Digital communications
M1 E3A - International Track

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SIAM

Signal, Image, AutoMatique

Objectives of this module

- Know the components et interfaces of a digital communication system
- Know how to adapt the information to the transmission support
- Know how to transmit the information then how to extract it and recover it
- Know how to evaluate the performances of a digital communication system
- Apply the previous items to a real system

Module sequencing

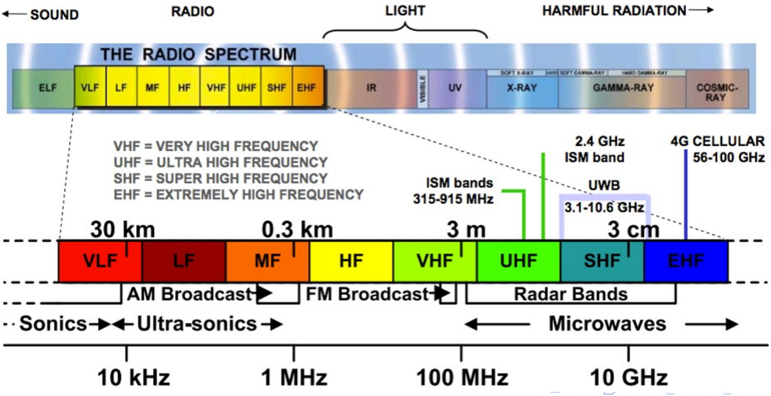
Communication system : a way to **transmit information from a source to a destination** (between 2 humans, between a human and an animal, between a human and a machine, between 2 machines...).

Radicommunication system : a way to transmit information using **radio(electric) waves**.

General notions and communication interfaces
Radio(electric) wave

Electromagnetic wave, frequency ranging from $3KHz$ to $300GHz$.

Radio spectrum :



General notions and communication interfaces

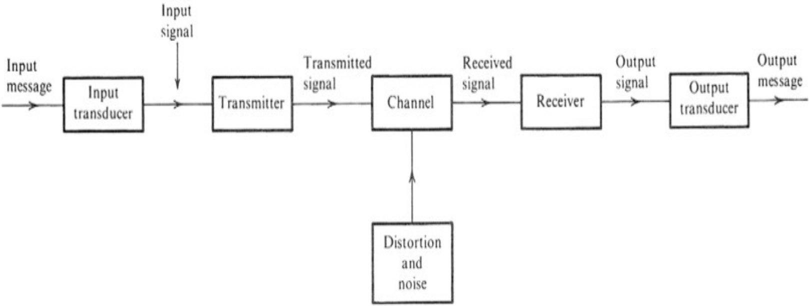
Radio(electric) wave (cont.)

Radio spectrum usage : some examples

- VLF ($3KHz$ to $30KHz$) : communication with submarines
- LF ($30KHz$ to $300KHz$) : AM radio diffusion (large wave)
- MF ($300KHz$ to $3MHz$) : radio diffusion (medium wave)
- HF ($3MHz$ to $30MHz$) : radio diffusion (short wave)
- VHF ($30MHz$ to $300MHz$) : FM radio diffusion
- UHF ($300MHz$ to $3GHz$) : GSM, GPS, wireless phones
- SHF ($3GHz$ to $30GHz$) : satellite radiodiffusion
- EHF ($30GHz$ to $300GHz$) : radar anticollision radars for cars

General notions and communication interfaces

Block diagram



General notions and communication interfaces

Block diagram (cont.)

Message to transmit = system input information

Essential blocks in a communication system :

- **Input transducer** : converts the message to electric signal
- **Transmitter** : adapts this signal to the transmission channel
- **Channel** : transmission medium of the emitted signal
- **Receiver** : extracts information from distorsions and noise
- **Output transducer** : converts information to its original form

General notions and communication interfaces

Transmitter

Simple design.

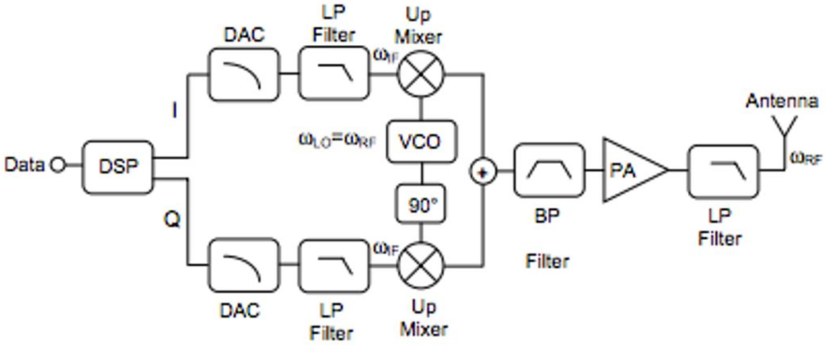
Mains components in a modern TX :

- Frequency source (example : oscillator)
- Modulator
- Power amplifier
- Antenna
- Alimentation
- Connector between TX and antenna

General notions and communication interfaces

Transmitter (cont.)

TX architecture : example (direct conversion)



General notions and communication interfaces

Receiver

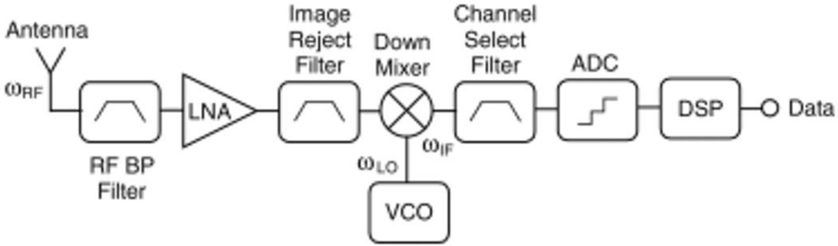
Progressively complex design.
Two problems : **sensitivity** et **selectivity**.

Main components of a modern RX :

- Antenna
- LNA : *low noise amplifier*
- Local oscillator
- Down mixer (for heterodyne RX)
- IF (*intermediate frequency*) synthetiser
- High gain amplifier
- Baseband demodulator

General notions and communication interfaces
Receiver (cont.)

RX architecture example (syper heterodyne)



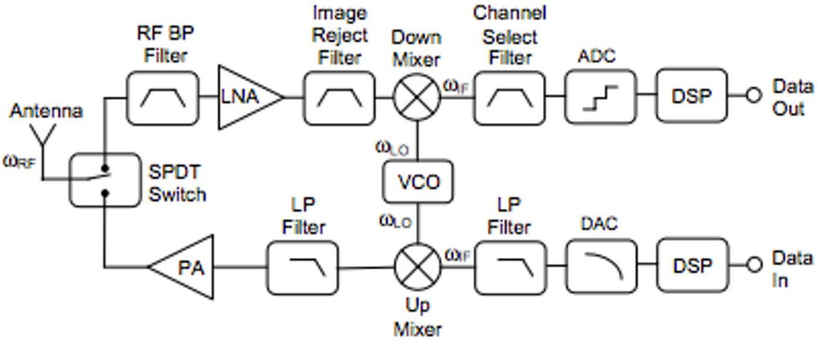
General notions and communication interfaces

Transceiver

Transceiver : operational unit including both TX and RX functions.

Advantage : more compact architectures

TRX architecture example (syper heterodyne)

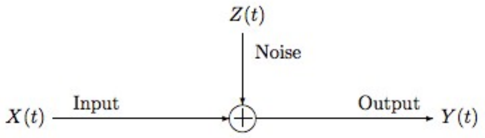


General notions and communication interfaces
Channel

The more frequently used model : AWGN

AWGN : Additive White and Gaussian Noise

Requires no *a priori* information about statistical properties of the input signal at the receiver.



General notions and communication interfaces

Digital signals vs. analog signals

Digital signal : built based on a finite number of symbols

(example : text file)

Analog signal : its values vary in a continuous space

(example : speech)

Digital signals are progressively replacing analog signals, for **immunity** reasons.

- Analog : error risk in presence of distrosion and/or noise
- Digital : in certain limits, possibility of signal recovery, error free

General notions and communication interfaces

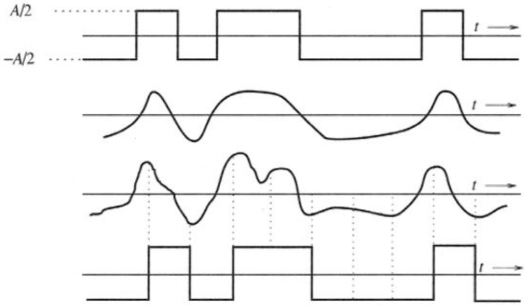
Digital signals vs. analog signals (cont.)

Signal 1 : emitted signal

Signal 2 : signal after distorsion

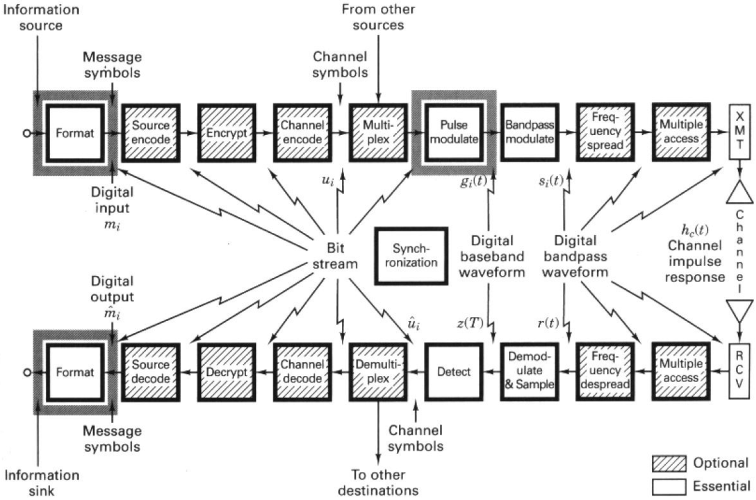
Signal 3 : signal after distorsion and noise

Signal 4 : recovered signal



General notions and communication interfaces

Digital communication system - Block diagram



Message to transmit = information at the system input

Essential blocks in a digital communication system :

- **Input format** : converts the message to binary stream
- **Baseband modulation** : converts the stream to electrical signal
- **Bandpass modualation** : adapts the signal to the channel
- **Demodulation** : converts the received signal to baseband
- **Detection** : extracts information from distorsions and noise
- **Output format** : converts the detected stream to its original form

General notions and communication interfaces

Digital communication system - Block diagram (cont.)

Complementary blocks :

- **Source coding** : compresses the data
- **Encrypt** : renforces data security
- **Channel coding** : adds redundancy to data
- **Multiplexng** : gather information of multiple transmitters
- **Spread spectrum** : enlarges the used frequency bandwidth
- **Multiple access** : arbitrates the access to the channel (time, frequency, space, code)

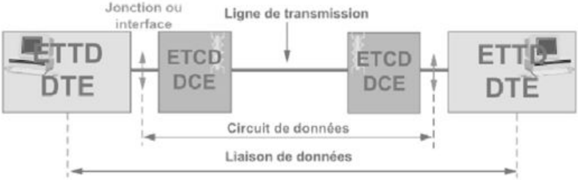
We have the same functions at the receiver (decoding, decrypt,...) .

General notions and communication interfaces

Communication interfaces

Physical supports to set up a transmission chain.

Elements of a transmission link : DTE, DCE, junction, line.



General notions and communication interfaces

Communication interfaces (cont.)

DTE (Data Treatment Equipment) :

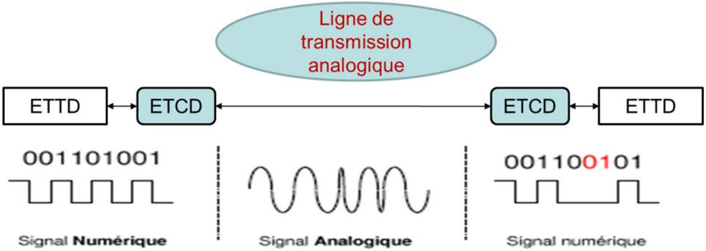
- Is responsible of exchanging data with the network
- But it is not directly connected to the transmission line
- Examples : computer, printer. . .

General notions and communication interfaces

Communication interfaces (cont.)

DCE (Data Circuit Equipment) :

- Is responsible of data tranmsission
- Adaptats the DTE signal to the transmission line, manages the link
- Examples : modem, multiplexer...

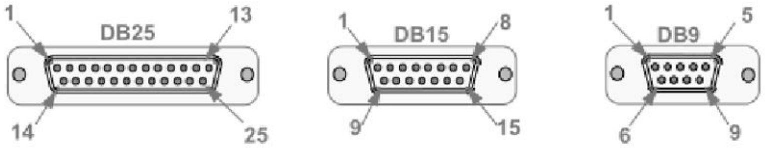


General notions and communication interfaces

Communication interfaces (cont.)

Junction :

- Interface between DTE and DCE
- Is responsible of controlling the DCE
- Examples :



General notions and communication interfaces

Communication interfaces (cont.)

Transmission line :

- Physical support enabling the link
- Guided support : wired (wire rope...) or optical (fibres)
- Free support : radio waves transmission

General notions and communication interfaces

Link operation : simplex vs. duplex

Simplex mode :

- One system ONLY transmits, the other ONLY receives
- Data stream in one way
- Examples : wired mouse to computer, FM radio broadcast

Half Duplex mode :

- Both systems can transmit and receive
- But emissions CAN NOT be made simultaneously
- Examples : wireless mouse, talkie walkie

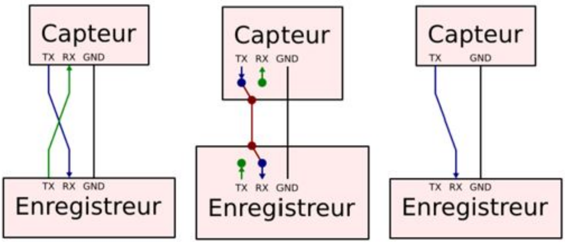
Full Duplex mode :

- Both systems can transmit and receive
- Emissions CAN be made simultaneously
- Examples : cellular phones, satellite commnications

General notions and communication interfaces

Link operation : simplex vs. duplex (cont.)

From left to right : Full duplex, Half duplex, Simplex.

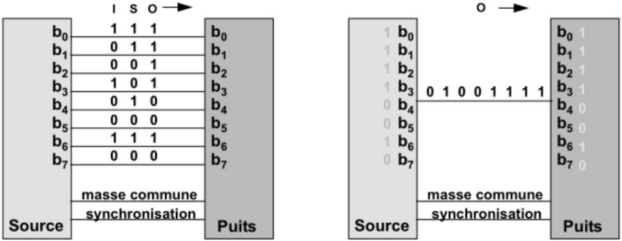


General notions and communication interfaces

Link operation : serial vs parallel

If the bits of a same word are transmitted simultaneously : **parallel transmission**.

If the bits of a same word are transmitted successively through the same line : **serial transmission**.

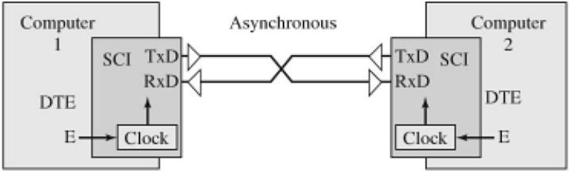


General notions and communication interfaces

Link operation : synchronous vs asynchronous

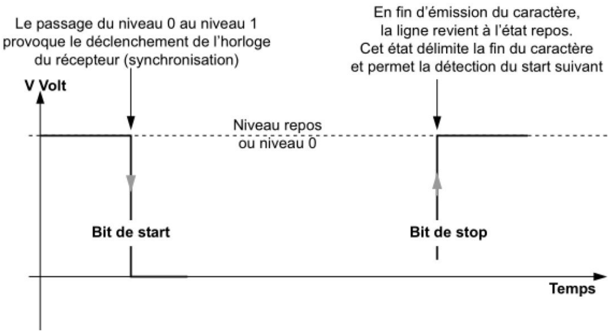
Asynchronous transmission :

- TX and RX clocks are independant
- Frames are delimited by : bit "start", bit "stop"
- Each data element is emitted in a irregular way in time
- Example : character entering through a computer keyboard



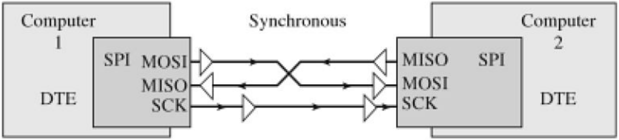
Asynchronous transmission : frame delimitation

- Before data transmission : specific control signal
- Bit "start" at the frame beginning
- Bit "stop" at the frame end



Synchronous transmission : synchronised clocks

- The RX continuously receives data
- At the rythm the TX sends them (even if no bit is transmitted)
- Bits are successively sent, without any separation
- This kind of link needs synchronisation elements
- Transmision rate is quite low to distinguish messages

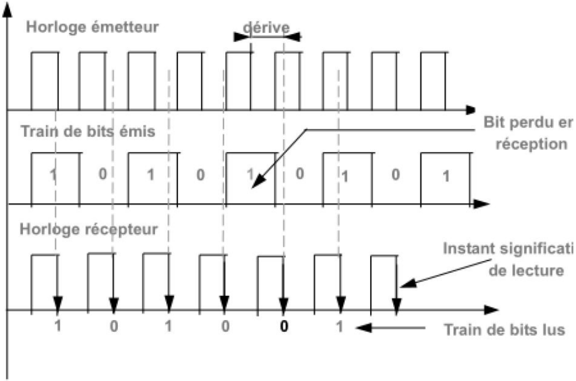


General notions and communication interfaces

Link operation : synchronous vs asynchronous (cont.)

