UNIVERSITY
OF TRENTO - Italy
Information Engineering
and Computer Science Department

Physical Layer Architecture and Error Correction Codes

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Introduction - Goals

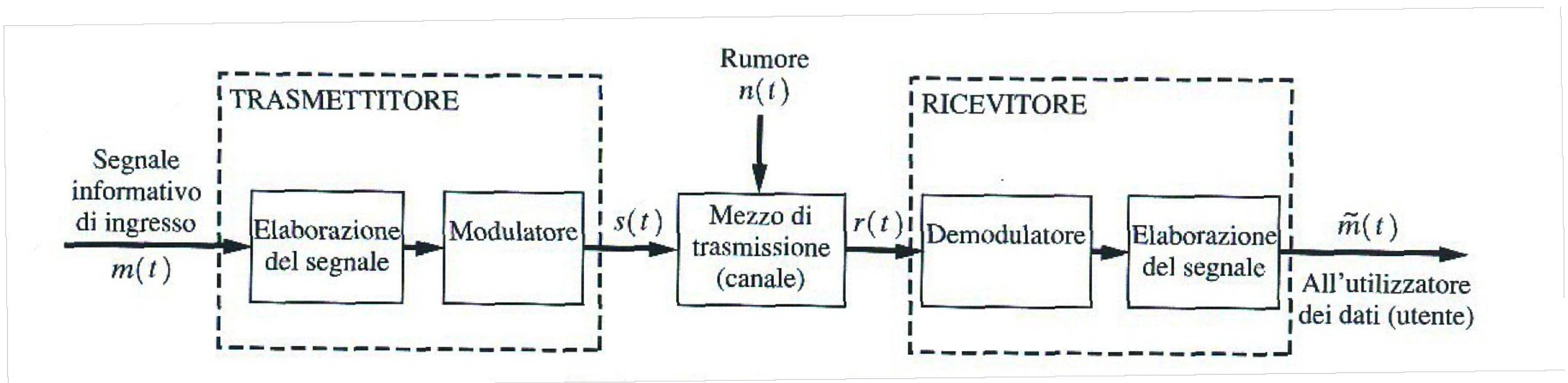
SEMINAR GOALS

- How a signal can be digitally transmitted over a network
- Which are the main problems that engineer must solve to have an efficient network to communicate
- Which are the techniques that permits error recovery when something goes wrong during communication

Let's Start!!

Introduction - Architecture of Communication System

- *Communicate:* means information can pass from point A to point B using standard conventions
- This is the architecture which allows to communicate between two or many points

