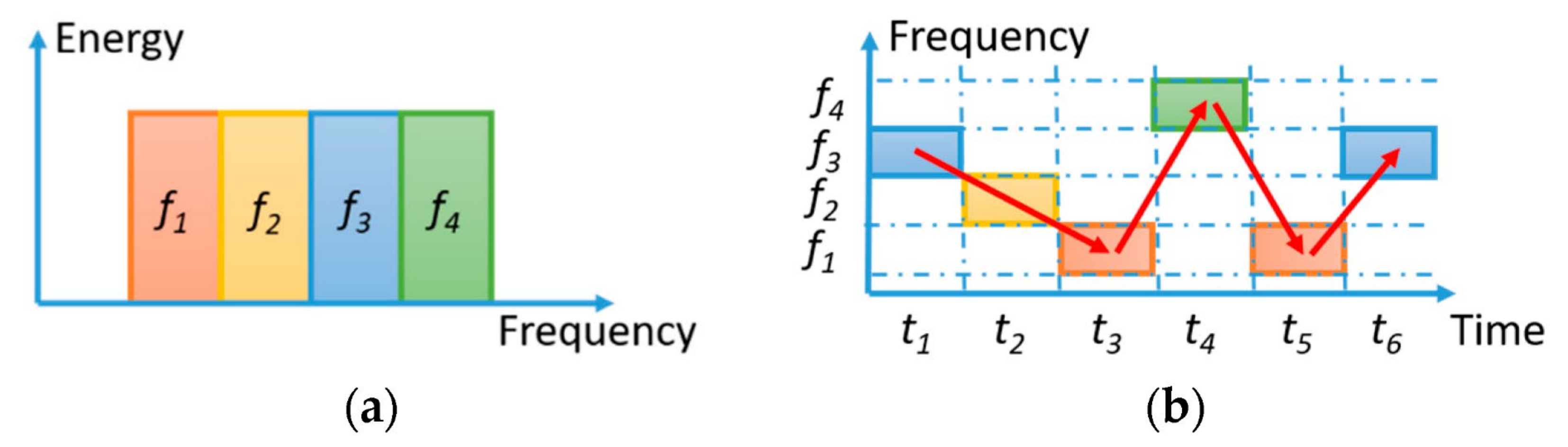


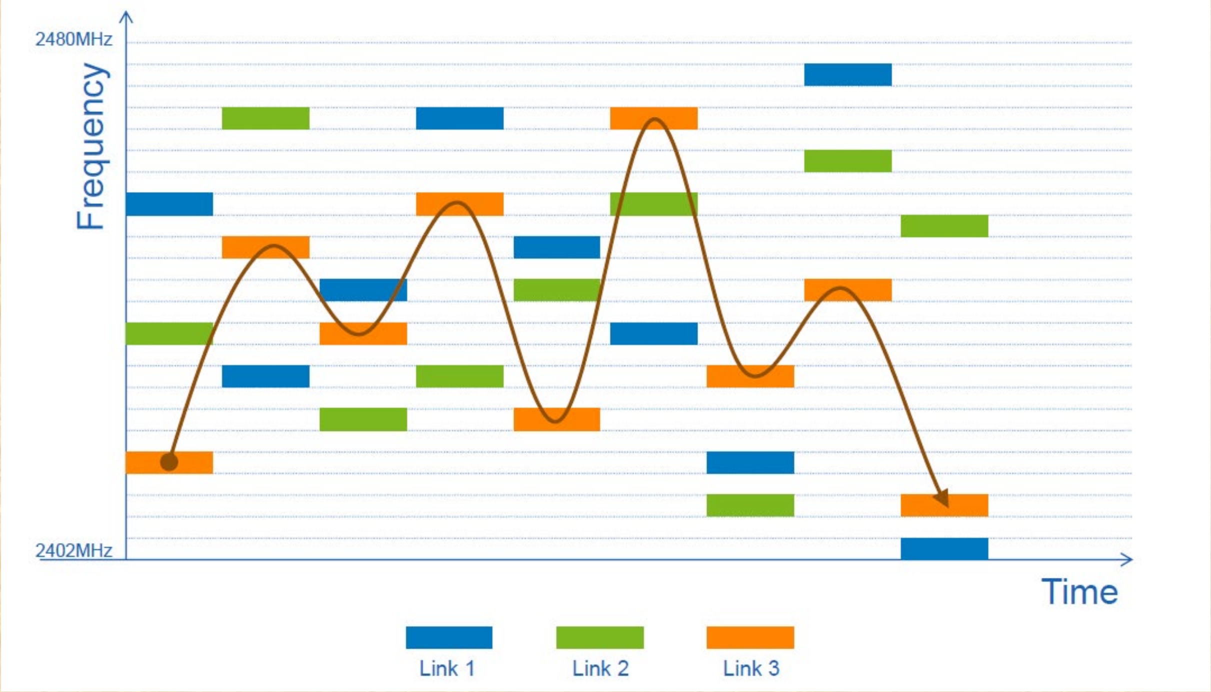




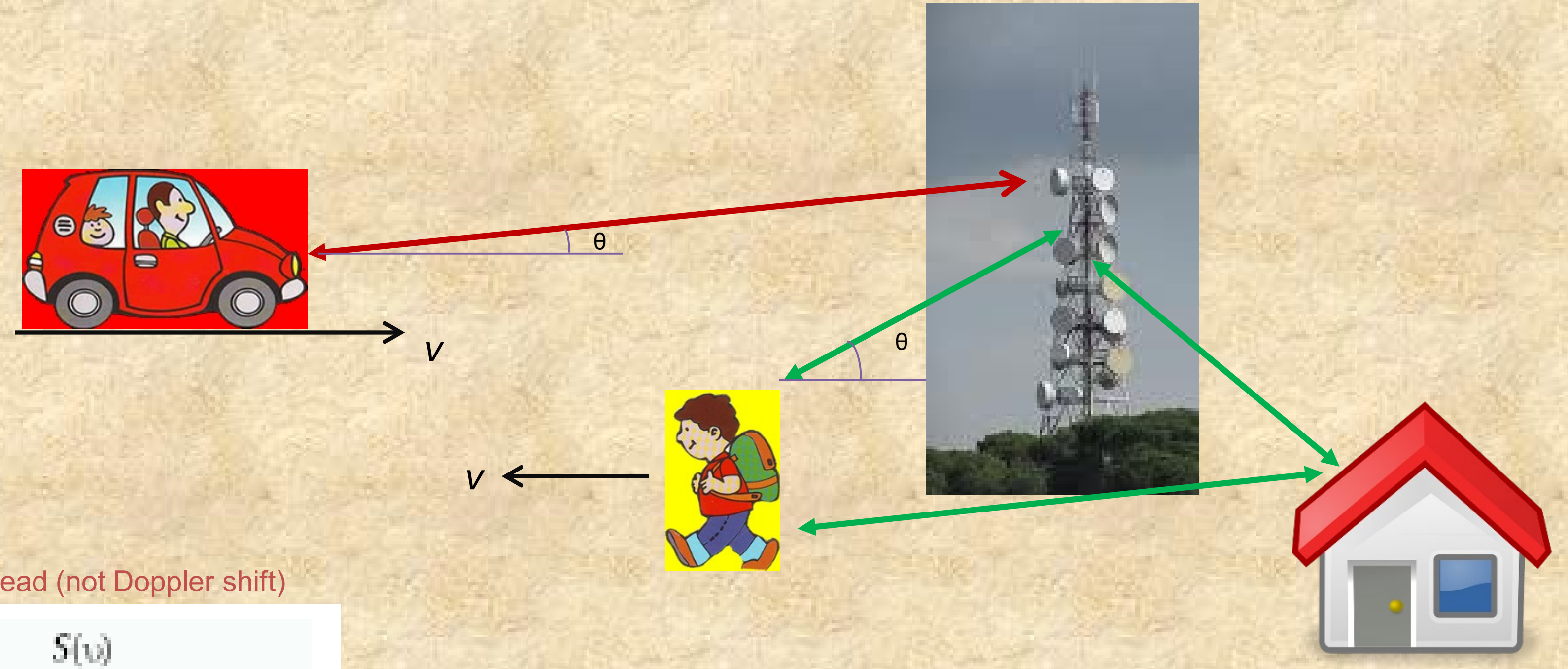


❑ Frequency hopping spread spectrum (FHSS)



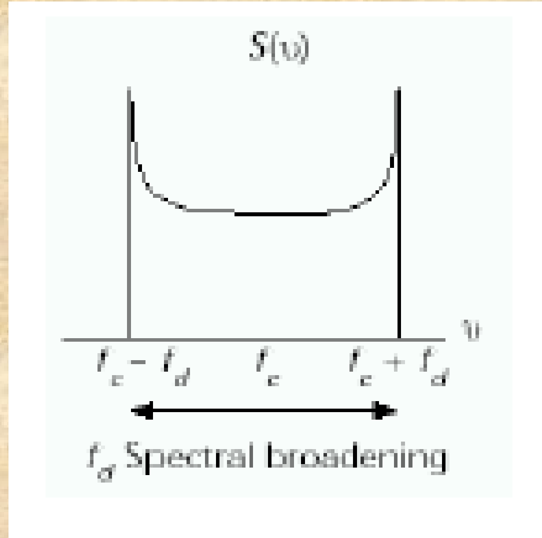


DOPPLER (DOPPLER SPREAD)



REMARK:

Doppler spread (not Doppler shift)

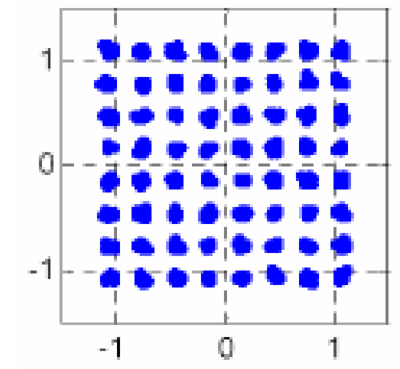