Synchronous transmission : clock drift

- "Little" time lag between TX and RX streams
- After some time : lost bit at the RX side

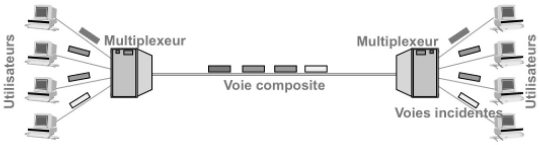


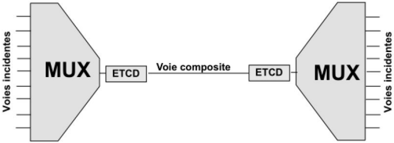
General notions and communication interfaces

Link operation : Multiplexing

Idea : gather many TX at the same transmission medium.

- The physical support is shared
- The signals are transmitted continuously (composite channel)

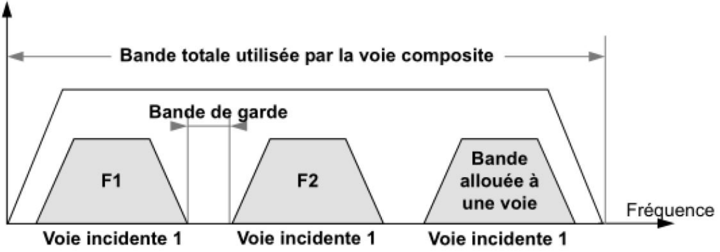




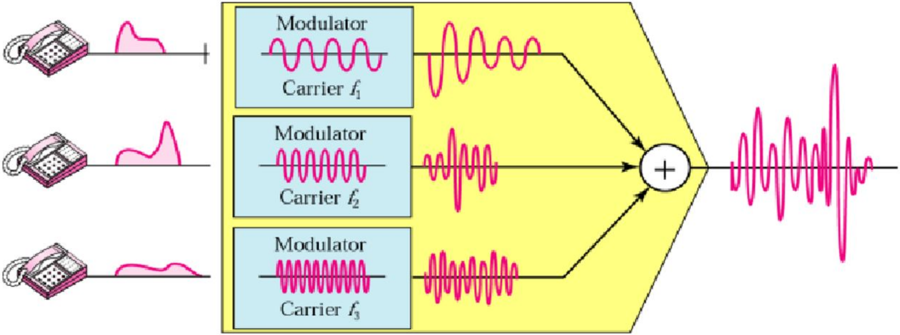
General notions and communication interfaces
Link operation : Multiplexing (cont.)

Frequency multiplexing : share the available frequency spectrum.

- The frequency bandwidth is divided into smaller channels.
- Guard bands separate user to avoid interferences



Frequency multiplexing : example.

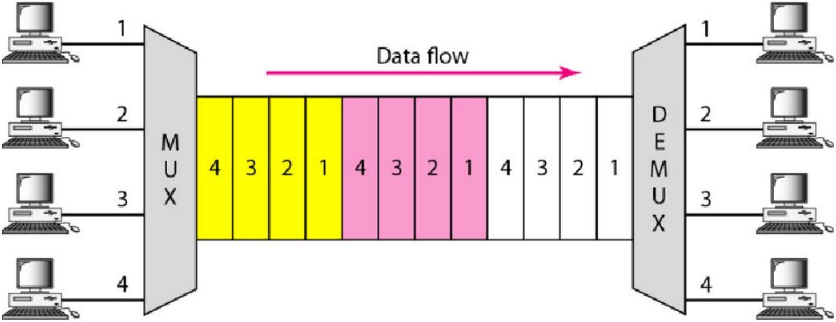


General notions and communication interfaces

Link operation : Multiplexing (cont.)

Time multiplexing : share the available occupation time.

- The time is divided into smaller intervals (time channels).
- Each channel is assigned to only one TX/RX.

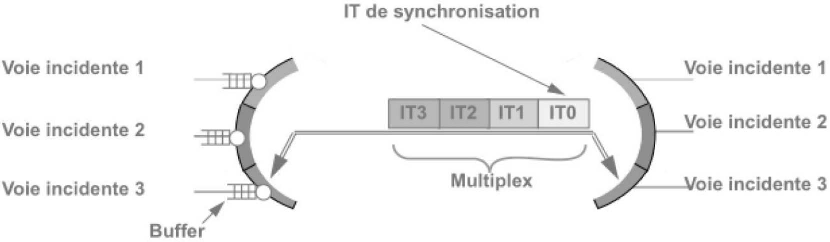


General notions and communication interfaces

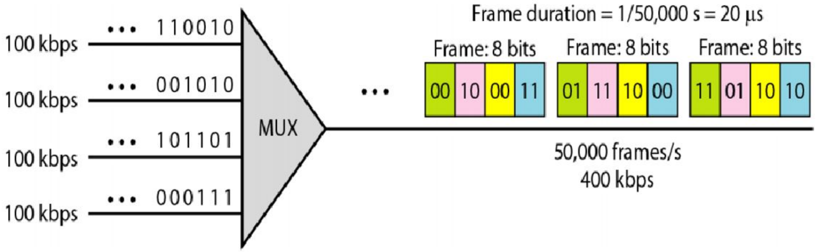
Link operation : Multiplexing (cont.)

Time multiplexing :

- A synchronisation interaval ($IT0$) delimits the frame and helps recovering the different channels.

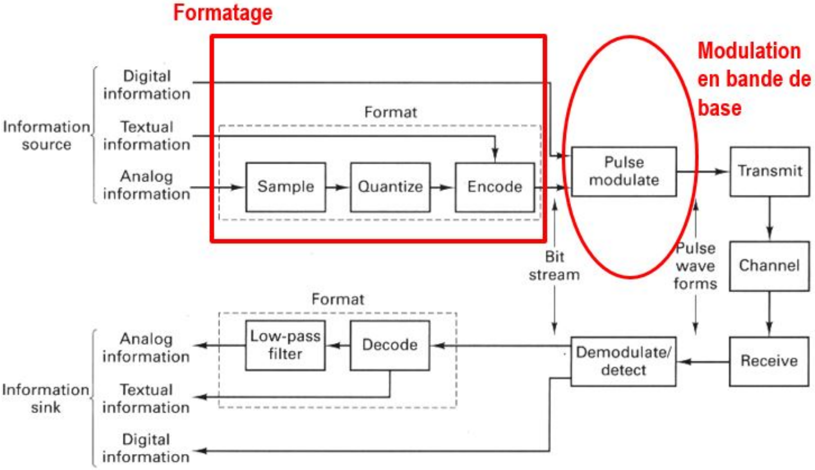


Time multiplexing : example.



Format and baseband signalling

Introduction



Format and baseband signalling

Format information

Starting point : input information (analog, textual, digital)

- digital information : no need to format
- textual information : only need to encode
- analog information : need to format

Format steps :

- sampling : transform information to discrete signal
- quantification : transform samples to predefined characters
- encoding : transform characters to binary stream

Goal : transform the analog signal to discrete signal

Problem : how to get the most faithful representation possible

Tool : Nyquist criterion

The sampling frequency F_s must satisfy the condition $F_s \geq 2.f_{max}$

f_{max} : maximal frequency contained in the analog signal.

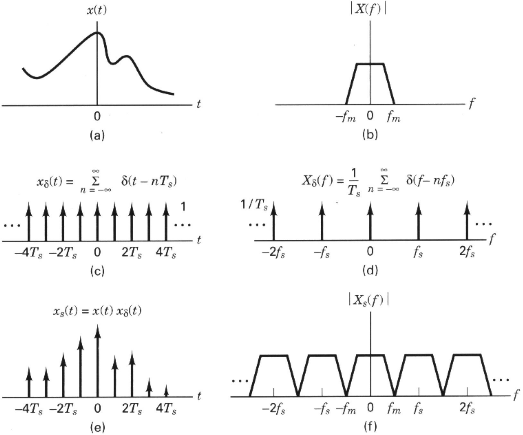
Consequence : the analog signal can be totally recovered at the receiver, through the samples, uniformly seperated by $T_s = \frac{1}{F_s}$

Format and baseband signalling

Format step 1 : Sampling (cont.)

Ideal sampling : use of Dirac comb (sampling train)

Consequence : we obtain a periodic spectrum

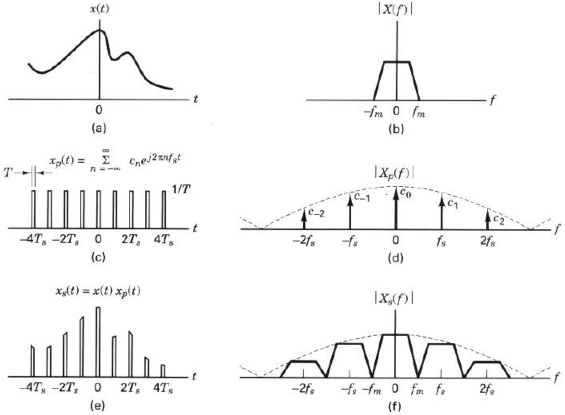


Format and baseband signalling

Format step 1 : Sampling (cont.)

Real sampling : use of impulsion train

Consequence : spectrum covered by a sinc function

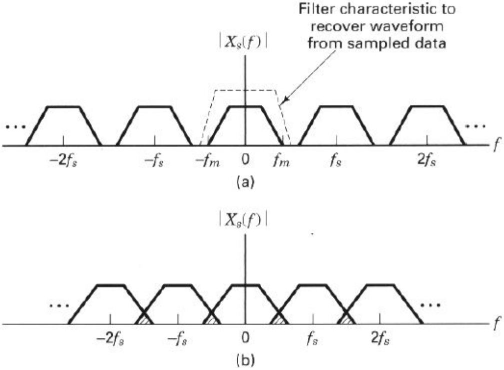


Format and baseband signalling

Format step 1 : Sampling (cont.)

Particular case : if Shannon criterion is not respected

Consequence : spectrum aliaising

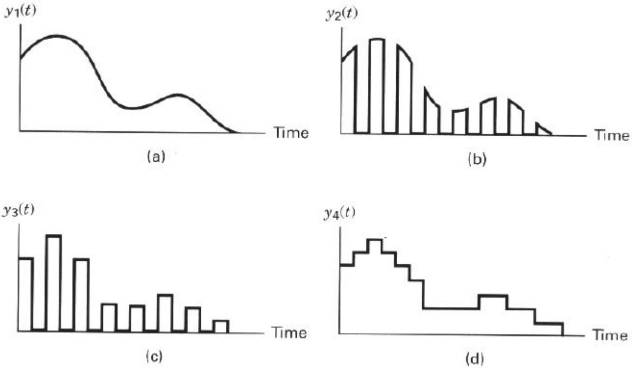


Format and baseband signalling

Format step 2 : Quantification

Goal : assemble samples into a smaller set of values

Example : from analog signal to quantified signal

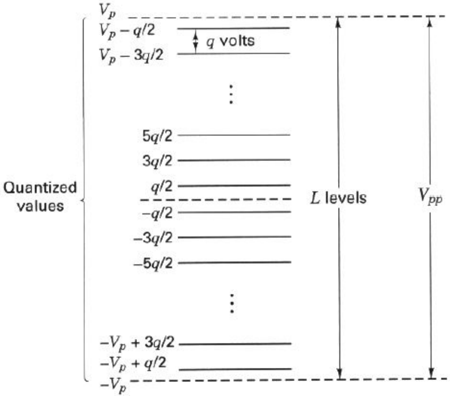


Format and baseband signalling

Format step 2 : Quantification (cont.)

Uniform quantification : quantized levels are uniformly spaced

Example :

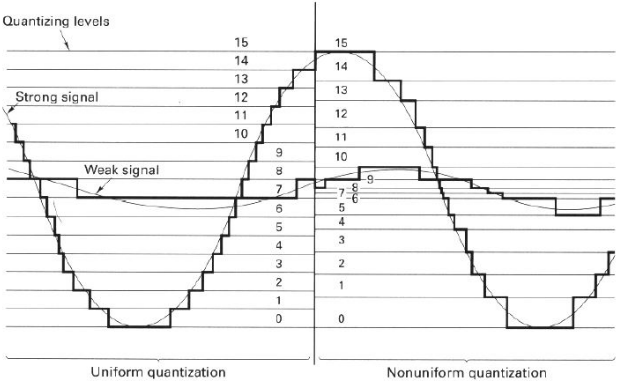


Format and baseband signalling

Format step 2 : Quantification (cont.)

Non uniform quantification : takes into account signal properties

Example :

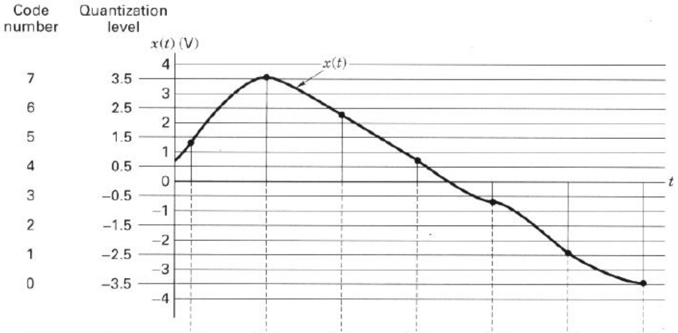


Format and baseband signalling

Format step 3 : encoding

Goal : transform quntified samples to codewords.

Example :



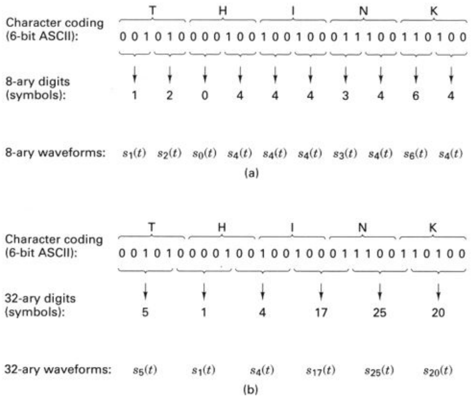
Natural sample value	1.3	3.6	2.3	0.7	−0.7	−2.4	−3.4
Quantized sample value	1.5	3.5	2.5	0.5	−0.5	−2.5	−3.5
Code number	5	7	6	4	3	1	0
PCM sequence	101	111	110	100	011	001	000

Format and baseband signalling

Format step 3 : textual information encoding

Goal : transform characters to binary stream

Example : ASCII coding of the word (" *think*").



Format and baseband signalling

Baseband modulation

Format output :binary stream / codewords to describe information

Probem : no physical sense !