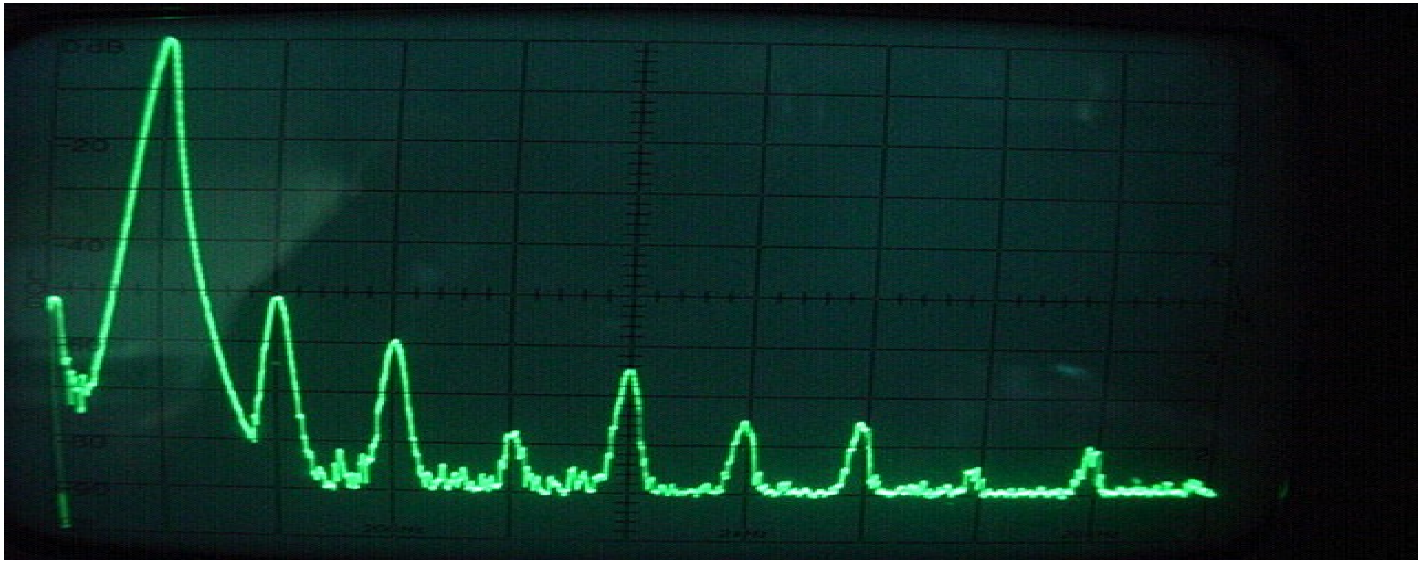


Chapter 1 - Signals

What is a Signal?

- Signal is a physical quantity which varies with respect to time, contains information and travels from source to destination

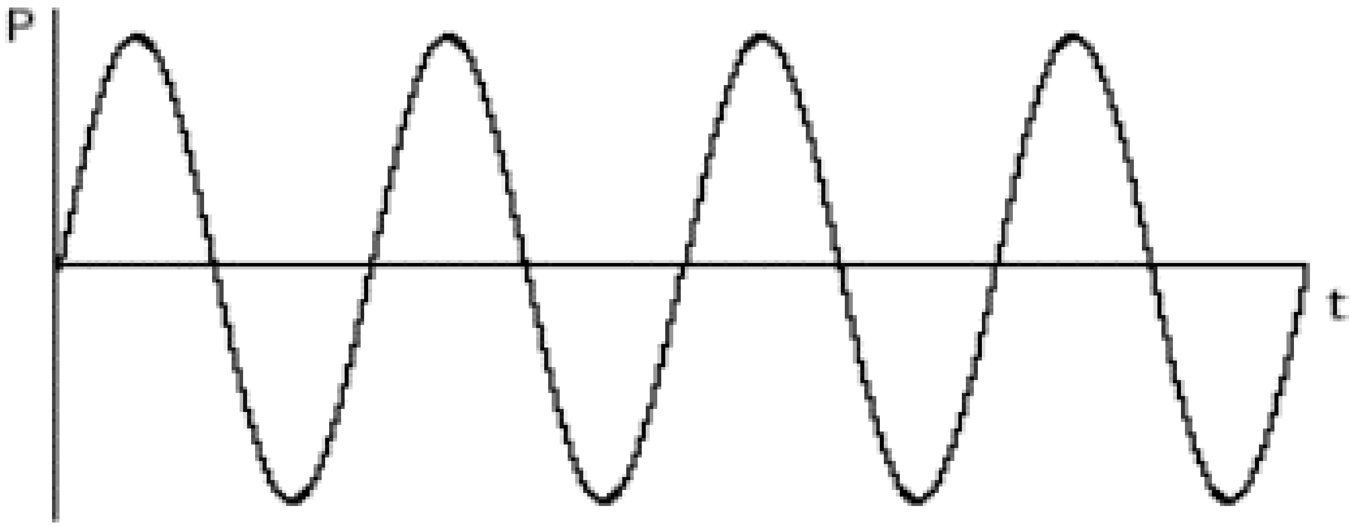
- The IEEE defines "signal" as follows: The term "signal" includes, among others, audio, video, speech, image, text, communication, etc.



Analog signal

- A signal that has a continuous nature, may vary in frequency, phase or amplitude in response to changes in physical phenomena

- Typically, for transmission purposes, we talk about a sinusoidal signal that has particular shape, see the figure:

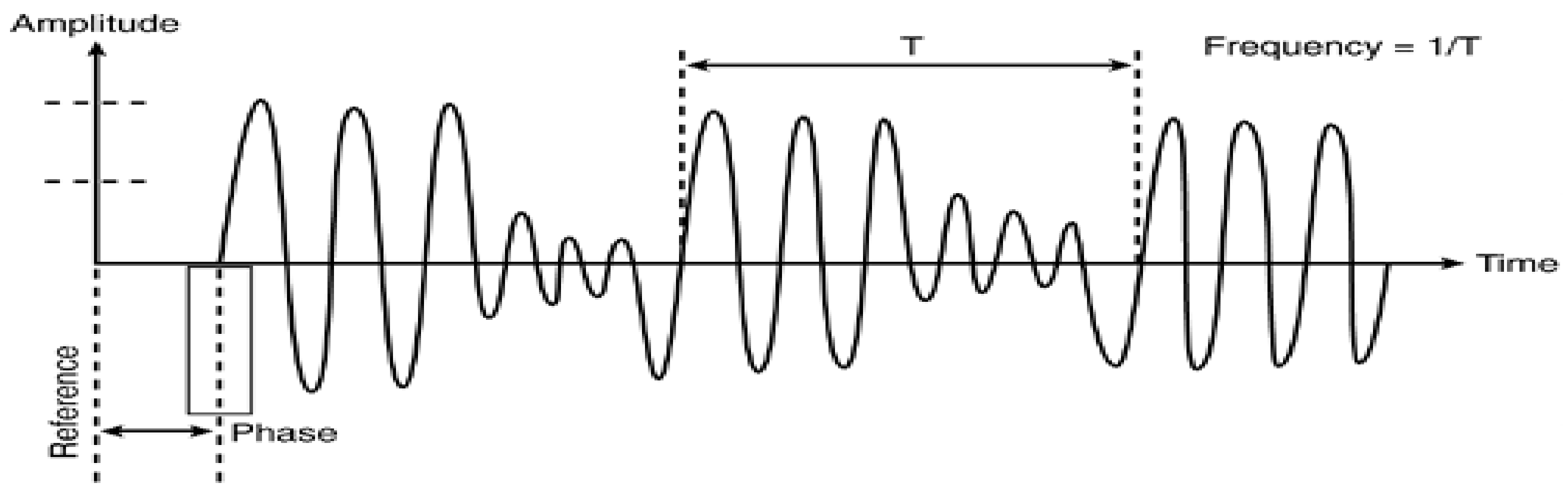


Properties of Sinusoidal Signal

- General formula for a continuous sinusoidal signal is:

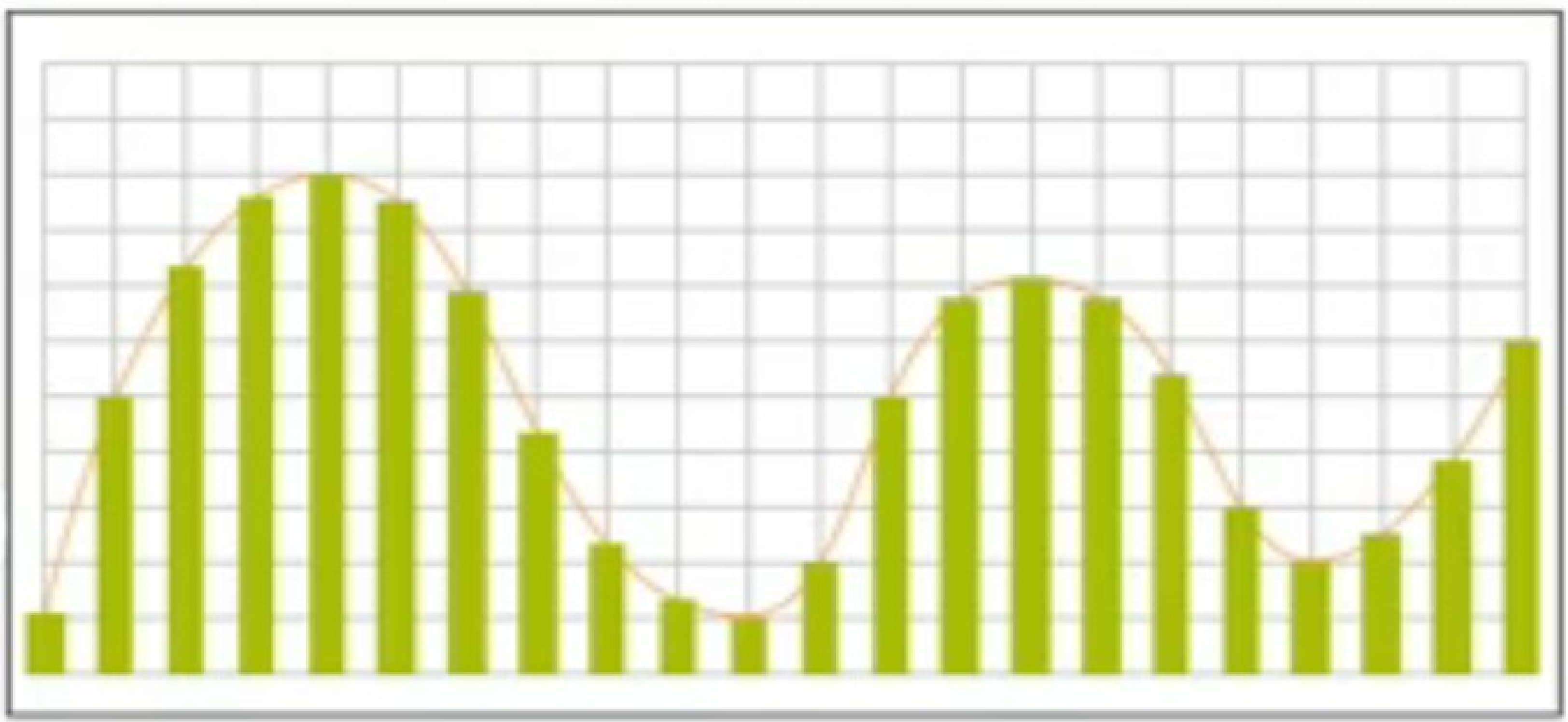
$$s(t) = A \sin(2\pi f t) + \Phi$$

- *Amplitude* (A) → measure intensity of the signal, substantially measure the height of the wave
- *Frequency* (f) → measure the number of occurrences of a wave repeating event in 1 sec
- *Phase* (Φ) → measure translation of the wave (along time axis)