Doppler shift : $$f_d = \frac{v}{c} f_c \cos(\theta)$$

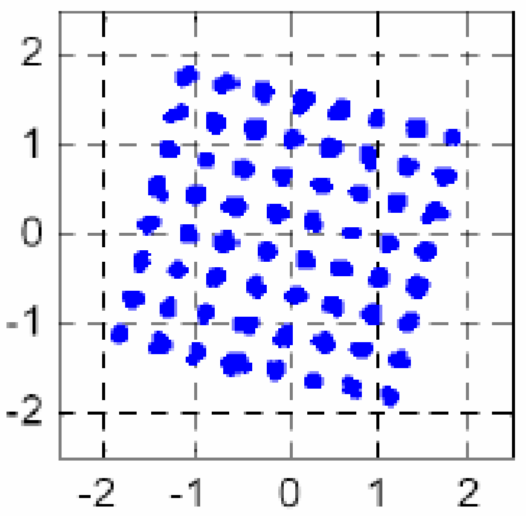
A walker at 4 Km/h, produces, at 5 GHz, a Doppler frequency of:

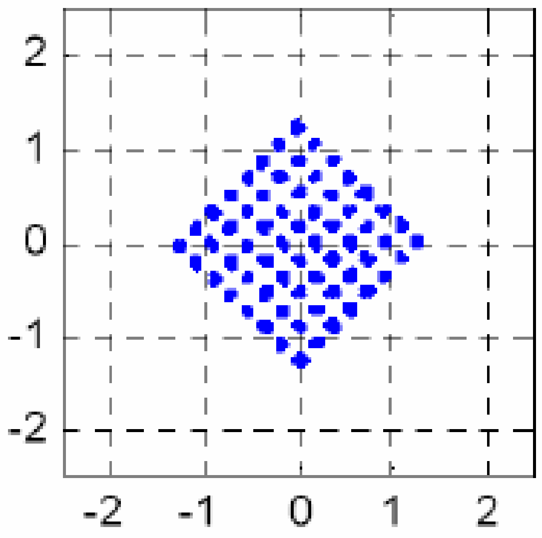
$$f_d = V / \lambda = 18.5\ Hz$$

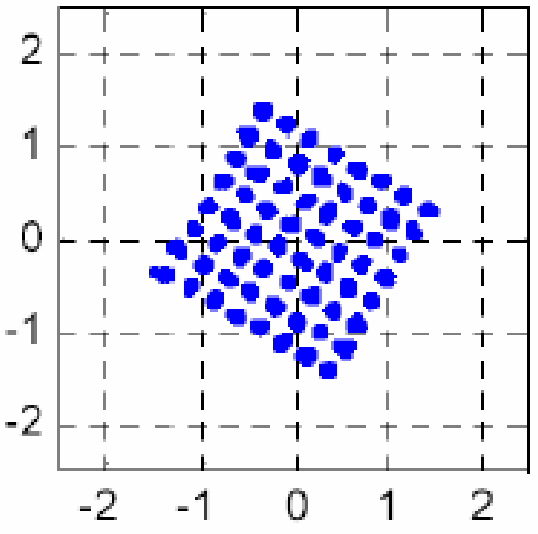
DOPPLER (DOPPLER SPREAD)