Goal : transform codewords onto electric signals (waveforms)

Tool : represent each bit by an elementary signal (code law)

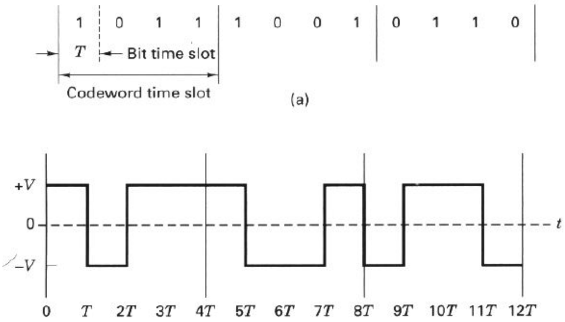
Consequence : modulator output is adapted to the transmission medium

Format and baseband signalling

Code law

Example : case of binary stream

Law : Bit "1" [+V], Bit "0" [-V]



Format and baseband signalling

Modulator categories

Case of binary stream : line code (PCM : *Pulse code modulation*)

- NRZ code (*Non return to zero*)
- RZ code (*Return to zero*)
- *Phase encoded*
- *Multilevel binary*

Case of codewords (more than 2) : pulse modulation (*M-ary PxM*)

- PAM Modulation (*Pulse amplitude modulation*)
- PPM Modulation (*Pulse position modulation*)
- PDM Modulation (*Pulse duration modulation*) = PWM (W : Width)

Format and baseband signalling

Line codes : NRZ

Signification : we don't use the level [0 Volt]

Usage : logical circuits, magnetic band recording

NRZ-L (level) law : "1" [+V], "0" [-V]

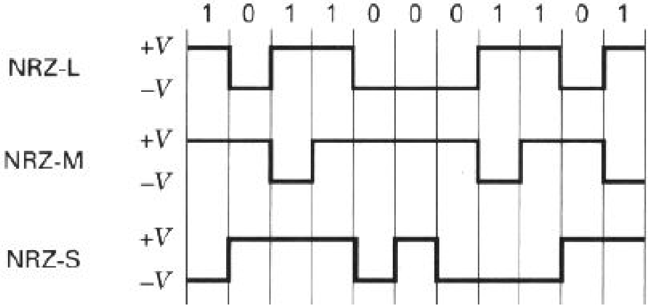
NRZ-M (mark) law : "1" [transition], "0" [no transition]

NRZ-S (space) law : "1" [no transition], "0" [transition]

Format and baseband signalling

Line codes : NRZ (cont.)

Illustration :



Format and baseband signalling

Line codes : RZ

Signification : we use the leval [0 Volt]

Usage : data baseband trasmission, recordings

unipolar RZ : "1" [transition +V to 0], "0" [0 Volt]

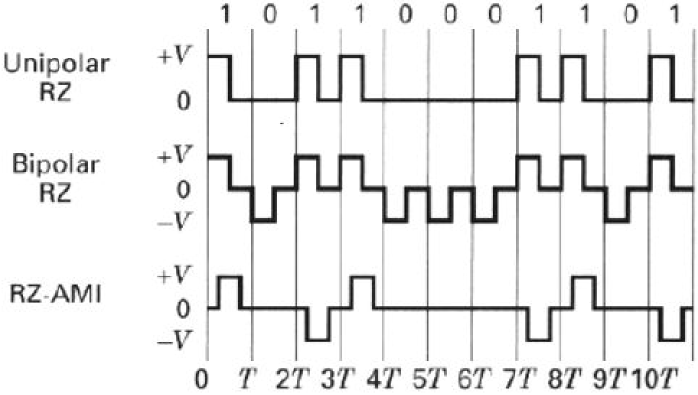
bipolar RZ : "1" [transition +V, 0, -V], "0" [transition -V, 0, +V]

RZ AMI (Alternate Mark Inversion) : "1" [alternatively +V, -V], "0" [0 Volt]

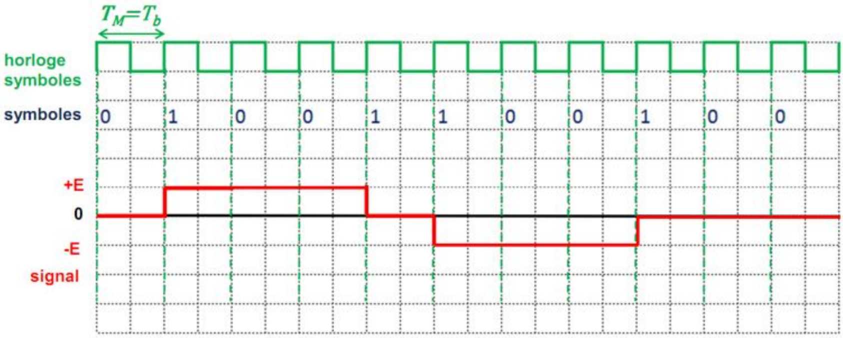
Format and baseband signalling

Line codes : RZ (cont.)

Illustration :



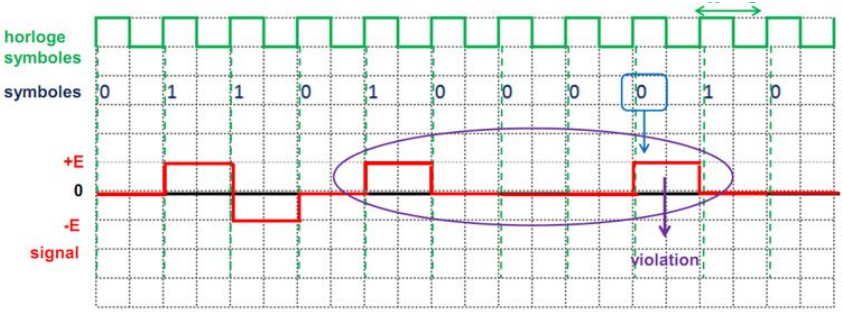
Your turn: MLT 3 (Multi Level Transmit 3) coding



Format and baseband signalling

Line codes : RZ (cont.)

Alternative : HDB3 (High Density Bipolar order 3)



Format and baseband signalling

Line codes : RZ (cont.)

Difference between HDB3 and RZ-AMI

symboles	1	1	0	0	0	0	0	0	0	0	1	1	0	0	0	0	0	1
AMI	+E	-E	0	0	0	0	0	0	0	0	+E	-E	0	0	0	0	0	+E
HDB3	+E	-E	0	0	0	-E	+E	0	0	+E	-E	+E	-E	0	0	-E	0	+E
						V	B			V			B			V		

[0 0 0 0] is coded [B 0 0 V] (excepted the first time)

V : violation - B : balance

Signification : we use transitions at time instants $\frac{T}{2}$

Usage : optical communications, telemetry, ethernet networks

Bi-ϕ-L = Manchester : "1" [transition +V to -V à $\frac{T}{2}$], "0" [transition -V to +V à $\frac{T}{2}$]

Bi-ϕ-M : transition at the begin of T, "1" [2nd ransition at $\frac{T}{2}$], "0" [no 2nd transition]

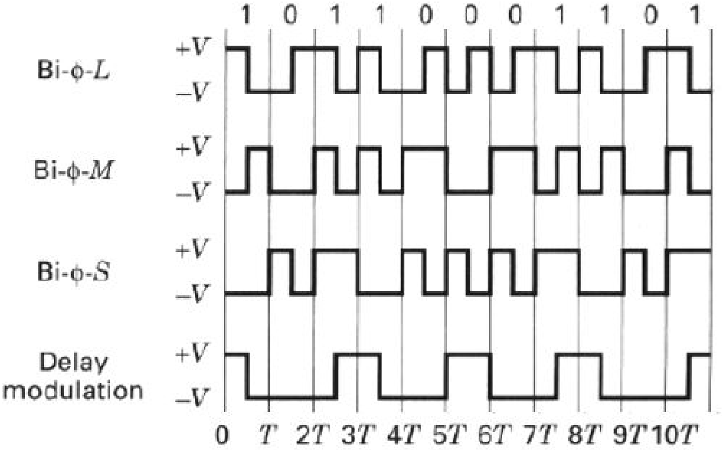
Bi-ϕ-S : complementary of Bi-ϕ-M

Delay Modulation :"1" [transition at $\frac{T}{2}$], "0" [no transition if followed by a "1" - transition at end of interval if followed by a 2nd "0"].

Format and baseband signalling

Line codes : phase encoded (cont.)

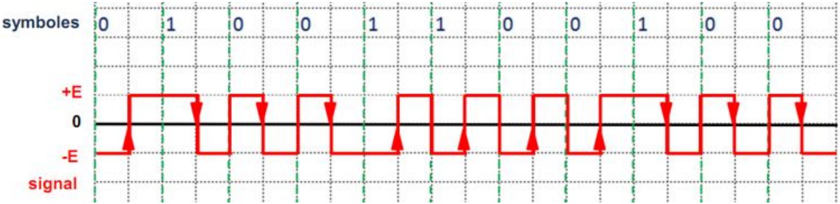
Illustration :



Format and baseband signalling

Line codes : phase encoded (cont.)

Your turn: Differential Manchester coding



Format and baseband signalling

Line codes : multilevel binary

Signification : we use other levels than [+V] and [-V]

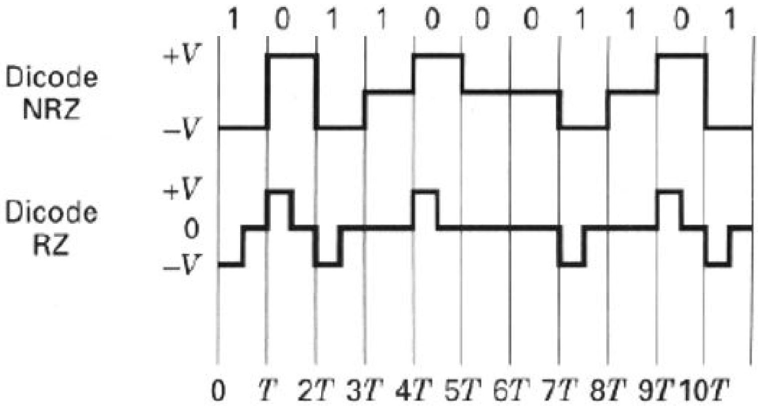
Dicode-NRZ : "0 to 1" or "1 to 0" [polarity change], "0 to 0" or "1 to 1" [0 Volts]

Dicode-RZ : "0 to 1" or "1 to 0" [half duration polarity change], "0 to 0" or "1 to 1" [0 Volts]

Format and baseband signalling

Line codes : multilevel binary (cont.)

Illustration :



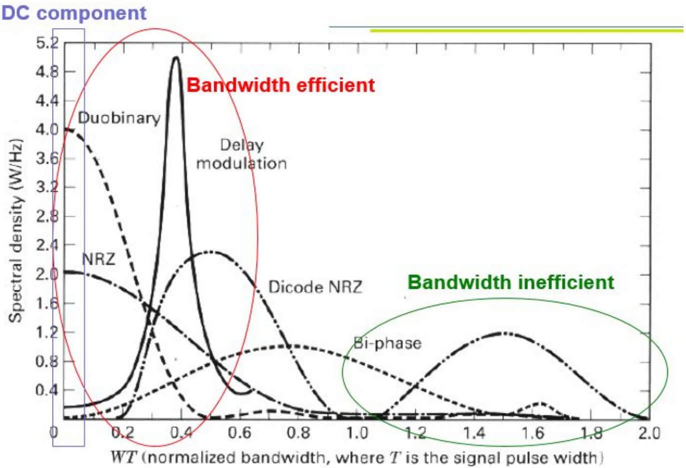
Criteria to be considered :

- **DC component** : magnetic recording circuits are sensitive to low frequencies
- **Synchronisation** : mandatory for some application, PCM codes have interesting properties
- **Error detection** : bits of redundancy
- **Bandwidth** : the most compressed it is, the more data by unit we can send through it
- **Polarity** : for differential codes, we can change the polarity without affecting data detection
- **Immunity to noise** : bit error rate function of Signal to Noise Ratio

Format and baseband signalling

Line codes : how to choose ? (cont.)

Illustration :



Format and baseband signalling

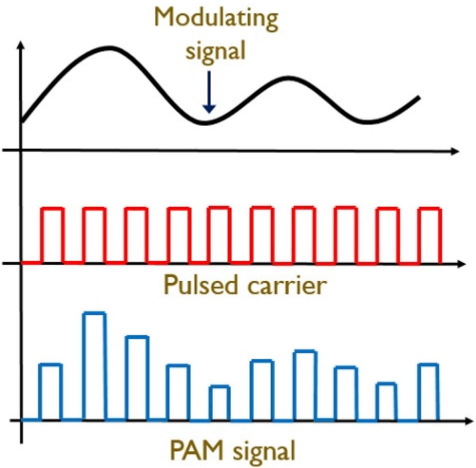
Pulse modulations

PAM : information is contained in amplitude (1 symbol = 1 amplitude among M possible values)

PPM : information is contained in position (1 symbol = 1 position among M possible values)

PDM / PWM : information is contained in width (1 symbol = 1 width among M possible values)

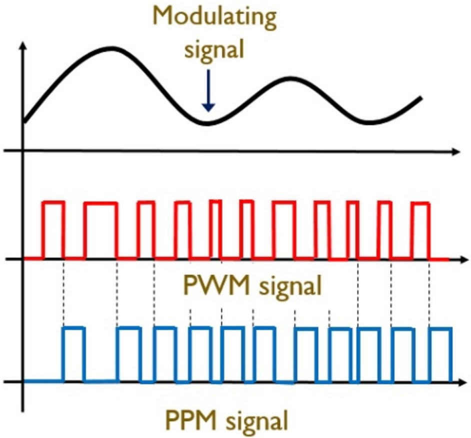
Illustration :



Format and baseband signalling

PPM modulations

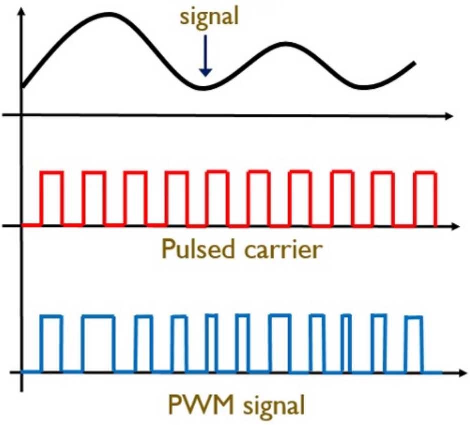
Illustration :



Format and baseband signalling

PWM modulations

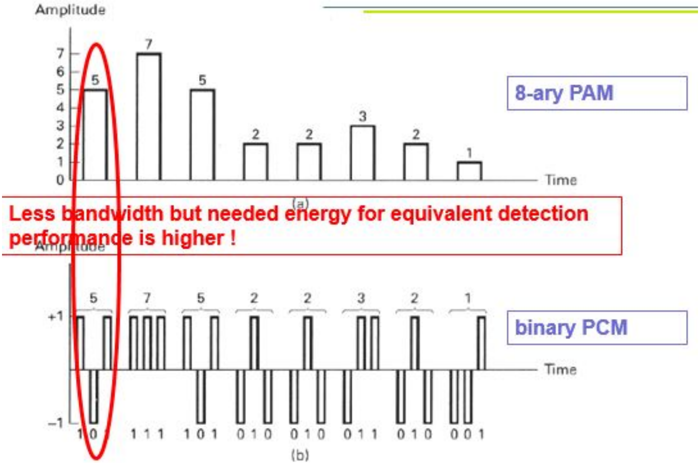
Illustration :



Format and baseband signalling

M-ary PAM vs Binary PCM : comparison

Illustration :



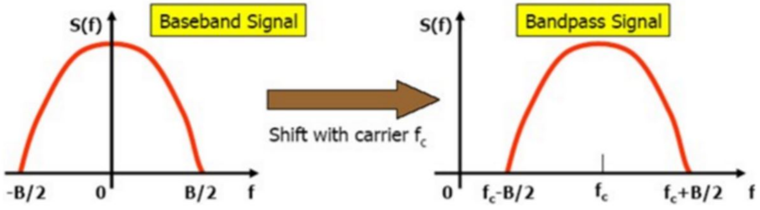
Bandpass modulation and demodulation

Introduction

Baseband signal : its spectrum (occupied bandwidth) is centered on the frequency $0Hz$)

Bandpass signal : its spectrum is centered on the carrier frequency f_c

Bandpass modulation : spectrum transposition from 0 to f_c



Bandpass modulation and demodulation

Introduction (cont.)

Baseband modulation : converts bits / codewords to electrical signals

Bandpass modulation : converts electrical signals to electromagnetic waves, at frequency f_c, to enable their propagation.

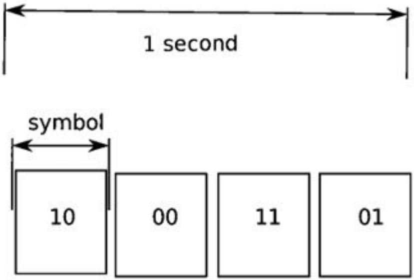
Why bandpass ? to adapted the emitted signal to the transmission support (otherwise, we would need an infinite-dimension-antenna...)

Utility ? gather multiple signals on the same antenna, mitigate interference between users.

Bandpass modulation and demodulation

Introduction (cont.)