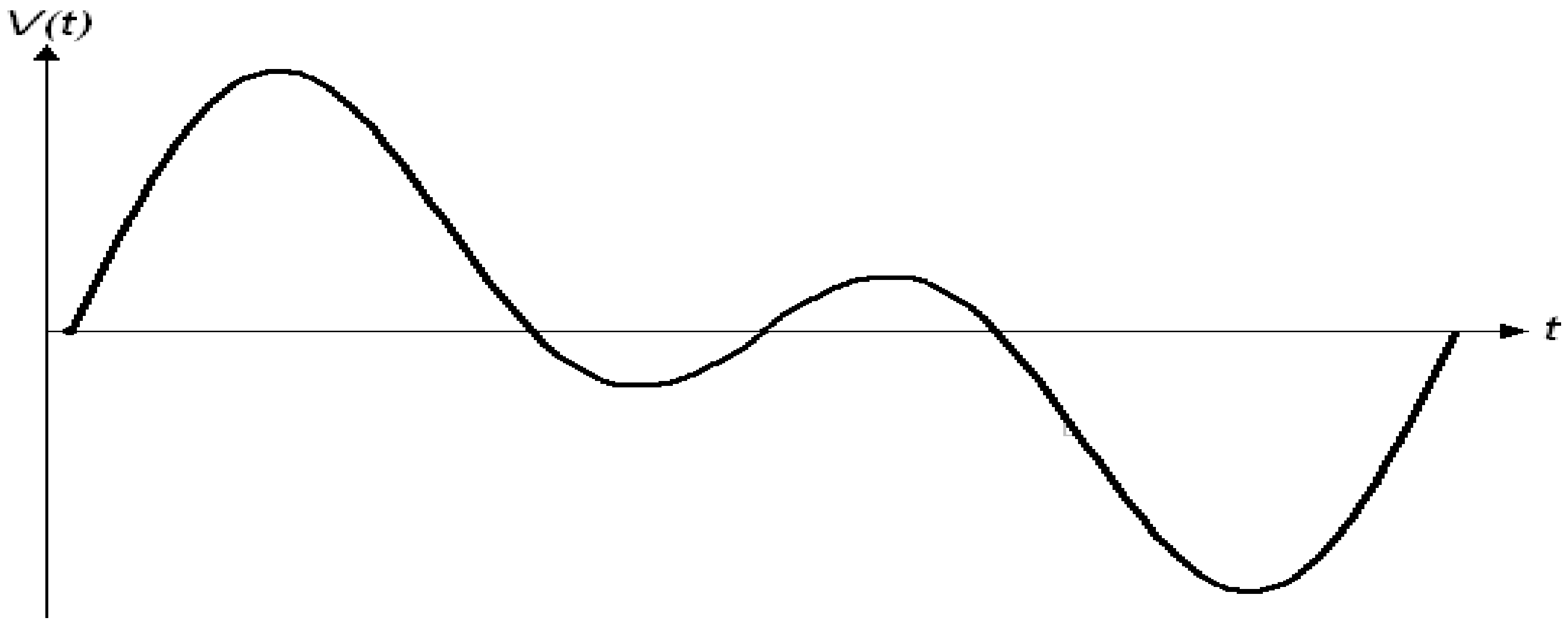
Digital Signal

- A digital signal has a discrete value measured at each sampling point.
- A digital signal can refer to an electrical signal that is converted into a pattern of bits by sampling



Sampling

- *Sampling:* is the reduction of a continuous signal to a discrete signal measuring its value at different moments
- This permits to convert an analog signal into a digital signal, making a well know: "digitalized analog signal"
- *Sampling Frequency:* (Sampling Rate) is the number of samples obtained in 1 second!



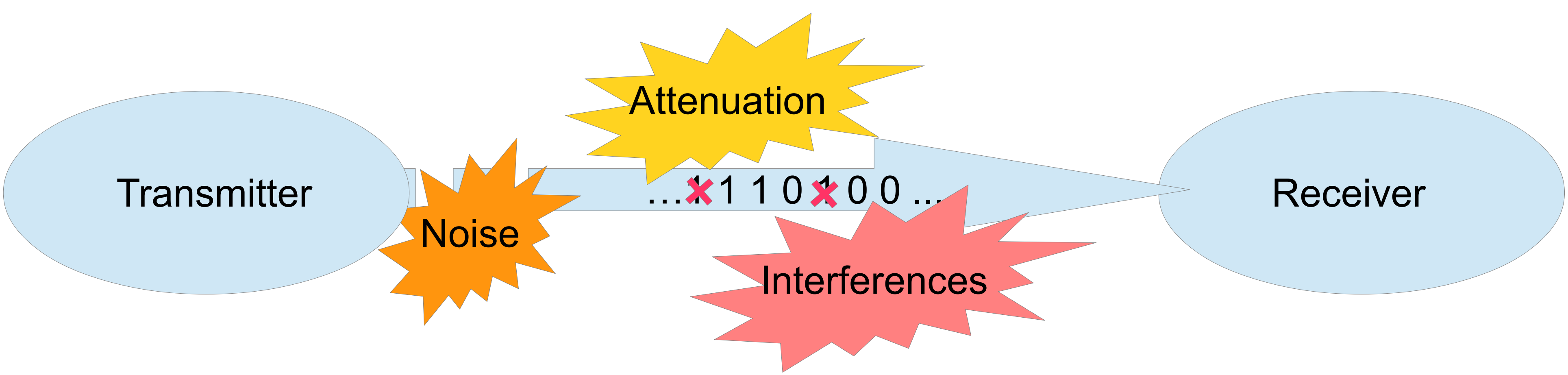
Chapter 2 – Transmission

Transmission

- ***Transmission:*** is the process of sending and propagating an analogue or digital information signal over a physical point-to-point or multipoint transmission medium that can be wired or wireless

- ***Data transmission:*** (or digital communication) is the transmission of a digital message or of a digitized analog signal

- In all types of transmission, there are many problems that can make the transmission very difficult: attenuation, noise, etc.