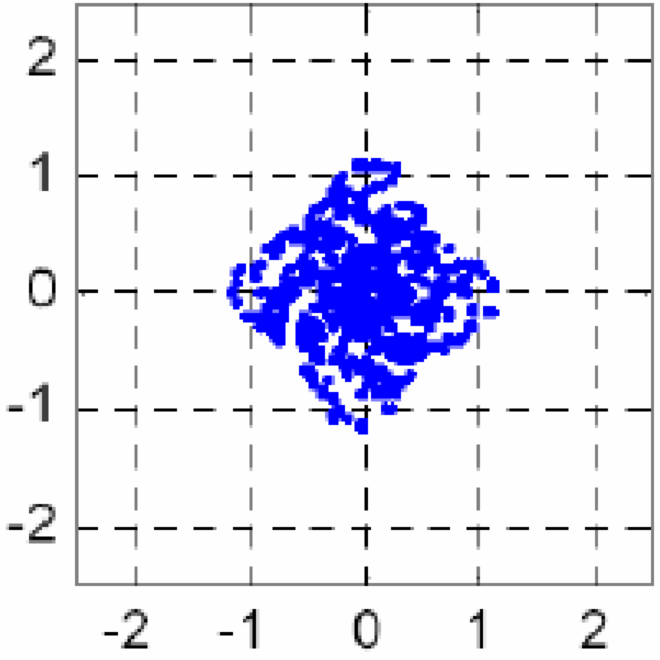
Ideal (equalised) constellation (SNR=30)







DOPPLER (DOPPLER SPREAD)



Joint Doppler and multipath effects on the modulated signal constellation

DOPPLER (DOPPLER SPREAD)

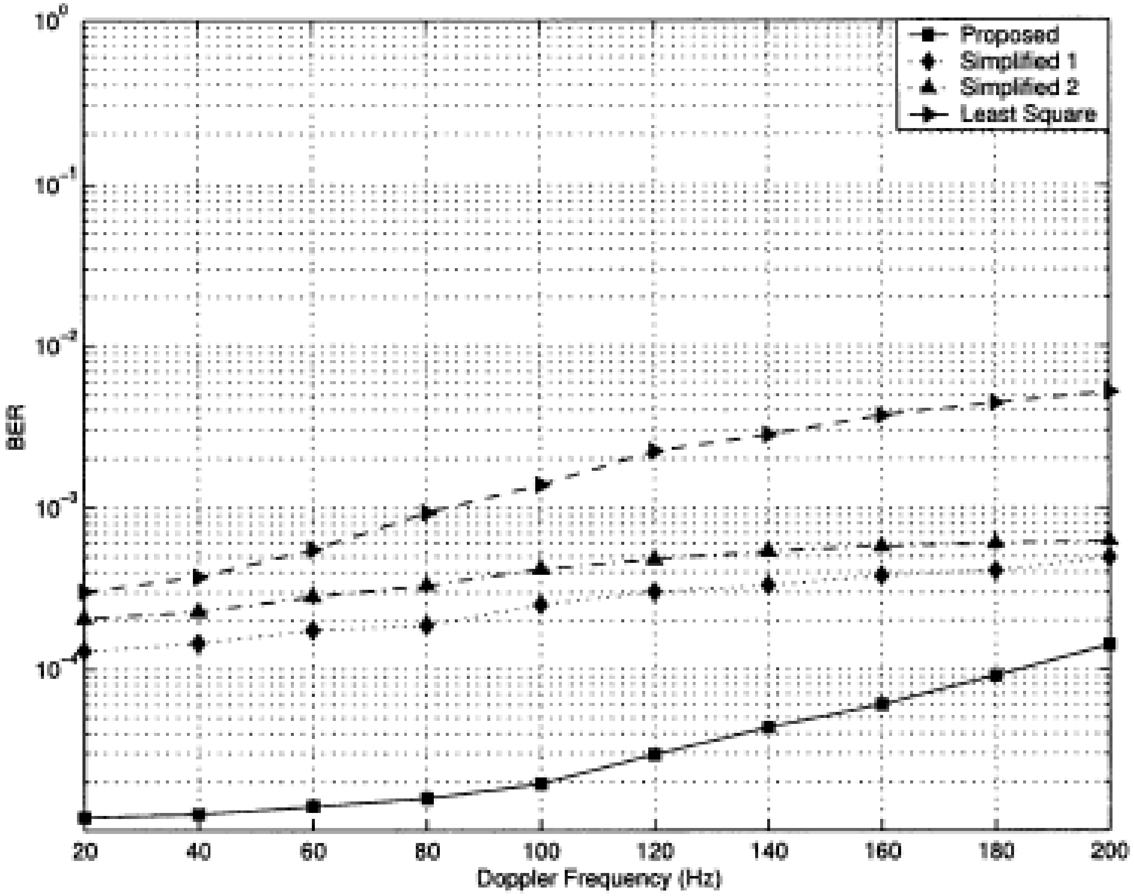


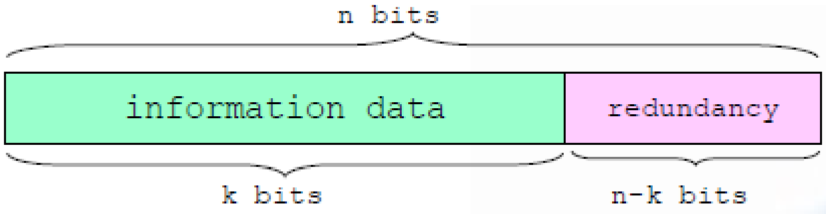
Fig. 3. BER performance for Doppler frequency based on various channel estimation schemes.

MODULE 4.4: FUNDAMENTALS *(*ERROR DETECTION AND CORRECTION *)*

Error control coding (channel coding)

ARQ: Detect errors and ask for frame retransmission. Achieves integrity by introducing some delay. ARQ needs a return link (full-duplex or semi-duplex link).

FEC: Correct errors, in order to reduce the BER, without increasing the received power. FEC needs an additional bandwidth to transmit redundant information. FEC achieves lower BER by introducing some throughput reduction.

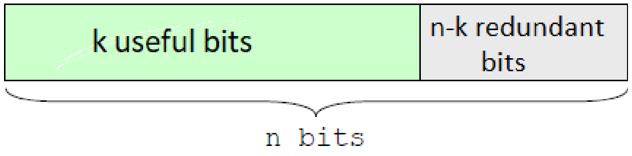


The redundant information is selected in a way that the resulting "codeword" belongs to a subset of all possible words (2^n) of size n bits. This allows error detection/correction. The probability of not detected error or incorrect decoding is not zero. If redundancy is added as a tail to the original frame the code is said to be "systematic".