Modulation (def. 2) : operation which transforms bits into symbols (other term : *mapping*)



Bandpass modulation and demodulation

Modulation principle

2 steps :

- baseband signal (*mapping*) : create I and Q streams
- bandpass signal (shift to f_c) : multiply by the carrier

3 parameters :

- instantaneous amplitude $A(t)$
- instantaneous phase $\theta(t)$ (frequency $f(t)$)
- modulation index h

General expression of the baseband signal :

$$s_b(t) = A(t)exp(jh\theta(t))$$

$$\theta(t) = 2\pi f(t)$$

We consider that the frequency is the **time derivative** of the phase

By projection onto the complex plane I-Q (constellation) :

- Phase stream I : real part of $s_b(t)$
- Quadrature stream Q : imaginary part of $s_b(t)$

Mapping types :

- If only $A(t)$ varies : amplitude modulation
  - example M-ASK (*M-ary Amplitude Shift Keying*)
- If only $\theta(t)$ (or $f(t)$) varies : angular modulation
  - example M-PSK (*M-ary Phase Shift Keying*)
- If $A(t)$ and $\theta(t)$ simultaneously vary : quadrature modulation
  - example M-QAM (*M-ary Quadrature Amplitude Modulation*)

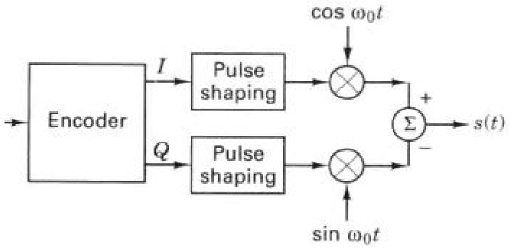
Bandpass modulation and demodulation

Modulation Step 2 : Transposition

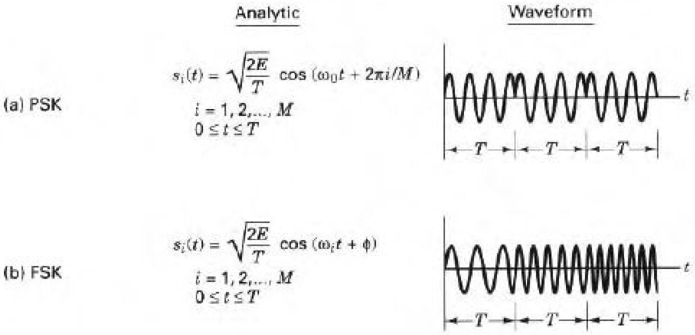
General expression of the bandpass signal :

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

Modulator complete (and general) block diagram :



Time representation of modulated signals M-PSK / M-FSK

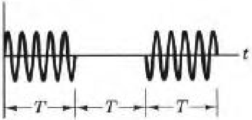


Time representation of modulated signals M-ASK / M-APK

(c) ASK

$$s_i(t) = \sqrt{\frac{2E_i(t)}{T}} \cos(\omega_0 t + \phi)$$

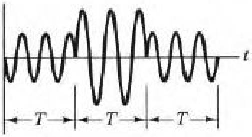
$i = 1, 2, \ldots, M$
$0 \leq t \leq T$



(d) ASK/PSK (APK)

$$s_i(t) = \sqrt{\frac{2E_i(t)}{T}} \cos[\omega_0 t + \phi_i(t)]$$

$i = 1, 2, \ldots, M$
$0 \leq t \leq T$



Bandpass modulation and demodulation

M-ASK Modulator

Signal expression :

$$s_{i,M-ASK}(t) = A_{i,M-ASK}(t)cos(2\pi f_c t + \theta)$$

$$A_{i,M-ASK}(t) = \sqrt{\frac{2E_i}{T}}, 0 \leq t \leq T, 1 \leq i \leq M$$

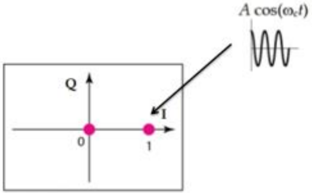
Example : $2 - ASK$

- Bit "1" : $s_1(t) = \sqrt{\frac{2E}{T}}.cos(2\pi f_c t)$
- Bit "0" : $s_0(t) = 0$

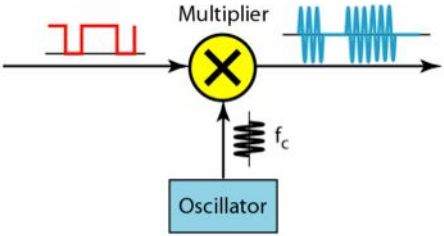
Bandpass modulation and demodulation

M-ASK Modulator (cont.)

Constellation :



Modulator block-diagram :



Bandpass modulation and demodulation

M-PSK Modulator

Signal expression :

$$s_{i,M-PSK}(t) = Acos(2\pi f_c t + \theta_{i,M-PSK}(t))$$

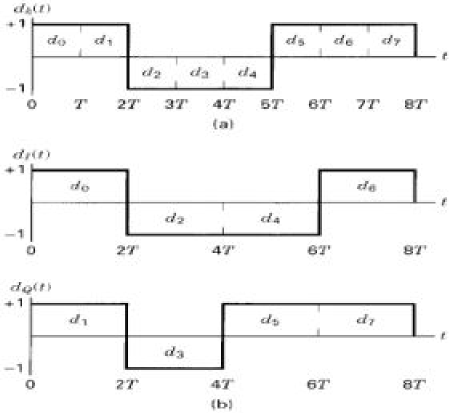
$$A = \sqrt{\frac{2E}{T}}, 0 \leq t \leq T$$

$$\theta_{i,M-PSK}(t) = \frac{2\pi i}{M}, 0 \leq t \leq T, 1 \leq i \leq M$$

Bandpass modulation and demodulation

M-PSK Modulator (cont.)

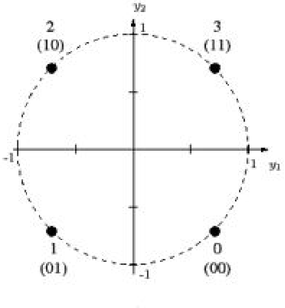
Example : $4 - PSK$ (also known as $QPSK$)



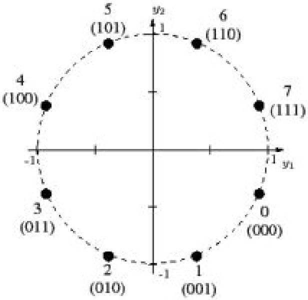
Bandpass modulation and demodulation

M-PSK Modulator (cont.)

Constellations :

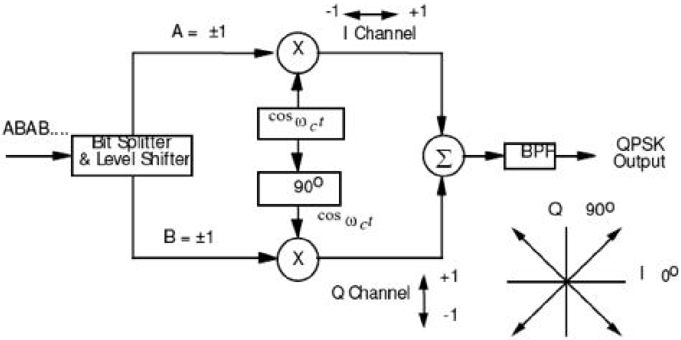


4-PSK



8-PSK

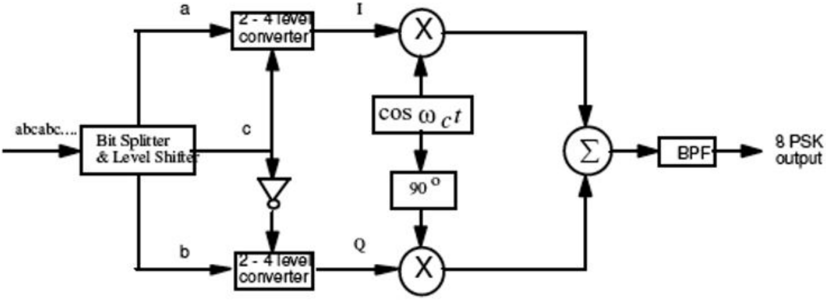
QPSK modulator block-diagram :



Bandpass modulation and demodulation

M-PSK Modulator (cont.)

8-PSK modulator block-diagram :



Signal expression :

$$s_{i,M-FSK}(t) = Acos(2\pi f_{i,M-FSK}(t)t + \theta)$$

$$A = \sqrt{\frac{2E}{T}}, 0 \leq t \leq T$$

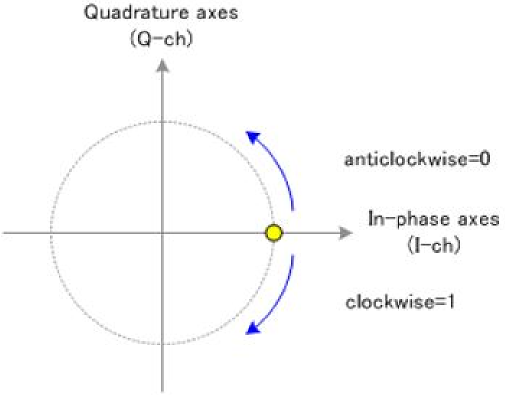
$$f_{i,M-FSK}(t) = f_1 = f_{min}, ..., f_M = f_{max}, 1 \leq i \leq M$$

$$h = \frac{f_{max} - f_{min}}{f_c}$$

Bandpass modulation and demodulation

M-FSK Modulator (cont.)

Constellation :

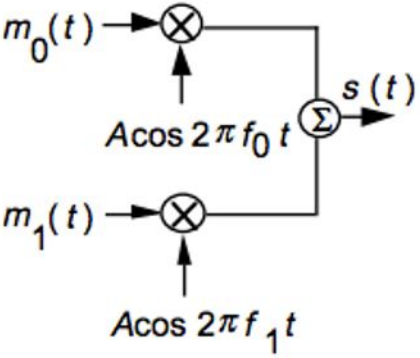


FSK

Bandpass modulation and demodulation

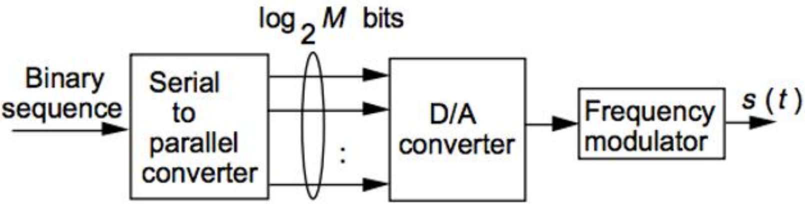
M-FSK Modulator (cont.)

2-FSK Modulator block-diagram:



Bandpass modulation and demodulation
M-FSK Modulator (cont.)

M-FSK modulator block-diagram (general case):



Bandpass modulation and demodulation

M-QAM Modulator

Signal expression :

$$s_{i,M-QAM}(t) = A_{i,M-QAM}(t)cos(2\pi f_c t + \theta_{i,M-QAM}(t)), 0 \leq t \leq T$$

$$A_{i,M-QAM}(t) = \sqrt{i_M^2 + q_M^2}, 1 \leq i \leq M$$

$$\theta_{i,M-QAM}(t) = arctan\frac{q_M}{i_M}, 1 \leq i \leq M$$

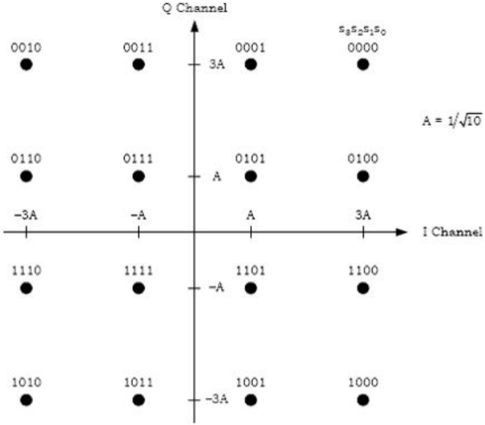
$$i_M = -(\sqrt{M}-1), -(\sqrt{M}-3), ...(\sqrt{M}-3), (\sqrt{M}-1)$$

$$q_M = -(\sqrt{M}-1), -(\sqrt{M}-3), ...(\sqrt{M}-3), (\sqrt{M}-1)$$

Bandpass modulation and demodulation

M-QAM Modulator (cont.)

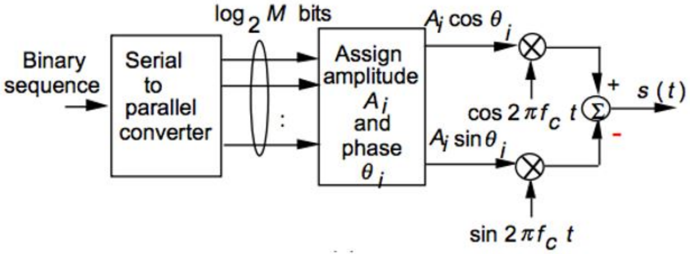
Constellation : example (16-QAM)



Bandpass modulation and demodulation

M-QAM Modulator (cont.)

QAM modulator block-diagram (general case)



Principle : At each ^{kth} transmission time, we send a phase given by

$$\phi_k = \Delta\phi_k + \phi_{k-1}$$

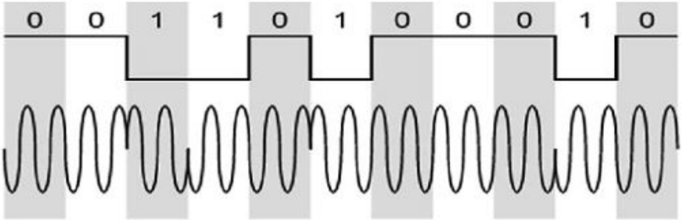
Example : case of D2PSK

- Bit "0" : absence of change in the signal phase
- Bit "1" : a change in the signal phase

Bandpass modulation and demodulation

Differential Modulators : *DPSK* (cont.)

Example : case of D2PSK



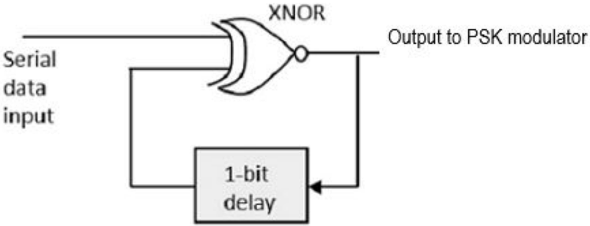
Bandpass modulation and demodulation

Differential Modulators : *DPSK* (cont.)

Example : D2PSK modulator block-diagram

$$b_k = \overline{b_{k-1} \oplus m_k} \Rightarrow \; m_k = 1 \rightarrow b_k = b_{k-1}$$

$$m_k = 0 \rightarrow b_k = \overline{b_{k-1}}$$



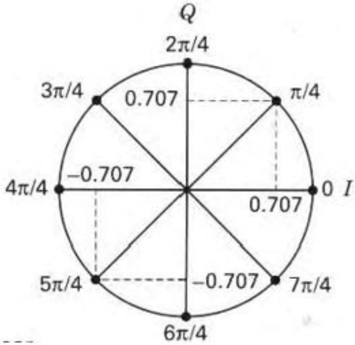
Bandpass modulation and demodulation

Differential Modulators : *DPSK* (cont.)

Example : case of D8PSK

Data encoding

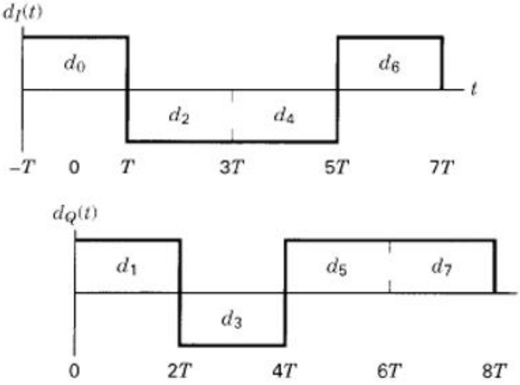
x_k	y_k	z_k	$\Delta\phi_k$
0	0	0	0
0	0	1	$\pi/4$
0	1	1	$2\pi/4$
0	1	0	$3\pi/4$
1	1	0	$4\pi/4$
1	1	1	$5\pi/4$
1	0	1	$6\pi/4$
1	0	0	$7\pi/4$



Bandpass modulation and demodulation

Offset QPSK

Principle : compared to QPSK (offset between I and Q : $\frac{T_s}{2}$)

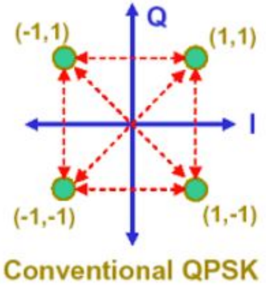


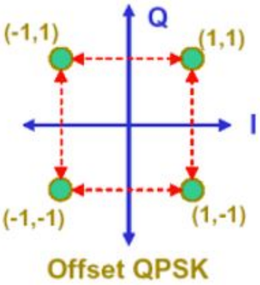
(b)

Bandpass modulation and demodulation

Offset QPSK (cont.)