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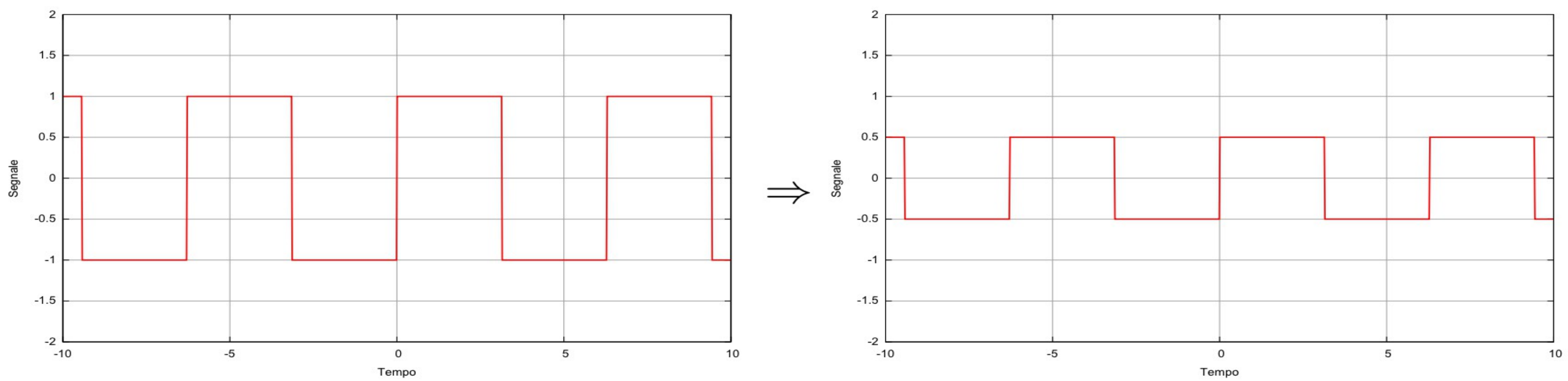
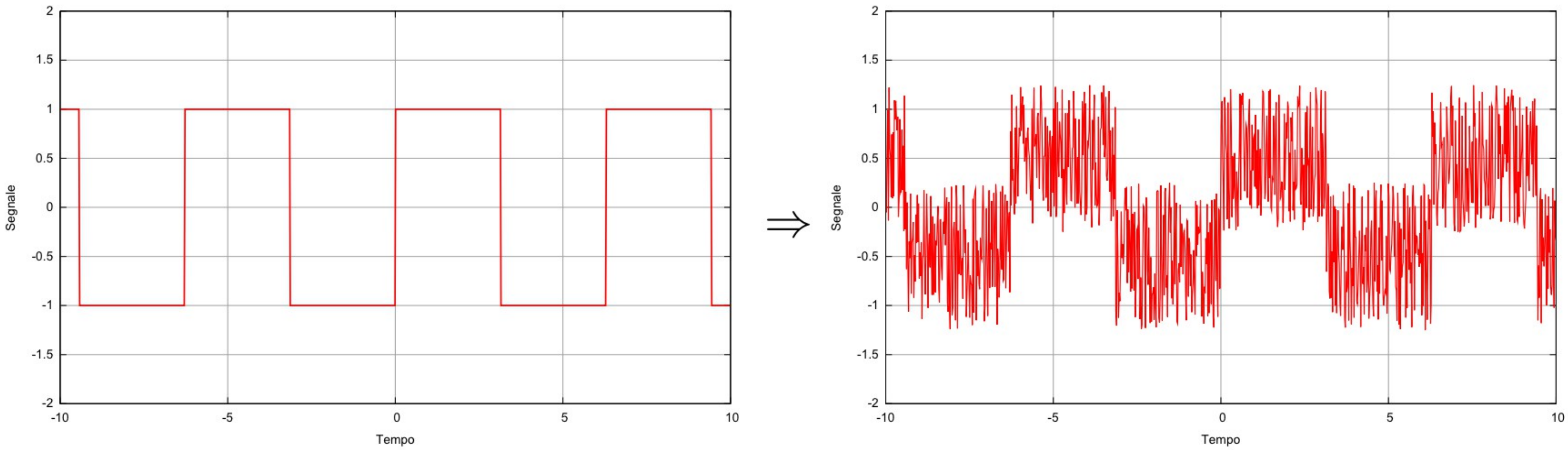
Attenuation

- Attenuation is the gradual loss of intensity of a wave through a medium.
- We can algebraically imagine attenuation as a multiplication of the signal to a coefficient c $\in$ [0,1]
- Attenuation affects the propagation of waves and signals in electrical circuits, in optical fibers, as well as in air (radio waves)