FEC schemes accomplish the expressions:

$$\frac{n}{R_b'} \equiv \frac{k}{R_b} \Rightarrow R_b' = R_b \frac{n}{k} = \frac{R_b}{r} \quad ; \quad r \equiv \frac{k}{n} = \frac{\text{info bits}}{\text{total bits}} < 1$$

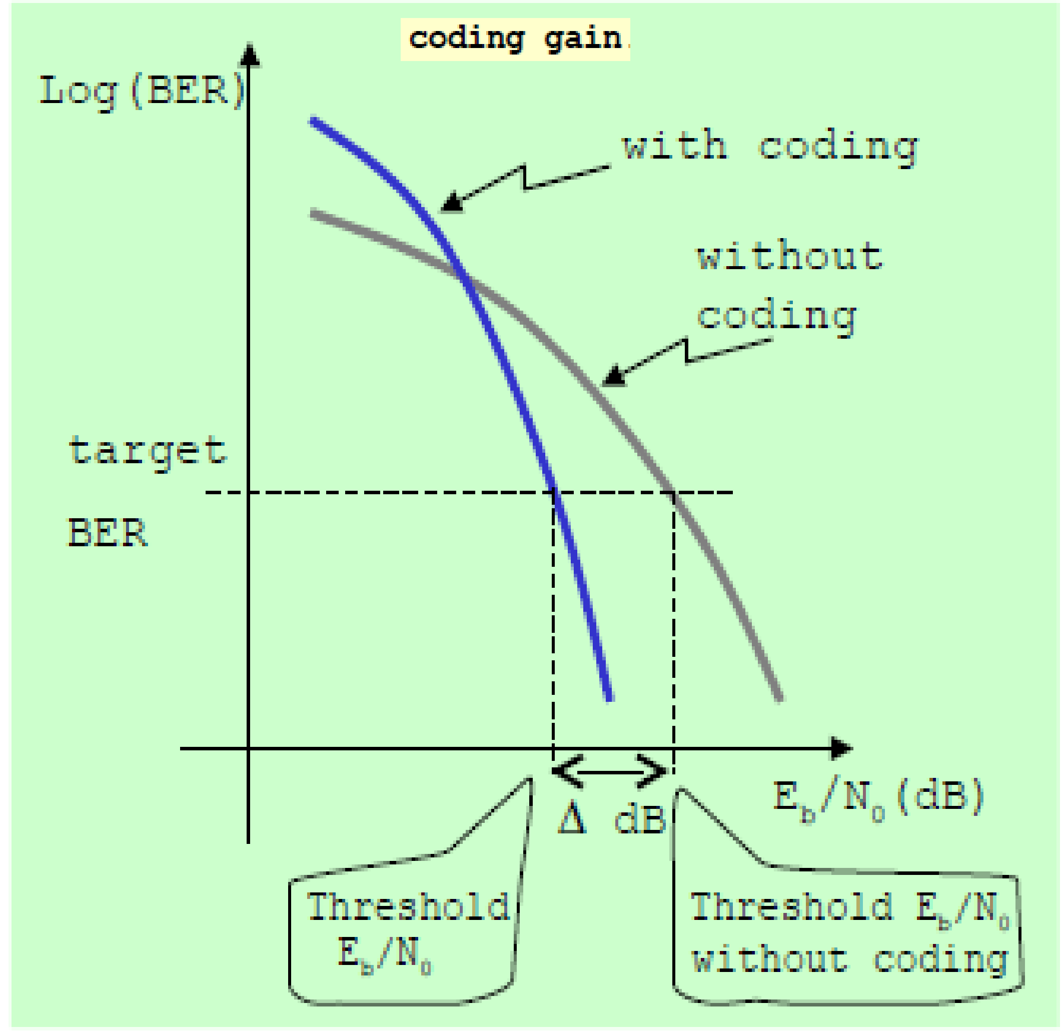
r= "rate" of the code. **Required bandwidth increases by a factor 1/r.**



code rate : **r=k/n**

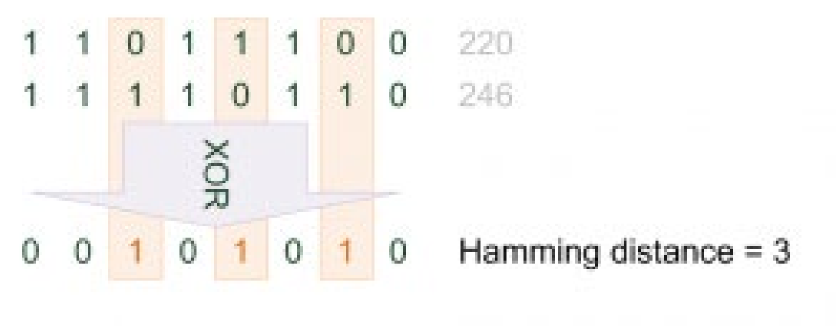
Error control techniques classification

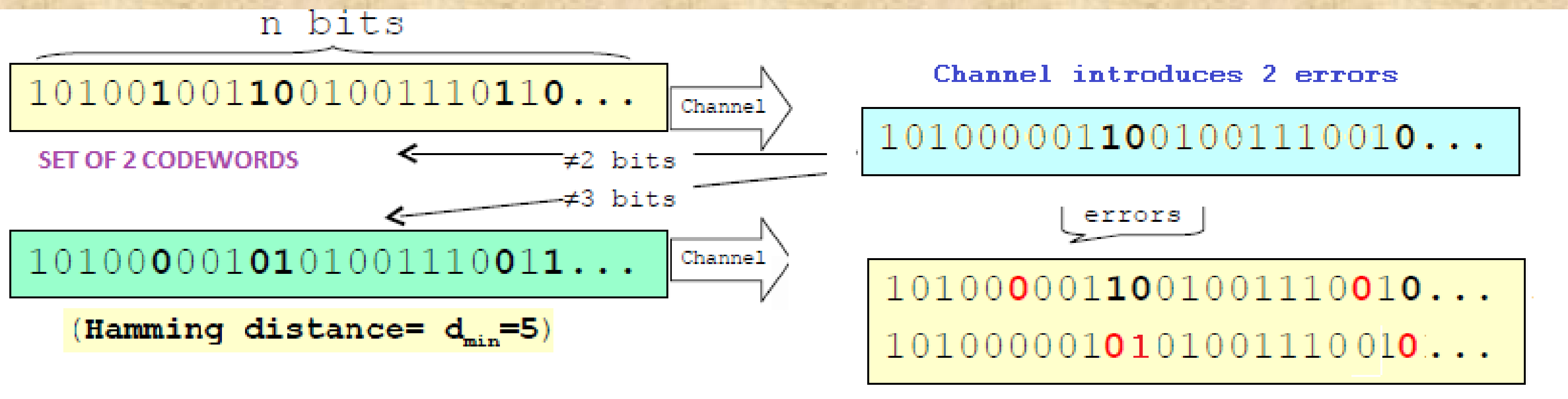
- Error control techniques
  - FEC
    - Block codes (detect and/or correct individual errors (one bit or one byte)
      - CRC
      - BCH
      - Reed-Solomon
      - ...
      - (Can't decode until full block is received)
    - Convolutional (detect the most probable transmitted sequence)
      - Conventional
      - Turbo-codes
      - (Can decode a flow of bits with a small initial delay)
  - ARQ (CRC tail and retransmissions)
    - Stop & Wait
    - Continuous
    - Selective
    - Hybrid type I or II
    - (Requires duplex link and introduces retransmission delay)