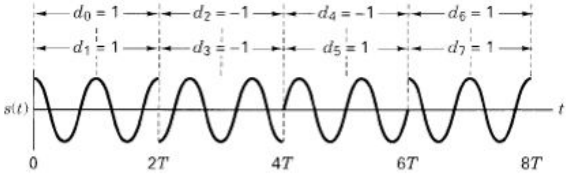
Constellation : compared to QPSK



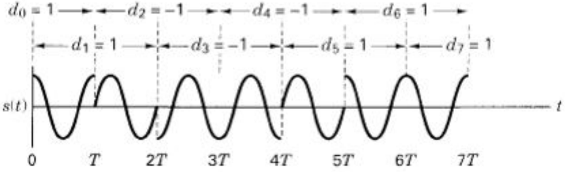


Bandpass modulation and demodulation
Offset QPSK (cont.)

Output time signal : compared to QPSK



(a) QPSK

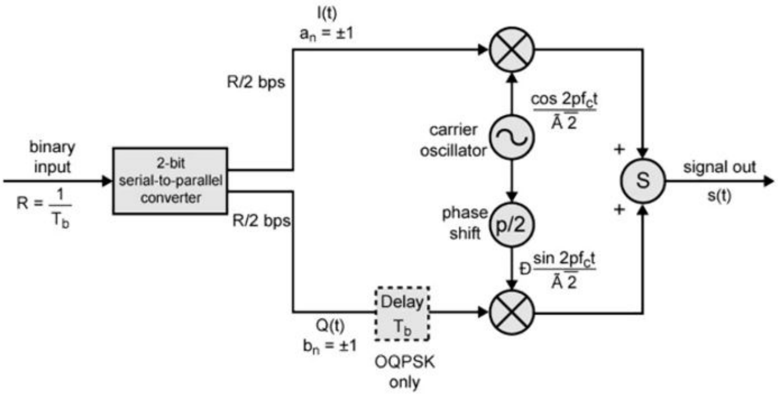


(b) OQPSK

Bandpass modulation and demodulation

Offset QPSK (cont.)

OQPSK modulator block-diagram :



Bandpass modulation and demodulation

Continuous Phase Modulators : *Minimum Shift Keying (MSK)*

Principle : Modulation index $h = 0.5$, amplitude is constant, phase is given by :

For time instants $kT_s \leq t \leq (k+1)T_s$

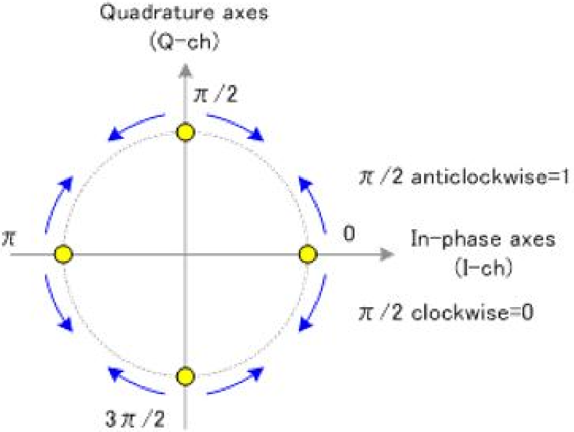
$$\theta_{MSK}(t) = \theta_k + i(t)$$

$$s_{MSK}(t) = cos[2\pi(f_c + \frac{d_k}{4T_s})t + \theta_k]$$

Bandpass modulation and demodulation

Continuous Phase Modulators : *Minimum Shift Keying (MSK)* (cont.)

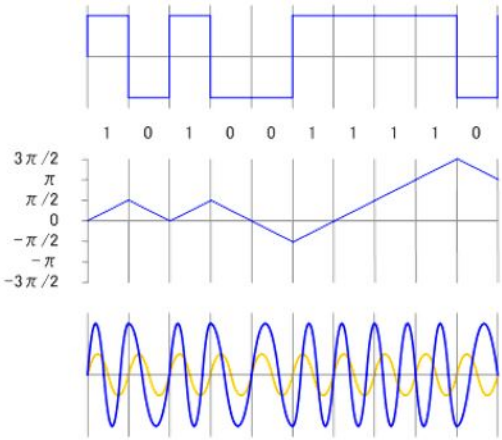
Constellation :



Bandpass modulation and demodulation

Continuous Phase Modulators : *Minimum Shift Keying (MSK)* (cont.)

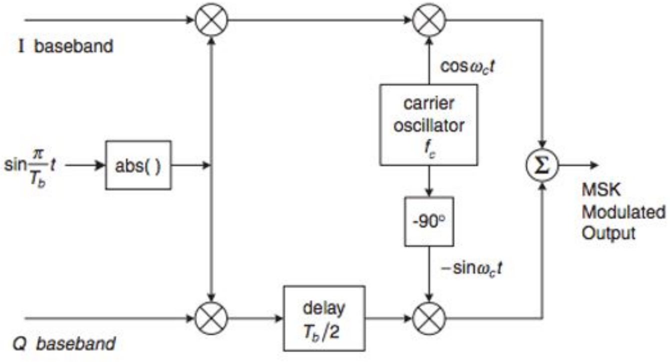
Modulated signal representation in the time domain :



Bandpass modulation and demodulation

Continuous Phase Modulators : *Minimum Shift Keying (MSK)* (cont.)

MSK modulator block-diagram :



Bandpass modulation and demodulation

Continuous Phase Modulators : *Gaussian Minimum Shift Keying (GMSK)*

Principle : Modulation index $h = 0.5$, amplitude is constant, phase is given by :

$$\theta_{GMSK}(t) = \theta_0 + g(t) * i(t)$$

Where $g(t)$ is the Gaussian filter given by :

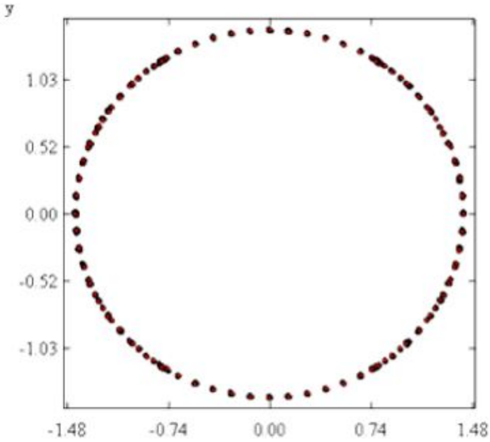
$$g(t) = \sqrt{\frac{2\pi}{log_2(2)}}.BT.exp(\frac{-2(\pi BT)^2}{log_2(2)}.t^2)$$

B and T are such that $BT = 0.3$

Bandpass modulation and demodulation

Continuous Phase Modulators : *Gaussian Minimum Shift Keying (GMSK)* (cont.)

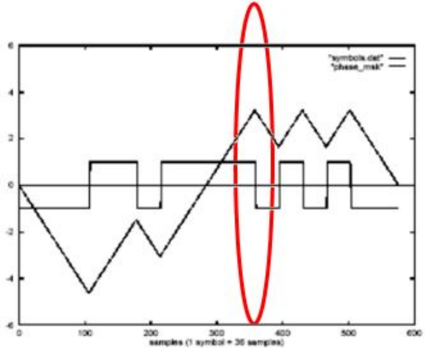
Constellation :

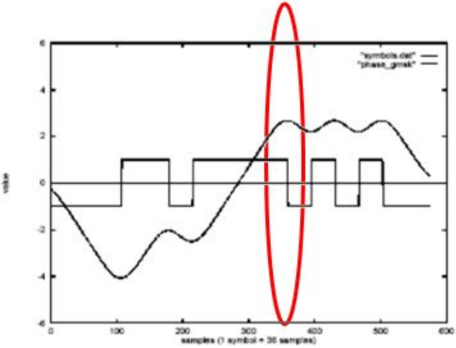


Bandpass modulation and demodulation

Continuous Phase Modulators : *Gaussian Minimum Shift Keying (GMSK)* (cont.)

Modulated signal representation in the time domain : compared to MSK

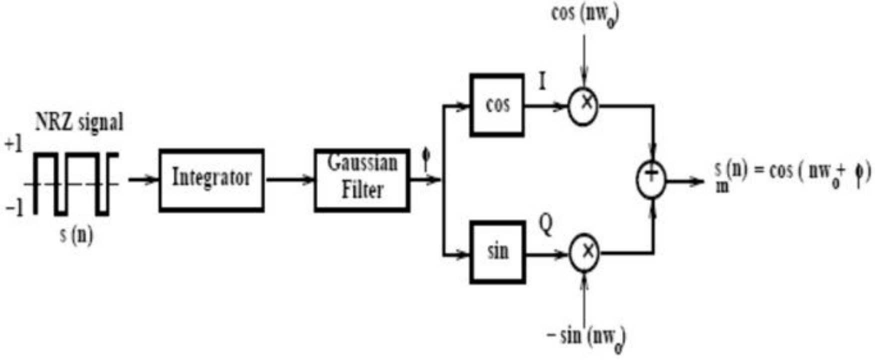




Bandpass modulation and demodulation

Continuous Phase Modulators : *Gaussian Minimum Shift Keying (GMSK)* (cont.)

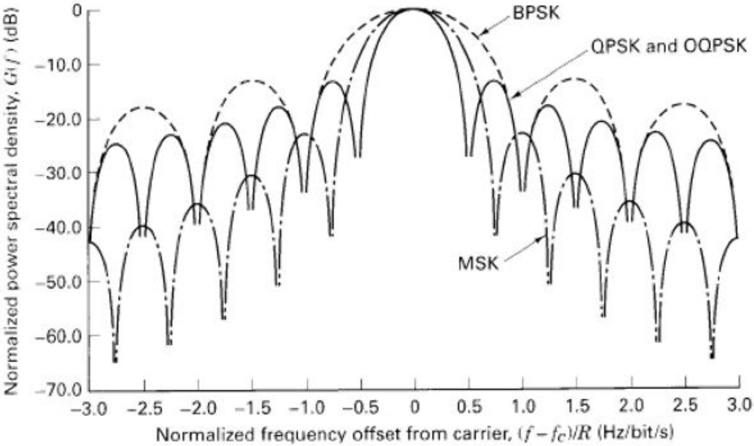
GMSK modulator block-diagram :



Bandpass modulation and demodulation

Comparaison of digital modulators : spectral efficiency

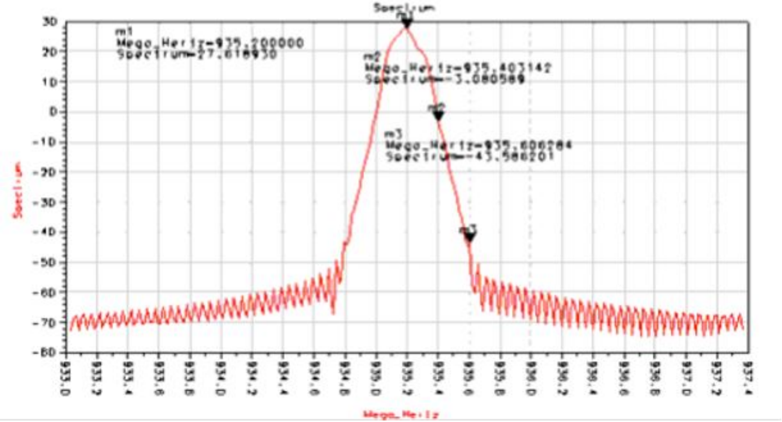
Case of BPSK, (O)QPSK and MSK :



Bandpass modulation and demodulation

Comparaison of digital modulators : spectral efficiency (cont.)

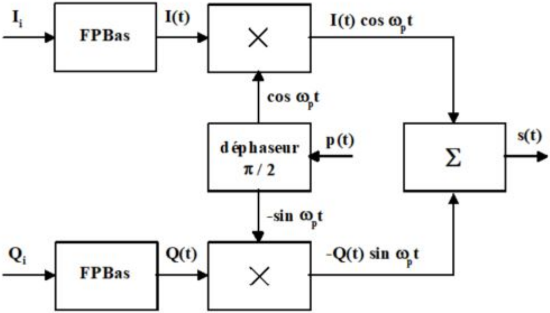
Case of GMSK :



Bandpass modulation and demodulation

Summary: modulator block diagram

Global scheme (”intermediate” step : low pass filter (generally the shaping filter) :



I_i **and** Q_i **: ”mapping” block outputs (digits)**

Constraints to be considered :

- Spectral efficiency (throughput per bandwidth unit : $Bits/s/Hz$)
- Mimimum power ensuring a threshold error probability
- Implementation cost

The 2 first constraints are contradictory !

- Spectral efficiency is predominant for fixed telephony
- Power management is predominant for mobile telephony

Bandpass modulation and demodulation

Spectral efficiency

Case of binary modulation :

- 1 symbol = 1 bit (so: 2 possible values)
- **Modulation speed** = binary rate ($D = \frac{1}{T_s} = f_b$ in bps)
- **Nyquist frequency** $f_{Ny} = \frac{D}{2} = \frac{f_b}{2}$ in Hz)
- **Roll-off factor** $0 \leq r \leq 1$
- **Occupied bandwidth** $B = 2f_{Ny}(1 + r) = D(1 + r)$ in Hz

Spectral efficiency is then lower than 1 bit/s/Hz (case $r = 0$)

Bandpass modulation and demodulation

Spectral efficiency (cont.)

Case of M-ary modulation :

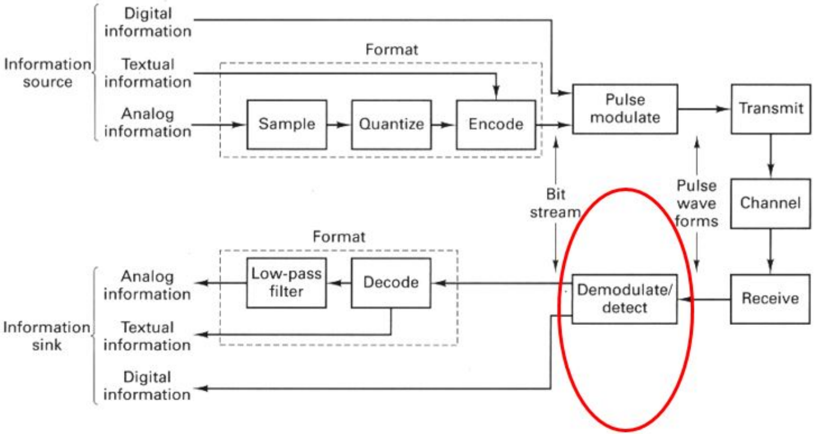
- 1 symbol $= log_2(M)$ bits $= k$ bits (so: 2^k possible values)
- **Modulation speed** $D_s = \frac{D}{k} = \frac{f_b}{k}$ in bauds)
- **Nyquist frequency** $f_{Ny} = \frac{D_s}{2} = \frac{f_b}{2k}$ in Hz)
- **Roll-off factor** $0 \leq r \leq 1$
- **Occupied bandwidth** $B = 2f_{Ny}(1 + r) = \frac{D(1+r)}{k}$ in Hz

Spectral efficiency is then lower than k bits/s/Hz (case $r = 0$)

Bandpass modulation and demodulation

Receiver block diagram : reminder

Objective : demodulate the received signal and detect symbols



Bandpass modulation and demodulation

Demodulation in linear systems

Linear system : described by linear equations (differential, or difference equations).

Feature : symbol detection is not affected by frequency shift.

Consequence : equivalence theorem

Performing linear processing of the bandpass signal, followed by heterodyning of the baseband signal, gives the same results as heterodyning of the bandpass signal, followed by linear processing of the baseband signal..