Interference

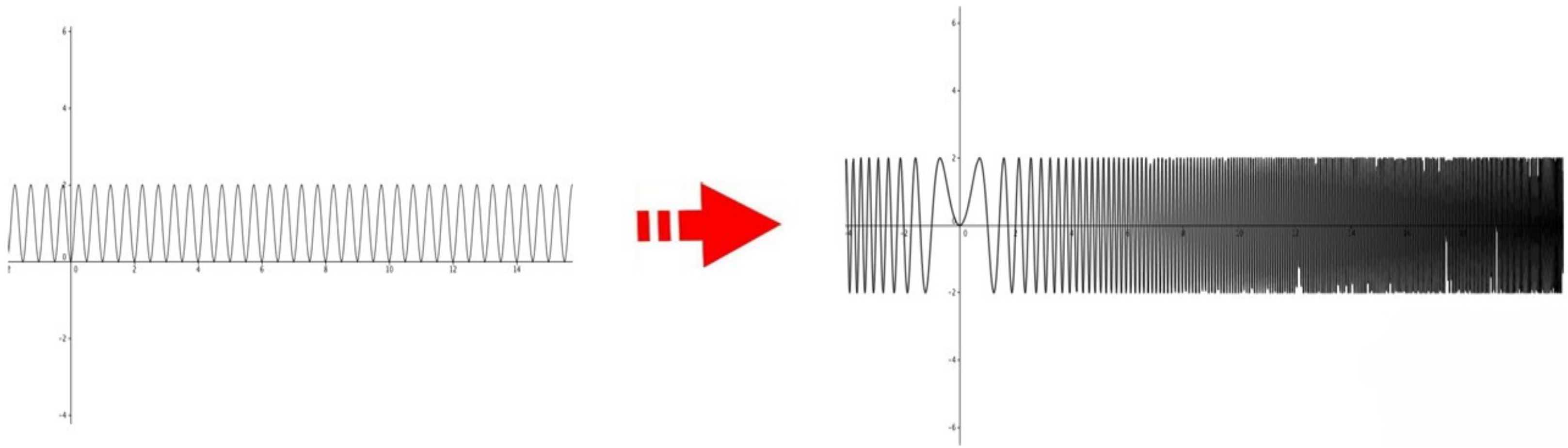
- Interference is a phenomenon in which two waves overlap to form a resultant wave of greater or lower amplitude
- We can algebraically imagine interferences as the result of addition of two or more waves
- Interference effects can be observed with all types of waves, for example, light, radio, acoustic, and surface water waves.
- Main causes of interference are nearby electromagnetic fields and energy from nearby wires



Distortion

- A distortion is the alteration of the original shape of a waveform
- Distortion occurs when the properties of waveform varying by a factor that is not always the same at all frequencies
- Is the only transmission problem that modify not linearly the waveform !

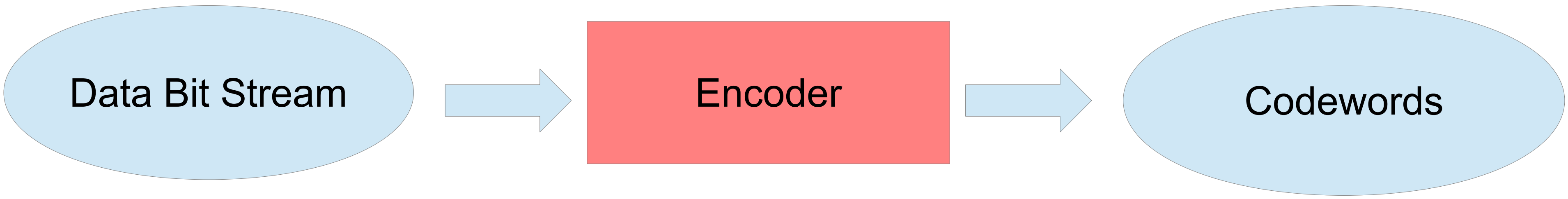
Frequency distortion



Chapter 3- Encoding

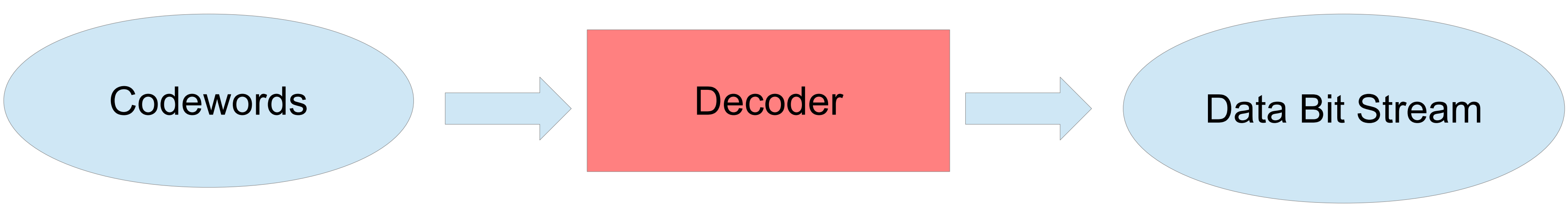
Encoding

- *Encoding:* is the process which bit informations are converted into codewords
- *Idea*: When codewords will be arrived at the receiver, it can understand if some errors occurs, even correct them
- *Encoder:* is a device, circuit, transducer, software program, algorithm, etc. that execute encoding