coding gain
Log(BER)
with coding
without coding
target BER
Δ dB
E_b/N_0(dB)
Threshold E_b/N_0
Threshold E_b/N_0 without coding

BLOCK CODES

Hamming distance = number of different bits in two codewords





n bits

1010010011001001110110...

Channel

SET OF 2 CODEWORDS

≠2 bits

≠3 bits

1010000010101001110011...

Channel

(Hamming distance= d_{min}=5)

Channel introduces 2 errors

1010000011001001110010...

errors

1010000011001001110010...

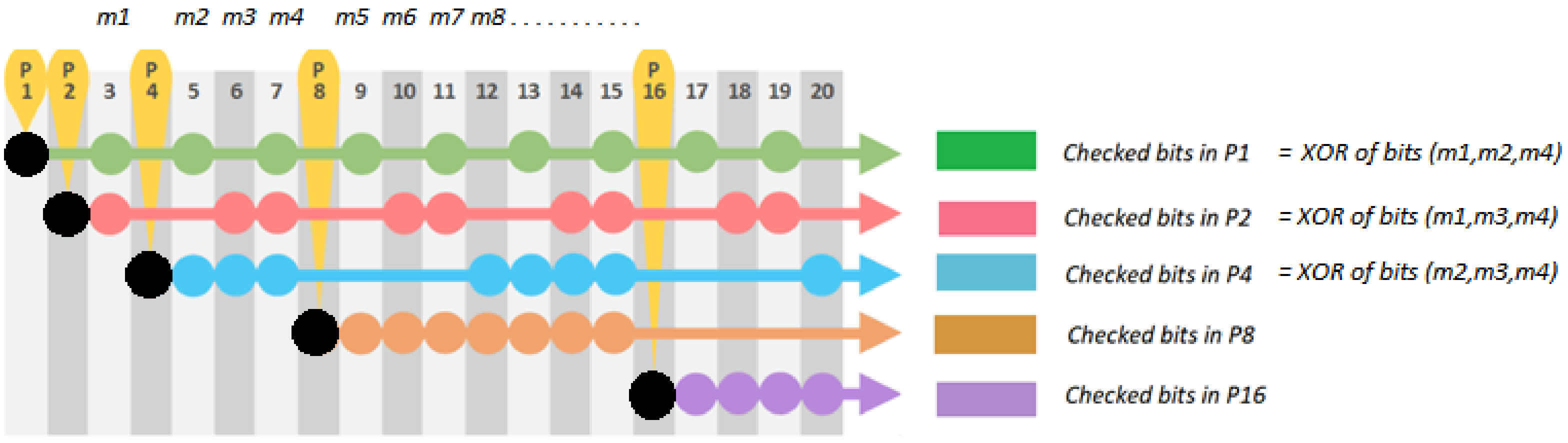
1010000010101001110010...

The maximum number of bit errors that can be **corrected** (t) is:

$$t = \lfloor \frac{d_{min}-1}{2} \rfloor$$

And the maximum number of bit errors that can be **detected** is **d_{min}-1**.

BLOCK CODES: Hamming



🟩 Checked bits in P1 = XOR of bits (m1,m2,m4)

🟥 Checked bits in P2 = XOR of bits (m1,m3,m4)

🟦 Checked bits in P4 = XOR of bits (m2,m3,m4)

🟧 Checked bits in P8

🟪 Checked bits in P16

Parity bits calculation

Inputs			outputs
W	X	Y	Q = A⊕B⊕C
0	0	0	0
0	0	1	1
0	1	0	1
0	1	1	0
1	0	0	1
1	0	1	0
1	1	0	0
1	1	1	1

Generator matrix (G) for code (7,4)

An example of Hamming (7,4) code generator matrix:

$$G = \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix}$$

$2^4 = 16$ codewords

$$\begin{array}{cccc} [1 & 0 & 1 & 1] \\ m1 & m2 & m3 & m4 \end{array} \begin{bmatrix} 1 & 1 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 \end{bmatrix} = \begin{array}{ccccccc} P1 & P2 & m1 & P3 & m2 & m3 & m4 \\ [0 & 1 & 1 & 0 & 0 & 1 & 1] \end{array}$$

Codewords have Hamming distance 3

$$codeword = [0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 1 \quad 1]$$

$$received\ codeword = [0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 1 \quad 0]$$

$$syndrome = [0 \quad 1 \quad 1 \quad 0 \quad 0 \quad 1 \quad 0] \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 1 \\ 0 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix} = [1 \quad 1 \quad 1]$$

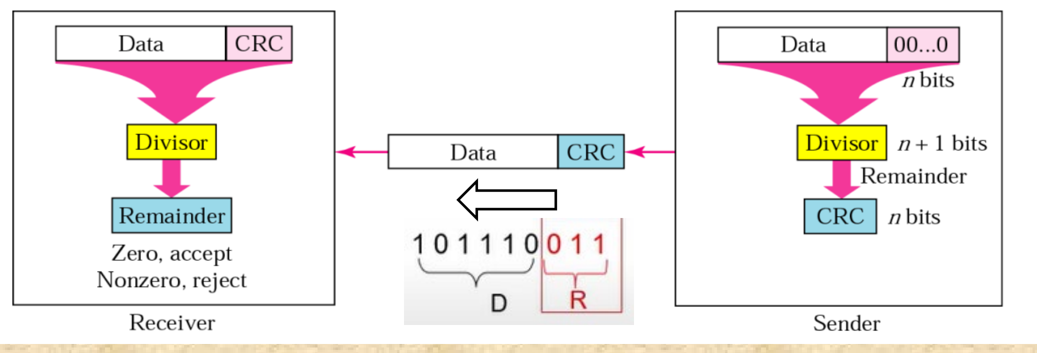
Parity check matrix (H) for code (7,4)