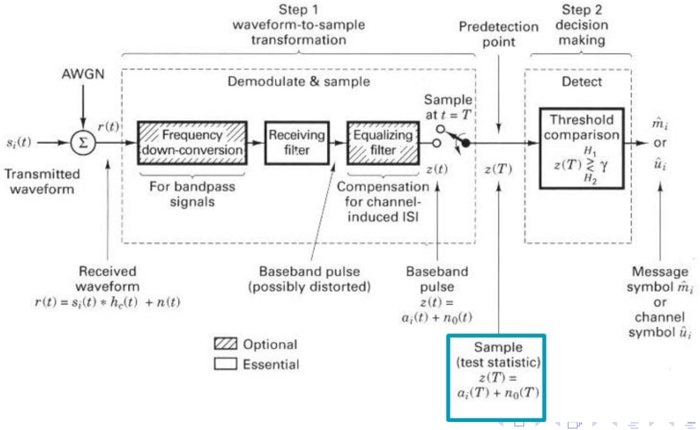
In practice : the whole detection step is made at baseband (**simpler !**)

Bandpass modulation and demodulation

Reception steps in linear systems

Step 1 : demodulate and sample the received signal

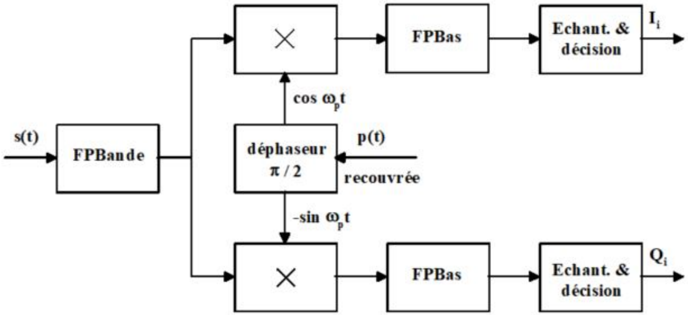
Step 2 : make decisions to detect symbols



Bandpass modulation and demodulation

Coherent demodulator : principle

Case of **synchronous (or coherent)** demodulator : carrier recovery is mandatory



Bandpass modulation and demodulation

Coherent demodulator : filters outputs

High frequency signal components are eliminated by low pass filters...

$$s(t)cos\omega_p t = (I(t)cos\omega_p t - Q(t)sin\omega_p t)cos\omega_p t$$

$$= \frac{1}{2}I(t) + \frac{1}{2}I(t)cos2\omega_p t - \frac{1}{2}Q(t)sin2\omega_p t$$

$$s(t)(-sin\omega_p t) = -(I(t)cos\omega_p t - Q(t)sin\omega_p t)sin\omega_p t$$

$$= \frac{1}{2}Q(t) - \frac{1}{2}I(t)sin2\omega_p t - \frac{1}{2}Q(t)cos2\omega_p t$$

Bandpass modulation and demodulation

Coherent demodulator : filters outputs (cont.)

If recovered carrier is shifted by Φ, I and Q are no longer separated !

Example at the I stream :

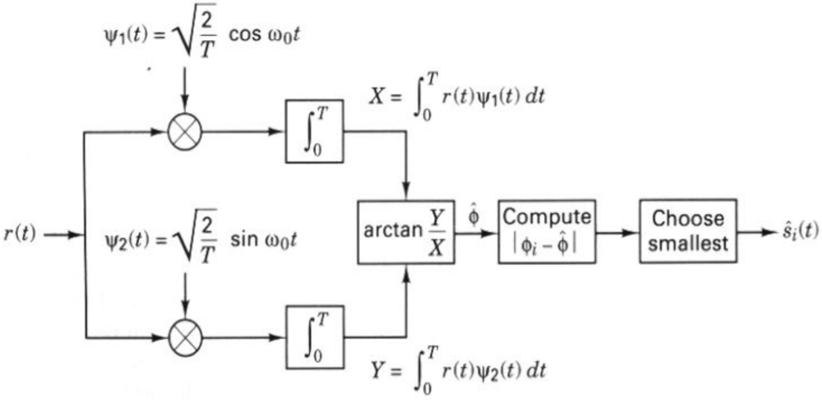
$$s(t)cos(\omega_p t + \Phi) = (I(t)cos\omega_p t - Q(t)sin\omega_p t)cos(\omega_p t + \Phi)$$

$$= \frac{1}{2}I(t)(cos\Phi + cos(2\omega_p t + \Phi)) + \frac{1}{2}Q(t)(sin\Phi - sin(2\omega_p t + \Phi))$$

At the low pass filter output :

$$= \frac{1}{2}I(t)cos\Phi + \frac{1}{2}Q(t)sin\Phi$$

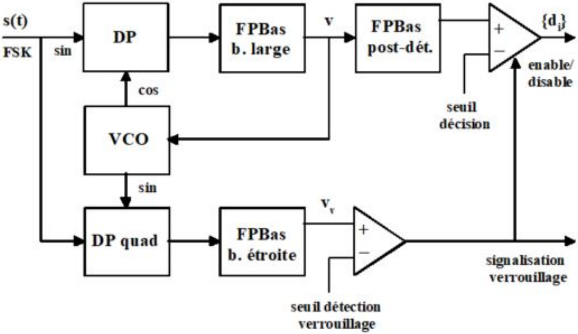
PSK coherent demodulator



Bandpass modulation and demodulation

Coherent demodulator : examples (cont.)

FSK coherent demodulator

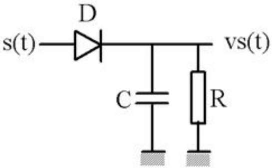


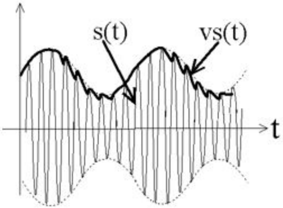
Bandpass modulation and demodulation

Non-coherent demodulator : principle

Case of **non coherent** demodulator : we don't need to recover the carrier, we use envelop detector.

The simplest implementation of envelop detector : diode + RC circuit





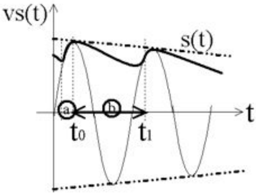
$$s(t) = V_p.(1 + \mu.\cos(\omega_m t))\sin(\omega_p t)$$

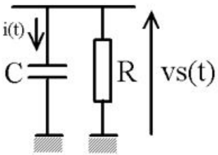
Bandpass modulation and demodulation

Non-coherent demodulator : steps

Envelop detection steps and time-domain representation (**mesh law**) :

- Step 1 : $s(t)$ rises from $s_{max} - 0.7$ to s_{max}, passing diode, C charges
- Step 2 : $s(t)$ drops from s_{max}, blocked diode, C discharges
- Step 2 continues until the next cycle $s_{max} - 0.7$





2 constraints to take into account :

- Capacitor discharge should be low ($RC >> \frac{1}{f_p}$)
- The decay slope of $v_s(t)$ should be more negative than those of $s(t)$ (the latter is related to the modulation index)

Consequence (h being the modulation index) :

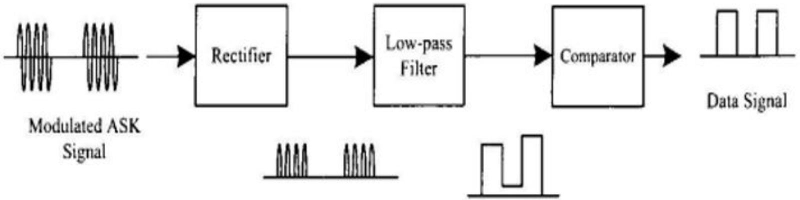
$$\frac{1}{f_p} << RC << \frac{\sqrt{1-h^2}}{h.2\pi.f_s}$$

Limit : $h > 1$ (the diode clips the negative part of the signal...)

Bandpass modulation and demodulation

Non-coherent demodulator : examples

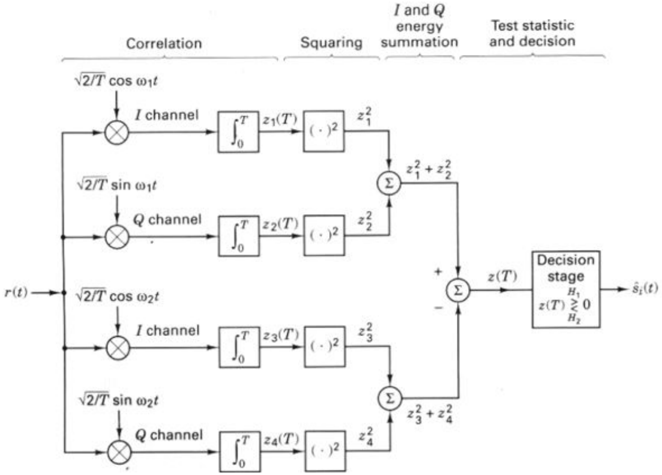
ASK non-coherent demodulator



Bandpass modulation and demodulation

Non-coherent demodulator : examples (cont.)

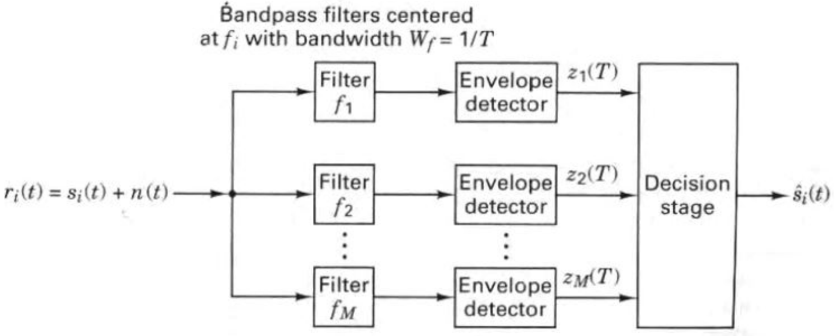
FSK non-coherent demodulator : correlation method



Bandpass modulation and demodulation

Non-coherent demodulator : examples (cont.)

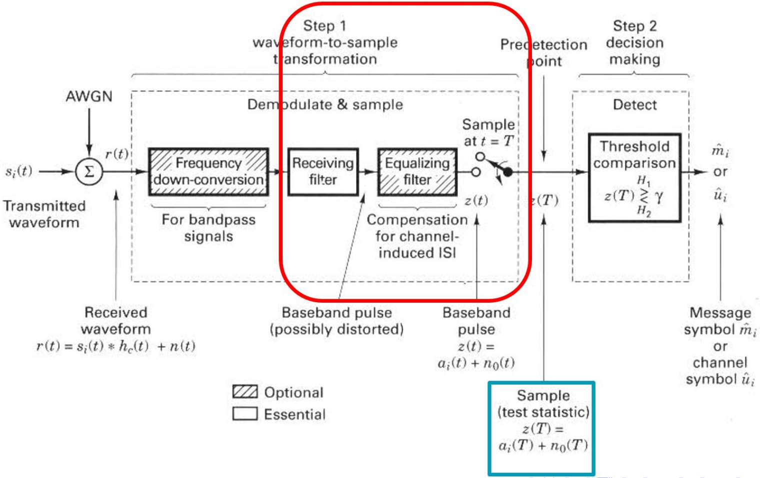
FSK non-coherent demodulator : filtering method



Baseband demodulation and detection

Intro

Reminder of the receiver block diagram :

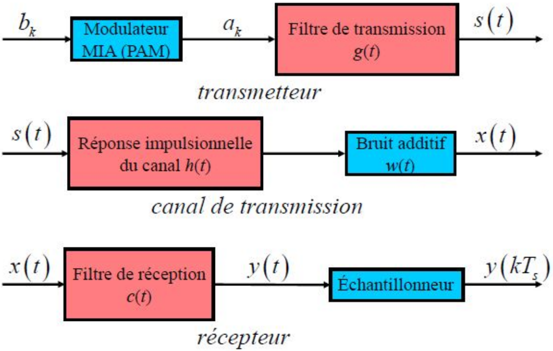


Baseband demodulation and detection

Channel characterisation

Objective : Describe the changes in the signal as it passes through the channel.

Phenomena : distorsion and noise



Baseband demodulation and detection

Channel characterisation (cont.)

Channel general model : $x(t)$ emitted signal, $c_t(t)$ channel impulse response, $y(t)$ signal after passing through the channel

$$y(t) = c_t * x(t) = \int_{-\infty}^{\infty} c_t(\tau) x(t-\tau) d\tau$$

$$(t,\tau) \to c_t(\tau) = \sum_{k=1}^{K(t)} A_k(t) p(\tau - \tau_k(t))$$

Parameters : τ_k (discernible path), A_k (its associated amplitude), $p(t)$ pulse shaping filter of bandwidth B (used by the emitted signal)

How to characterize : Study $c_\tau(t)$ with respect to τ and t

Baseband demodulation and detection

Channel characterisation (cont.)

Study with respect to τ : analyze if the channel is time dispersive (frequency selective) or not

- Dispersion time T_d : time-domain support of the impulse response (related to the maximum delay time τ_{max})
- Coherence bandwith B_c : maximal separation between 2 frequencies f_1 and f_2 such that the impulse response is almost identical at f_1 and f_2

$$T_d = \frac{10}{B_c}$$

Baseband demodulation and detection

Channel characterisation (cont.)

Study with respect to t : analyse if the channel is static or not

- Coherence time T_c : maximal separation between time instants t_1 et t_2 such that the instantaneous spectrum is almost identical at t_1 and t_2
- Doppler bandwidth B_d : created bandwidth by time variations of the channel

$$T_c = \frac{10}{B_d}$$

Baseband demodulation and detection

Channel characterisation (cont.)

Simplification from τ viewpoint :

- If $T_d \leq T_s$, similarly $B \leq B_c$: the occupied bandwidth by the signal is lower than the coherence bandwidth. The distorsion is just attenuation and phase shift : flat fading channel

- If $T_d \geq T_s$, similarly $B \geq B_c$: the occupied bandwidth by the signal is higher than the coherence bandwidth. The convolution product doesn't disappear : non flat fading channel

Baseband demodulation and detection

Channel characterisation (cont.)

Simplification from t viewpoint :

- Si $T_s \ll T_c$ the channel varies slightly from one symbol to another, hence it can be considered as static
- Si $T_s \approx T_c$ the channel varies from one codeword to another, hence it can be considered as slow / block fading
- Si $T_s \gg T_c$ the channel varies before one codeword is tranmitted, hence it can be considered as fast fading

Baseband demodulation and detection

Channel characterisation (cont.)

Three typical channels : Case 1

- $T_d \leq T_s$ and $T_s \ll T_c$: the channel is flat fading and static. The frequency response is constant and is equal to its value at intial time t_0 and center frequency f_0. Gaussian Channel

$$y(t) = x(t) + w(t)$$

Baseband demodulation and detection

Channel characterisation (cont.)

Three typical channels : Case 2

- $T_d \leq T_s$ and $T_s \approx T_c$: flat fading and slow fading channel. The frequency response is equal to its value at center frequency f_0 BUT it changes at the beginning of each symbol. Rayleigh Channel

$$y(t) = C_t(f_0)x(t) + w(t)$$

Three typical channels : Case 3

- $T_d \geq T_s$ and $T_s \ll T_c$: non flat and static channel. The frequency response slightly varies by time but depends on the frequency. Frequency Selective Channel

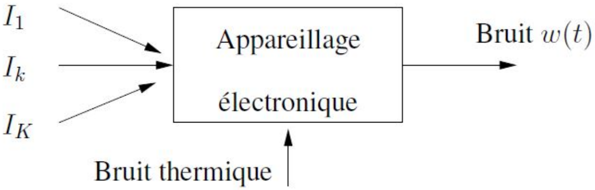
$$y(t) = C_{t_0} * x(t) + w(t)$$

Baseband demodulation and detection

Noise characterisation

Noise origins :

- thermal noise
- interference from other users at adjacent channels



Baseband demodulation and detection

Noise characterisation (cont.)

$$w(t) = w_{thermal}(t) + \sum_{k=1}^{K} I_k$$

The thermal noise is Gaussian (by definition)

Central-limit theorem : a sum of independent random variables tends towards a Gaussian distribution

Consequence : the sum of the interferences is modelled by a Gaussian law (generally)

Density of probability : the total noise $w(t)$ is assumed to be Gaussian (mean value : 0).

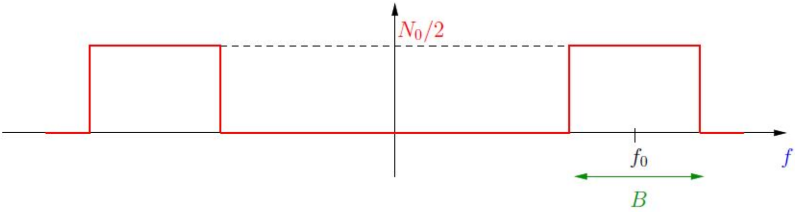
Baseband demodulation and detection

Noise characterisation (cont.)

Power spectral density : the noise energy is equal to equal to the ratio between the total power-on-carrier and the positive band of the signal-on-carrier (uniquely defined worldwide).

The I and Q components of the noise are decorrelated and independent.

The total power spectral density is N_0, the power spectral density in the positive band is $\frac{N_0}{2}$



Baseband demodulation and detection

Inter-Symbol-Interference : ISI

Origin : **time dispersion** caused by the combination of transmission channel, pulse shaping filter and reception filter.

$$y(t) = [h_{TX}(t) * h_{channel}(t)] * h_{RX}(t) + w(t)$$

By defining

$$Kh(t) = h_{TX}(t) * h_{channel}(t) * h_{RX}(t)$$

We obtain

$$y(t) = [K \sum_{k=-\infty}^{\infty} a_k(t).h(t - kT_s)] + w(t)$$

Baseband demodulation and detection

Inter-Symbol-Interference : ISI (cont.)

Using Fourier Transform

$$KH(f) = H_{TX}(f).H_{channel}(f).H_{RX}(f)$$

At the discrete time instant $t = iT_s$ we receive the symbol

$$y(iT_s) = [K \sum_{k=-\infty}^{\infty} a_k(iT_s).h[(i-k)T_s]] + w(iT_s)$$

This is equivalent to

$$y(iT_s) = K.a_i + [K \sum_{k=-\infty, k\neq i}^{\infty} a_k(iT_s).h[(i-k)T_s]] + w(iT_s)$$

Baseband demodulation and detection

Inter-Symbol-Interference : ISI (cont.)

Ka_i represents the desired signal at time $t = iT_s$

$K\sum_{k=-\infty,k\neq i}^{\infty} a_k(iT_s).h[(i-k)T_s]$ represents ISI at time $t = iT_s$

$w(iT_s)$ is the filtered noise at time iT_s

Nyquist criterion : We aim at removing ISI at the sampling time instants

- $h[(i-k)T_s] = 1$ si $i = k$
- $h[(i-k)T_s] = 0$ si $i \neq k$

Nyquist criterion (cont.) : We use properties of Fourier transfom of discrete signals, and Dirac functions.

The corresponding spectrum is :

$$H_{sampled}(f) = \frac{1}{T_s} \sum_{n=-\infty}^{\infty} H(f - n\frac{1}{T_s}) = h(0) = 1$$

$$\sum_{n=-\infty}^{\infty} H(f - n\frac{1}{T_s}) = T_s$$

Result : to eliminate ISI, the frequency response $H(f)$ must be defined such that its infinite sum shifted by multiples of the symbol rate is constant.

Example of filter satisfying Nyquist criterion : ideal rectangular filter

$$H(f) = \frac{1}{2W}, -W \leq f \leq W$$

$$H(f) = 0, elsewhere$$

$$h(t) = sinc(2Wt) = \frac{sin(2\pi Wt)}{2\pi Wt}$$

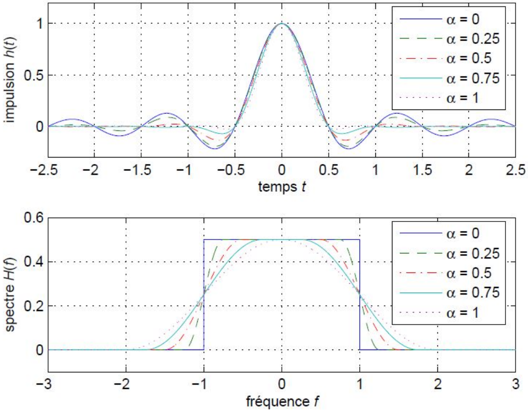
Filter difficult to implement because it must be of constant amplitude and there is no margin of error at sampling times !

Baseband demodulation and detection

Inter-Symbol-Interference : ISI (cont.)

Example 2 : raised cosine filter

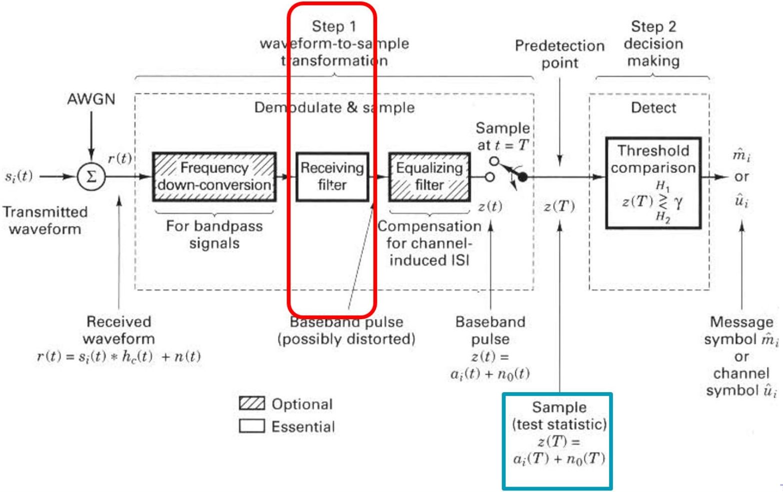
Roll-off factor : $\alpha = 1 - \frac{f_1}{W}$



Baseband demodulation and detection

Receiving filter

Objective : maximize the signal energy before the detection stage



Baseband demodulation and detection

Receiving filter (cont.)

The corresponding filter is the **matched filter** (to the pulse shaping filter)

The maximum Signal to Noise Ratio (SNR) is given by

$$max(SNR)_T = \frac{2E}{N_0}$$

Where E is the signal energy

$$E = \int_{-\infty}^{\infty} |S(f)|^2 df$$

Baseband demodulation and detection

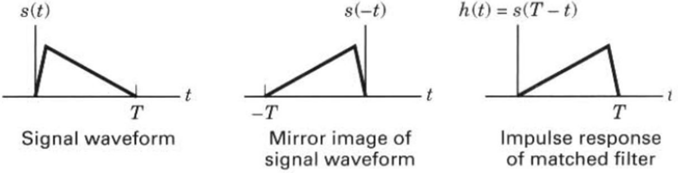
Receiving filter (cont.)

The matched filter impulse response is

$$h(t) = K.s(T - t), 0 \leq t \leq T$$

$$h(t) = 0, elsewhere$$

Illustration :



Baseband demodulation and detection

Receiving filter (cont.)

At the filter output **(predetection point)**, the signal expression is

$$z(t) = \int_0^t r(\tau).h(t-\tau)d\tau = \int_0^t r(\tau).s[T-(t-\tau)]d\tau$$

At the time instant $t = T$:

$$z(T) = \int_0^T r(\tau).s(\tau)d\tau$$

At the predetection point, the signal is the correlation of $r(t)$ with $s(t)$

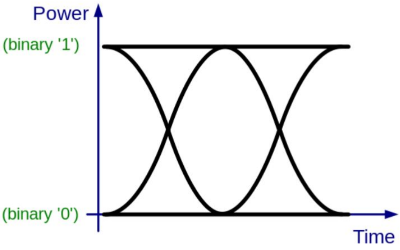
Baseband demodulation and detection

Eye pattern

Definition : display the power of the received (demoulated) signal as function of time ($[0, 2T]$)

Superposition of all possible realizations of the signal within the interval $[t_0,\ t_0 + 2T]$

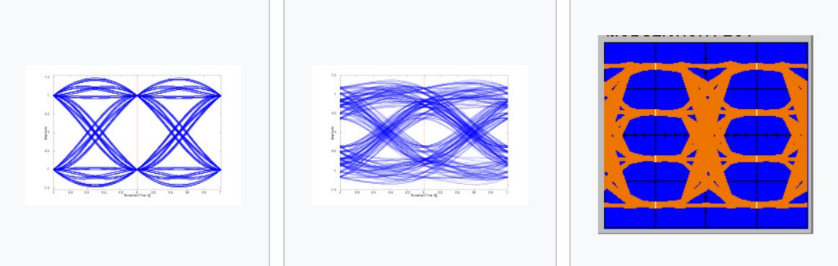
Objecive : evaluate effects of noise and ISI on the system performance



Baseband demodulation and detection

Eye pattern (cont.)

Examples : (from left to right) BPSK, BPSK with multipath interference, 4QAM



Baseband demodulation and detection

Eye pattern (cont.)

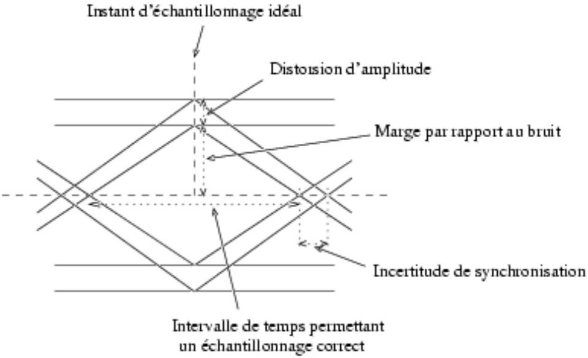
Measurements from the eye diagram :

Eye-diagram feature	What it measures
Eye opening (height, peak to peak)	Additive noise in the signal
Eye overshoot/undershoot	Peak distortion due to interruptions in the signal path
Eye width	Timing synchronization & jitter effects
Eye closure	Intersymbol interference, additive noise

Baseband demodulation and detection

Eye pattern (cont.)

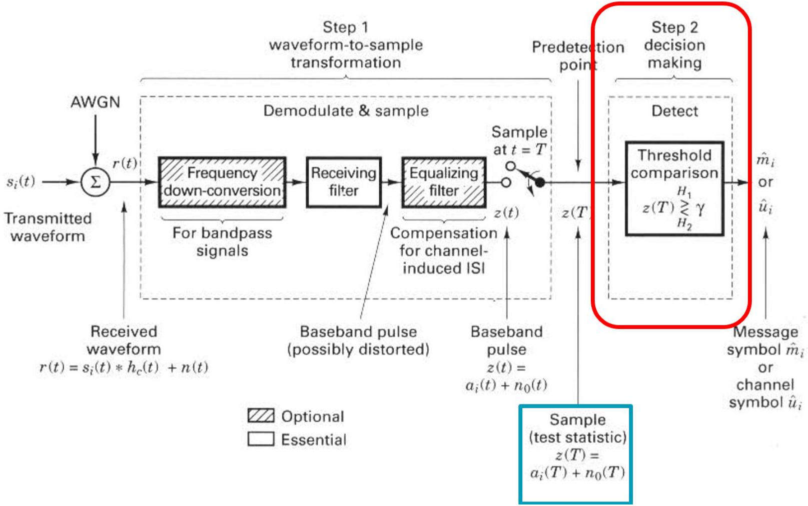
Illustration :



Baseband demodulation and detection

Detection : intro

Objective : decision making on demodulated and sampled symbols



Baseband demodulation and detection

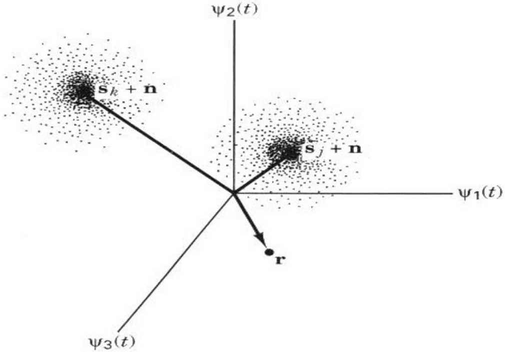
Detection : intro (cont.)

Received demodulated and sampled signal : r

Reference signals : s_j, s_k ...

Sampled noise : n

Question : how to make a decision ?



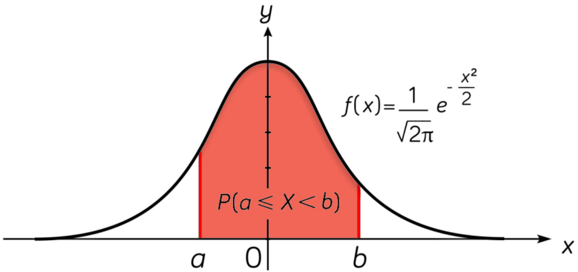
Baseband demodulation and detection

Detection : principle

Starting point : **AWGN noise**

Its *Probability Density Function* (PDF) follows a Gaussian law with 0 mean and σ_0^2 variance.

$$p(n) = \frac{1}{\sigma_0\sqrt{2\pi}}.e^{-\frac{1}{2}(\frac{n}{\sigma_0})^2}$$



Baseband demodulation and detection

Detection : principle for binary signals

Case of binary signals (examples : 2-ASK , 2-PSK)

Constellation symbols : a_1 (signal s_1), a_2 (signal s_2)

Conditionnal PDFs (likelihoods) :

$$p(z|s_1) = \frac{1}{\sigma_0\sqrt{2\pi}}.e^{-\frac{1}{2}(\frac{z-a_1}{\sigma_0})^2}$$

$$p(z|s_2) = \frac{1}{\sigma_0\sqrt{2\pi}}.e^{-\frac{1}{2}(\frac{z-a_2}{\sigma_0})^2}$$

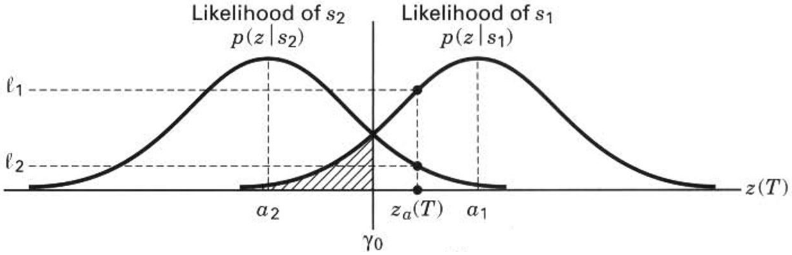
Baseband demodulation and detection

Detection : principle for binary signals (cont.)

The most important parameter in the detection process is **the energy of the received sampled symbol** and not its waveform.

The amplitude $z(T)$ at the predetection point is proportional to this energy

Decision making : comparison of **likelihoods**



Baseband demodulation and detection

Detection : principle for binary signals (cont.)

How to decide ? we detect a_1 if $p(z|s_1) > p(z|s_2)$ and a_2 otherwise

We define **two hypothesis:**

- H_1 : we assume that the symbol a_1 was transmitted
- H_2 : we assume that the symbol a_2 was transmitted

Decision threshold : γ_0 : hypothesis check

$$z(T) > \gamma_0 :\rightarrow \textit{retain} \;\; H_1$$

$$z(T) < \gamma_0 :\rightarrow \textit{retain} \;\; H_2$$

We are likely to have **detection errors :**

- we retained H_2 whereas a_1 was transmitted
- we retained H_1 whereas a_2 was transmitted

The corresponding probabilities :

$$p(e|s_1) = p(H_2|s_1) = \int_{-\infty}^{\gamma_0} p(z|s_1)dz$$

$$p(e|s_2) = p(H_1|s_2) = \int_{\gamma_0}^{+\infty} p(z|s_2)dz$$

Baseband demodulation and detection

Detection : probability of error (cont.)

How to **choose** the decision threshold γ_0 ?

- "maximum of likelihood" detector
- Threshold expression : $\gamma_0 = \frac{a_1+a_2}{2}$

The corresponding bit error rate (probability) :

$$p_B = p(s_2)\cdot\int_{\frac{a_1+a_2}{2}}^{+\infty} \frac{1}{\sigma_0\sqrt{2\pi}}.e^{-\frac{1}{2}(\frac{z-a_2}{\sigma_0})^2} dz + p(s_1)\cdot\int_{-\infty}^{\frac{a_1+a_2}{2}} \frac{1}{\sigma_0\sqrt{2\pi}}.e^{-\frac{1}{2}(\frac{z-a_1}{\sigma_0})^2} dz$$

Baseband demodulation and detection

Detection : probability of error (cont.)

By defining

$$u = \frac{z - a_2}{\sigma_0}$$

We obtain another form of the bit error rate

$$p_B = \int_{\frac{a_1 - a_2}{2\sigma_0}}^{+\infty} \frac{1}{\sqrt{2\pi}}.e^{-\frac{u^2}{2}} du = Q(\frac{a_1 - a_2}{2\sigma_0})$$

Q is the complementary PDF and is approached by :

$$Q(x) \approx \frac{1}{\sqrt{2\pi}} \int_{x}^{+\infty} e^{-\frac{u^2}{2}} du$$

Communication chain performance

Intro

The most important metric in a digital communication system :

Probability of bit error p_B as function of $\frac{E_b}{N_0}$

Also called **Bit Error Rate (BER)**

- E_b : used energy to send a bit
- N_0 : noise power spectral density (PSD)

For a fixed BER p_B, the lower is the required $\frac{E_b}{N_0}$, the more efficient is the detection process.