$2^2 + 2^1 + 2^0 = 7$ (error position)

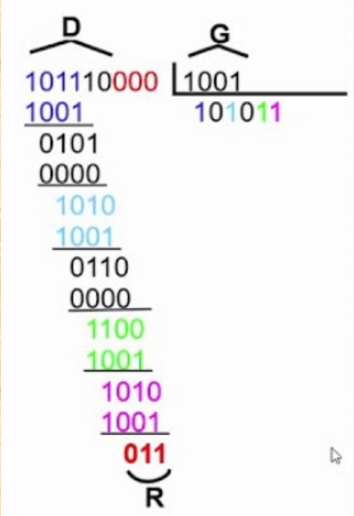
dmin = 3 → t= (3-1)/1 = 1 bit corrected

BLOCK CODING: CRC (cyclic redundancy check)

Error detection code. Errors not isolated (bursts). CRC (N,k)

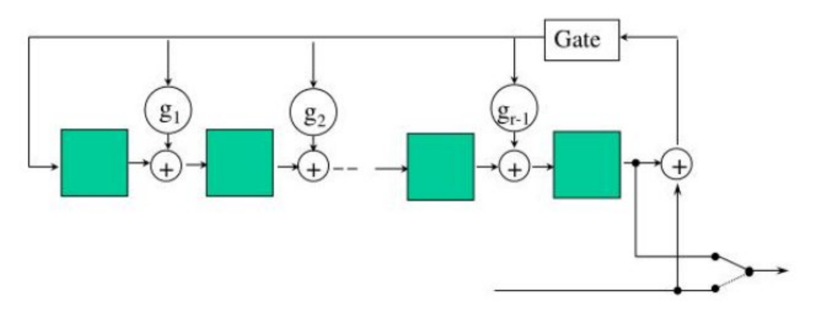


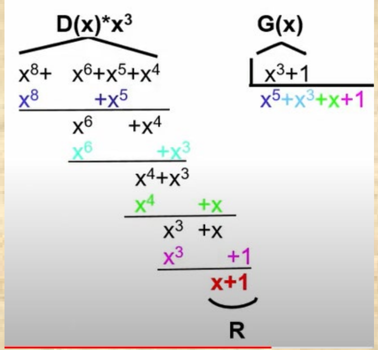
EX CRC(9,6)
DATA, D= 101110
Polynomial generator, G= 1001



Receiver: the sequence 101110011
is divided by 1001(G),
if the residual is 0,
the data is received correctly

This division can be easily done
by using XOR (mod 2 arithmetic).



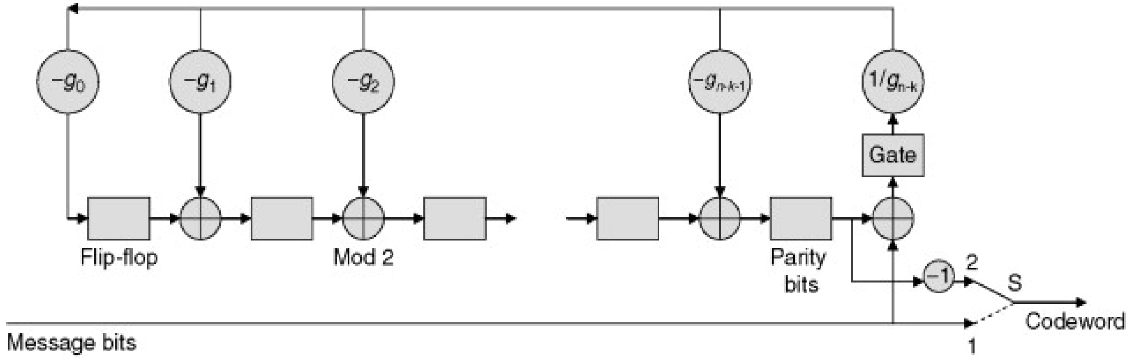


CYCLIC CODES: Block codes, where the circular shifts of each codeword gives another word that belongs to the code

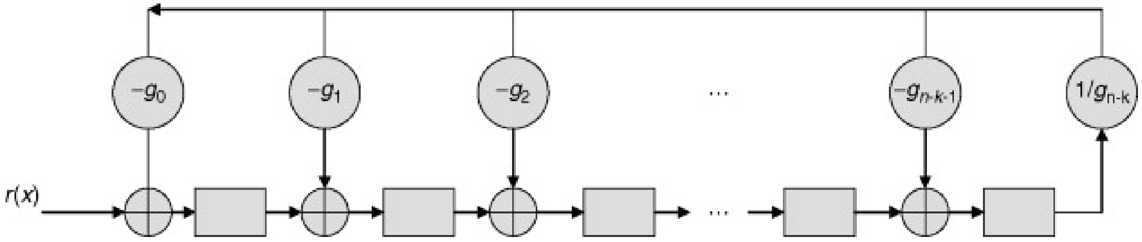
***I.e, Bose-Chaudhuri-Hocquenghem* (BCH) codes** are multi-bit error correcting codes. The BCH codes essentially combine multiple polynomials into a single generating polynomial with predictable distance properties and the ability to correct multiple bit errors. A subclass are **Reed Solomon (RS) codes** (operation on multiple bits rather than individual bits, largest possible code minimum distance for any linear code with the same encoder input and output block lengths).

generating polynomial $g(x) = g_0 + g_1x + \ldots + g_{n-k}x^{n-k}$

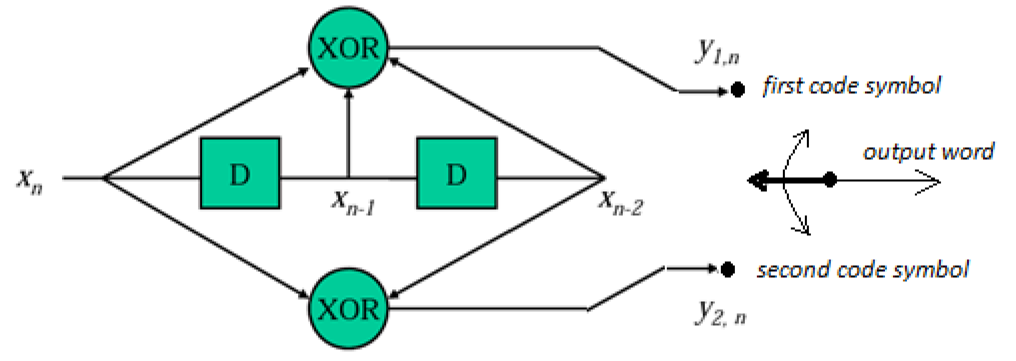
codeword polynomial $r(x) = r_0 + r_1x + \ldots + r_{n-1}x^{n-1}$

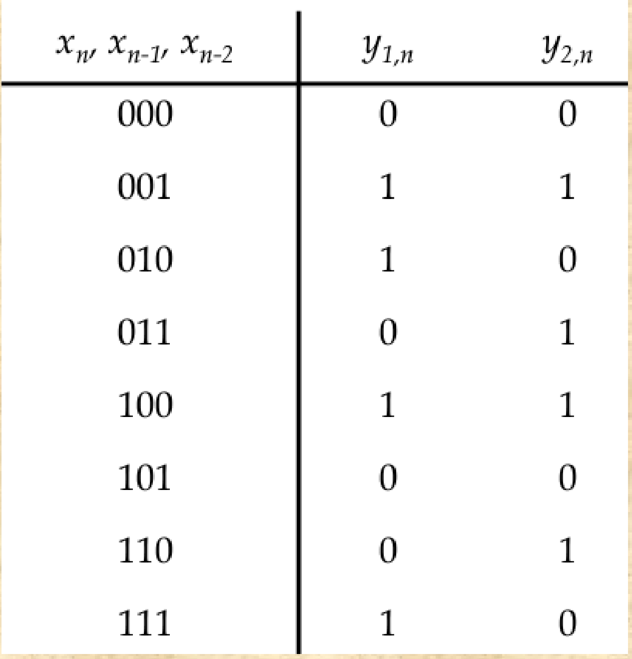


syndrome polynomial $s(x) = \text{rem}[r(x)/g(x)]$



Convolutional Coding

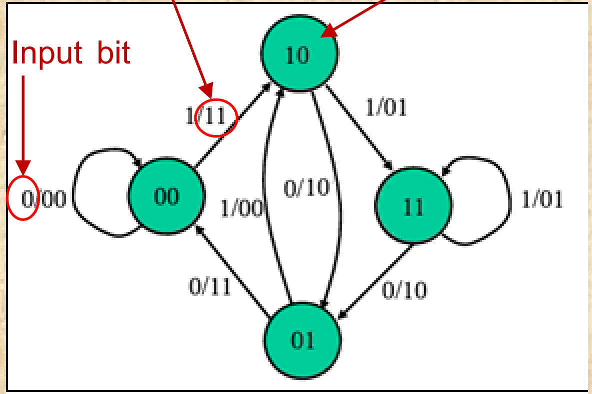




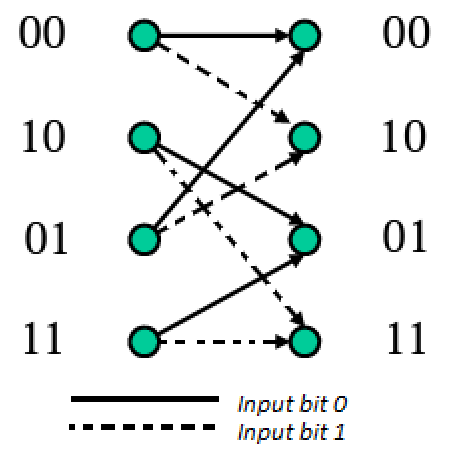
x_n, x_{n-1}, x_{n-2}	$y_{1,n}$	$y_{2,n}$
000	0	0
001	1	1
010	1	0
011	0	1
100	1	1
101	0	0
110	0	1
111	1	0

output word

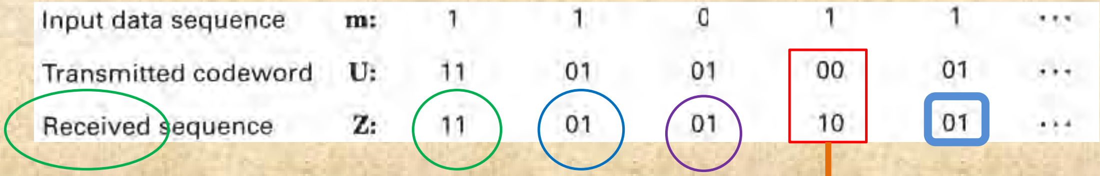
State transition (encoder)