Communication chain performance

Link to the signal to noise ratio

SNR (*Signal to Noise Ratio*) :

- S : power of the signal
- N : power of the noise

Relationship between $\frac{E_b}{N_0}$ and SNR :

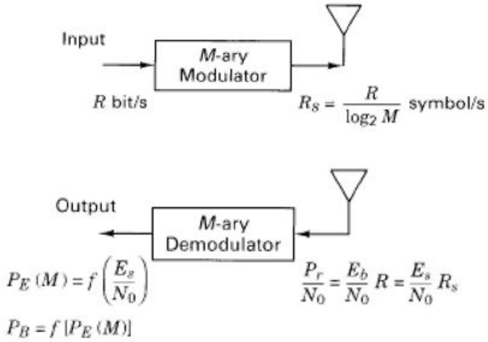
$$\frac{E_b}{N_0} = \frac{S.T_b}{\frac{N}{W}} = \frac{\frac{S}{D_b}}{\frac{N}{W}}$$

Which means :

$$\frac{E_b}{N_0} = \frac{S}{N}.\frac{W}{D_b} = SNR.\frac{W}{D_b}$$

Communication chain performance

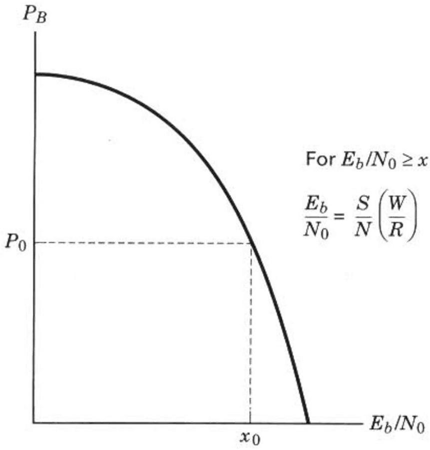
Link with the Signal to Noise Ratio (cont.)



Communication chain performance

Link with the Signal to Noise Ratio (cont.)

Illustration : "waterfall" profile



Communication system example : the LTE(-A)

What is it about ?

LTE : *Long Term Evolution*

First version appeared in 2009 (*release 8*)

Developed by the 3GPP group : *3rd Generation Partnership Project*

- Objective : establish technical specifications of 3G (and beyond) mobile networks
- Europe (ETSI : *European Telecommunications Standards Institute*)
- Asia (ARIB : *Association of Radio Industries and Business* ...)
- USA (ATIS : *Alliance for Telecommunications Industry Solutions*)

Communication system example : the LTE(-A)

What is it about ? (cont.)

LTE : *Long Term Evolution*

- its development began before the standard $4G$
- known as: generation $3.9G$

LTE-A : *Long Term Evolution - Advanced*

- adapted version of LTE to meet the standard $4G$

Communication system example : the LTE(-A)

Context

History of mobile phone standards :

- $0G$ (1970..) : communications in vehicles (police)
- $1G$ (1980..) : AMPS (*Advanced Mobile Phone System*)
- $2G$ (1991) : GSM (*Global System for Mobile Communications*)
- $2.5G$ (2000) : GPRS (*General Packet Radio Service*)
- $2.75G$ (2000) : EDGE (*Enhanced Data for GSM Evolution*)
- $3G$ (2000) : UMTS (*Universal Mobile Telecommunications System*)
- $3.5G$ (2002) : HSDPA (*High Speed Download Packet Access*)
- $3.75G$ (2005) : HSUPA (*High Speed Uplink Packet Access*)
- $3.9G$ (2009) : WiMAX (*Worldwide Interoperability for Microwave Access*)

Communication system example : the LTE(-A)

Context (cont.)

Evolution from analogue to digital :

- $0G$ and $1G$ systems: analogue
- $2G$ (and beyond) systems : digital

Evolutions from $2G$ to $4G$: the **throughputs**

- throughput of the (*downlink, download*)
- throughput of the (*uplink*)

Evolution from $5G$: la **energy consumption**

Communication system example : the LTE(-A)

Context (cont.)

Comparison of downlink **average** throughputs of mobile telephony :

Génération	Débit moyen (kbit/s)
2G (**GSM**)	9,6
2.5G (**GPRS**)	48
2.75G (**EDGE**)	171
3G (**UMTS**)	384
3.5G (**HSDPA**)	750
3.9G (**WiMAX**)	35000 (35Mbps)
3.9G (**LTE**)	100000 (100Mbps)

According to standards, the downlink rate achievable by HSDPA is $14 Mbps$ and that of LTE is $326 Mbps$, *i.e.* 23 times greater.

The speed of LTE is even higher than that of optical fibre (average: $304.83 Mbps$ in France).

Communication system example : the LTE(-A)

General Architecture

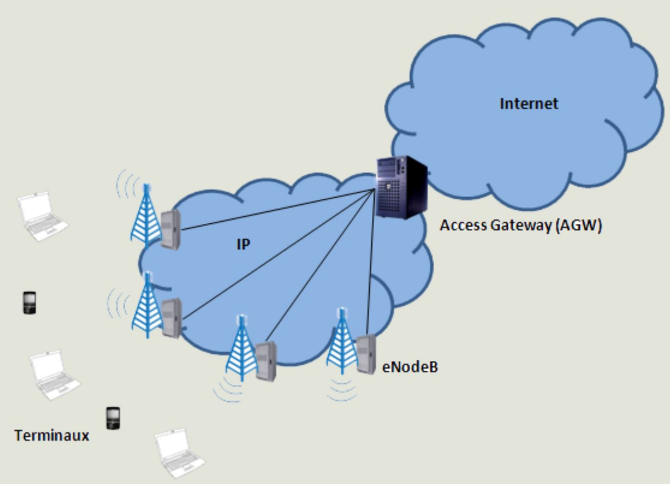
Three main elements :

- The **terminals** (EU *User Equipment*, end-users)
- The **base stations** (eNB: *eNodeB*, communicate with the UE, manage radio resources)
- The **access managers** (AGW: *access gateway*, manages access to services and mobility)

Communication system example : the LTE(-A)

General Architecture (cont.)

Illustration :



Communication system example : the LTE(-A)

SAE Architecture

The *AGW* is also called SAE (*System Architecture Evolution*).

Services : internet, voice, video, messaging...

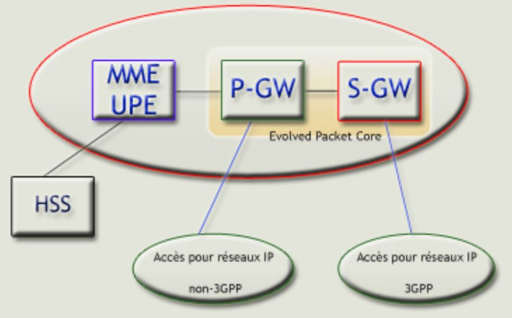
SAE components:

- **S-GW** (*Serving Gateway*): routes and transfers data packets locally to the UE, connection between LTE and other 3GPP networks
- **P-GW** (*Packet Data Network Gateway*): entry and exit point for UE traffic, connection between 3GPP and non-3GPP networks, allocation of IP addresses, access policy
- **MME** (*Mobile Management Entity*): management of all UE procedures (authentication, encryption, mobility...)

Communication system example : the LTE(-A)

SAE Architecture (cont.)

MME includes a **UPE** (*User Plane Entity*) to register user profiles and manage standby UEs, and communicates with a **HSS** (*Home Subscribe Service*) via the DIAMETER authentication protocol.



Communicates with the UE through the **NAS** layer (*Non-Access Stratum*)

Communication system example : the LTE(-A)

eNodeB Architecture

Connected to the SAE by a RAN (*Evolved Radio Access Network*) : evoluted radio interface called **E-UTRA** (*Evolved UMTS Terrestrial Radio Access*).

Communicates with the UE through layers :

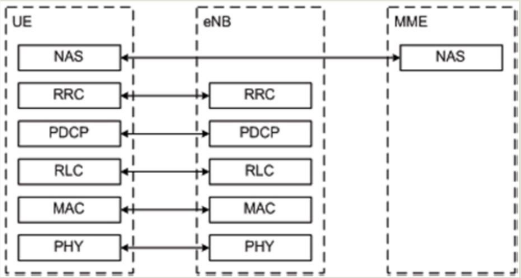
- physical (PHY)
- MAC (*Medium Access Control*)
- RLC (*Radio Link Control*)
- PDCP (*Packet Data Control Protocol*)
- RRC (*Radio Resource Control*)

Communication system example : the LTE(-A)

Organisation of the communication

LTE operates on a layered system between the UE, eNB and MME.

Each layer communicates with its equivalent of the same level (of the OSI model).



Communication system example : the LTE(-A)

Organisation of the communication (cont.)

The present layers are :

- **PHY** : effective transmission of signals between interlocutors
- **MAC** : interface between the upper layers and the physical layer
- **RLC** : reliability of data transmission in packet mode
- **PDCP** : compression and decompression of data for routing on the network
- **RRC** : control of resources to ensure quality of service (QoS)
- **NAS** : network communicating between the UE and the MME, managing calls and mobility

Communication system example : the LTE(-A)

Physical layer : technologies

- DL : **OFDMA** (*Orthogonal frequency-division multiple access*)
- UL : **SC-FDMA** (*Single-carrier frequency-division multiple access*)

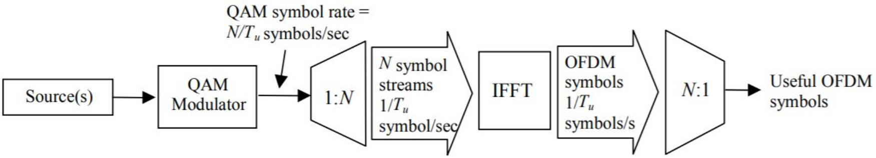
- already used on other existing systems (WiFi, ADSL...)
- reduced complexity of implementation
- compatibility with MIMO technologies for antennas
- resistance to multipath channels
- high spectral efficiency
- allocation of resources in terms of time and frequency
- Error recovery capability (FEC *Forward Error correction*)

Communication system example : the LTE(-A)

Physical layer : technologies (cont.)

Principle (OFDM schemes): distribution of the digital signal to be transmitted over a large number of **sub-carriers**.

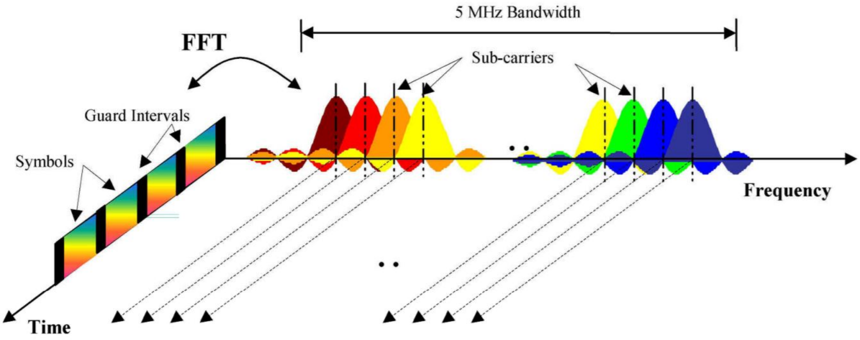
Mathematical operations: serial/parallel conversion, then inverse Fourier transform (IFFT)



Communication system example : the LTE(-A)

Physical layer : technologies (cont.)

Frequency-time representation :



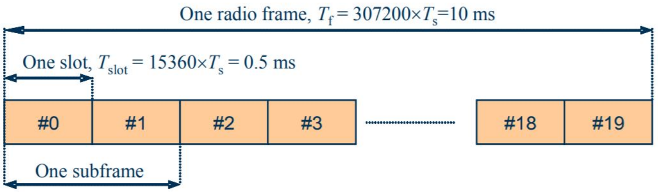
Communication system example : the LTE(-A)

Physical layer : radio frame

Two types of frames: type 1 (FDD frame) and type 2 (TDD frame).

Type 1 (FDD): duration of 10*ms*, divided into 20 slots of 0.5*ms* each, numbered from 0 to 19.

Illustration : type 1 frame dimensionning

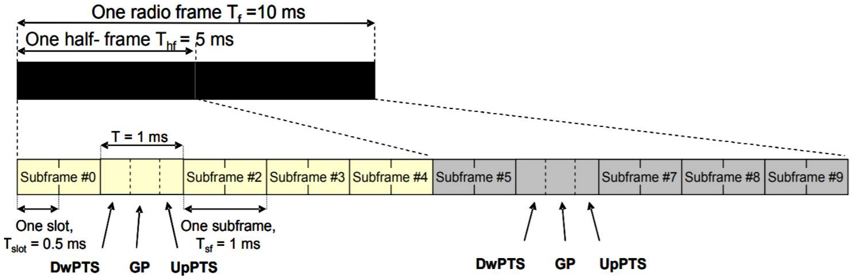


Communication system example : the LTE(-A)

Physical layer : radio frame (cont.)

Type 2 (TDD): duration of $10ms$, divided into 2 half frames of $5ms$, each divided into 5 subframes of $1ms$. Numbering from 0 to 9.

Non-specialised sub-frames are divided into 2 slots of $0.5ms$. Special subframes are divided into 3 equal parts (DL pilot, guard interval, UL pilot)



Communication system example : the LTE(-A)

Physical layer : frequencies

E-UTRA Operating Band	Uplink (UL) operating band BS receive UE transmit F_{UL_low} – F_{UL_high}	Downlink (DL) operating band BS transmit UE receive F_{DL_low} – F_{DL_high}	Duplex Mode
1	1920 MHz – 1980 MHz	2110 MHz – 2170 MHz	FDD
2	1850 MHz – 1910 MHz	1930 MHz – 1990 MHz	FDD
3	1710 MHz – 1785 MHz	1805 MHz – 1880 MHz	FDD
4	1710 MHz – 1755 MHz	2110 MHz – 2155 MHz	FDD
5	824 MHz – 849 MHz	869 MHz – 894MHz	FDD
6	830 MHz – 840 MHz	875 MHz – 885 MHz	FDD
7	2500 MHz – 2570 MHz	2620 MHz – 2690 MHz	FDD
8	880 MHz – 915 MHz	925 MHz – 960 MHz	FDD
9	1749.9 MHz – 1784.9 MHz	1844.9 MHz – 1879.9 MHz	FDD
10	1710 MHz – 1770 MHz	2110 MHz – 2170 MHz	FDD
11	1427.9 MHz – 1447.9 MHz	1475.9 MHz – 1495.9 MHz	FDD
12	698 MHz – 716 MHz	728 MHz – 746 MHz	FDD
13	777 MHz – 787 MHz	746 MHz – 756 MHz	FDD
14	788 MHz – 798 MHz	758 MHz – 768 MHz	FDD
17	704 MHz – 716 MHz	734 MHz – 746 MHz	FDD
...			
33	1900 MHz – 1920 MHz	1900 MHz – 1920 MHz	TDD
34	2010 MHz – 2025 MHz	2010 MHz – 2025 MHz	TDD
35	1850 MHz – 1910 MHz	1850 MHz – 1910 MHz	TDD
36	1930 MHz – 1990 MHz	1930 MHz – 1990 MHz	TDD
37	1910 MHz – 1930 MHz	1910 MHz – 1930 MHz	TDD
38	2570 MHz – 2620 MHz	2570 MHz – 2620 MHz	TDD
39	1880 MHz – 1920 MHz	1880 MHz – 1920 MHz	TDD
40	2300 MHz – 2400 MHz	2300 MHz – 2400 MHz	TDD

Communication system example : the LTE(-A)

Physical layer : other parameters

Channel coding	Turbo code
Mobility	350 km/h
Channel Bandwidth (MHz)	1.4 3 5 10 15 20
Transmission Bandwidth Configuration NRB : (1 resource block = 180kHz in 1ms TTI)	6 15 25 50 75 100
Modulation Schemes	UL: QPSK, 16QAM, 64QAM(optional) DL: QPSK, 16QAM, 64QAM

Communication system example : the LTE(-A)

Physical layer : other parameters (cont.)

Multiple Access Schemes	UL: SC-FDMA (Single Carrier Frequency Division Multiple Access) supports 50Mbps+ (20MHz spectrum) DL: OFDM (Orthogonal Frequency Division Multiple Access) supports 100Mbps+ (20MHz spectrum)
Multi-Antenna Technology	UL: Multi-user collaborative MIMO DL: TxAA, spatial multiplexing, CDD ,max 4x4 array
Peak data rate in LTE	UL: 75Mbps(20MHz bandwidth) DL: 150Mbps(UE Category 4, 2x2 MIMO, 20MHz bandwidth) DL: 300Mbps(UE category 5, 4x4 MIMO, 20MHz bandwidth)
MIMO (Multiple Input Multiple Output)	UL: 1 x 2, 1 x 4 DL: 2 x 2, 4 x 2, 4 x 4
Coverage	5 - 100km with slight degradation after 30km

Communication system example : the LTE(-A)

Physical layer : other parameters (cont.)

QoS	E2E QOS allowing prioritization of different class of service
Latency	End-user latency < 10mS