Input bit

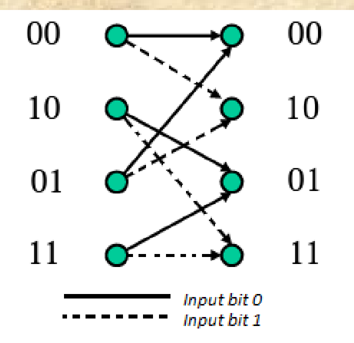
Trellis

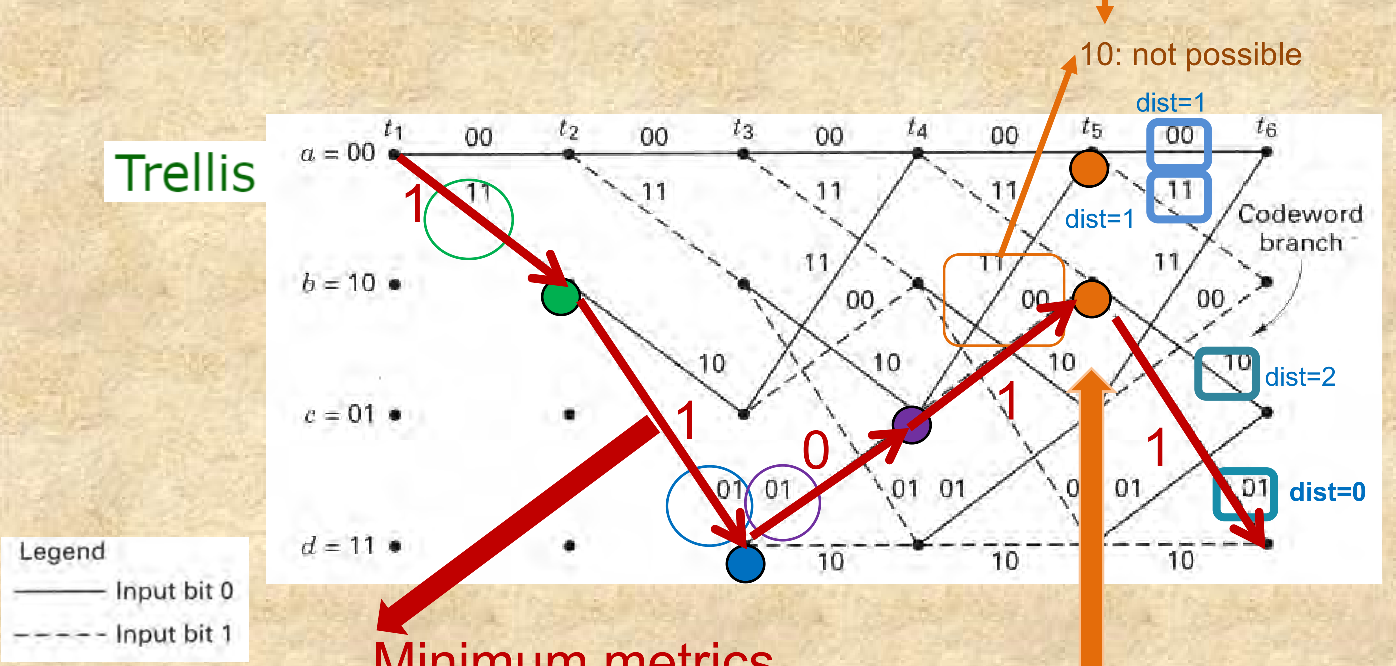


- Assume start in state 00
- Input sequence: 1 1 0 1 1
- Output codeword: 11 01 01 00 01



Input data sequence	m:	1	1	0	1	1	···
Transmitted codeword	U:	11	01	01	00	01	···
Received sequence	Z:	11	01	01	10	01	···





Trellis

10: not possible

Legend
Input bit 0
Input bit 1

Minimum metrics

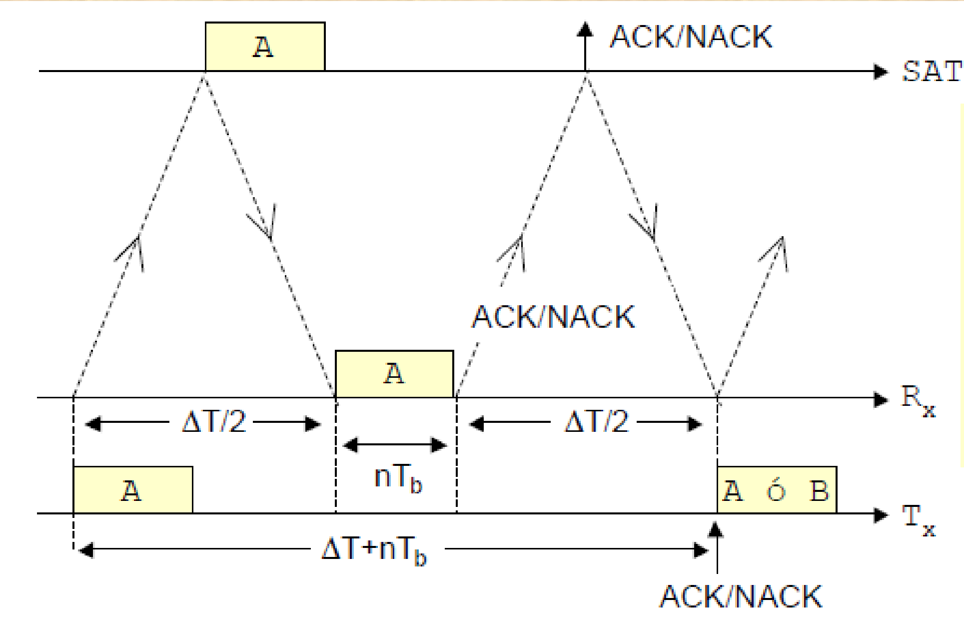
Equal metrics ??? (not solved)

ARQ (Automatic Retransmission Request)

Error-control method that uses acknowledgements
(messages sent by the receiver indicating that it has correctly received a packet)

Stop-and-wait, Go-Back-N and Selective Repeat

Stop & Wait)



Go Back N

Multiple frames are sent before receiving the acknowledgment for the first frame. The frames are finite and sequentially numbered. The maximum number of frames that can be sent depends upon the size of the sending window (time delay). If the acknowledgment of a frame is not received and agreed upon a time period, ***all frames starting from that frame are retransmitted***. It's to say, the transmitter **goes back to the sequence number** of the last acknowledgement received.

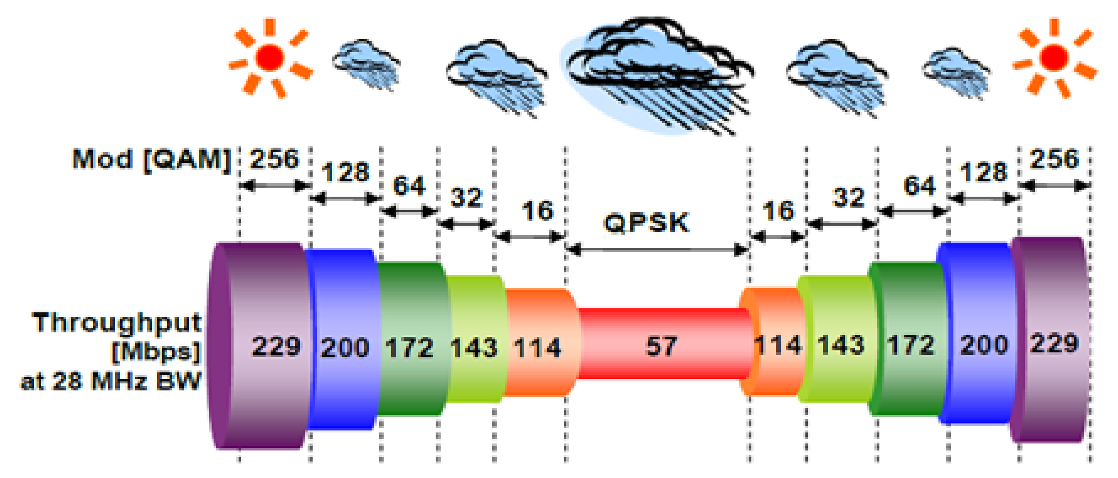
selective ARQ

It is similar to Go Back N, but only the suspected or damaged frames are retransmitted

ERROR CONTROL (ALTERNATIVE) : Link adaptation

Link adaptation: comprises **adaptive modulation** and/or **coding** (as well as transmit power control). to maintain a given fixed instantaneous BER for each symbol while maximizing the average data rate. The transmission scheme is adapted to the channel characteristics.

- Choice of the modulation type
- Choice of FEC data rate.



Do not confuse with Transmodulation, which converts the RF signal from one kind of modulation or standard to another.