Decoding

- *Decoding:* is the process that convert back codewords into a data bit stream
- Decoding process means also errors detection and correction
- If the decoding technique used can only discover wrong codewords then decoder typically use ARQ techniques to request for a retransmission of that wrong codeword
- *Decoder:* is a device, circuit, transducer, software program, algorithm which does the reverse operation of encoder

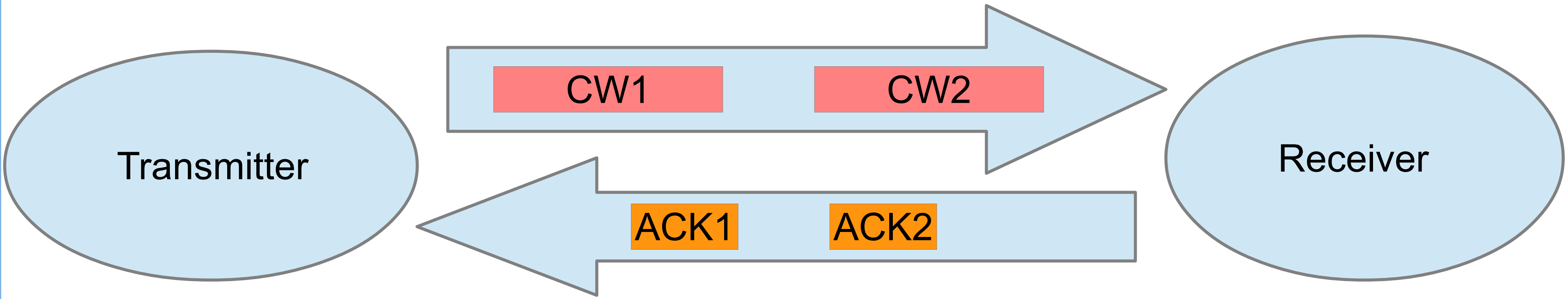


ARQ (Automatic Repeat Re-Quest)

- This technique uses ACK and timeouts to achieve reliable data transmission.
- If receiver detects some parity bit errors inside a packet then it can ask sender to retransmit this packet.
- Main ARQ techniques are:

  - *Stop and Wait*
  - *Go Back-N*
  - *Selective Repeat*

Same used by TCP to ask for retransmission



FEC (Forward Error Correction)

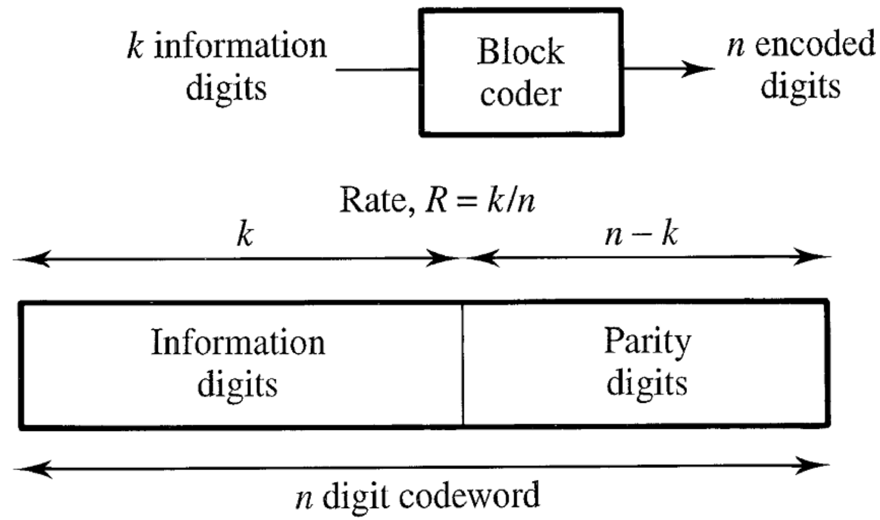
- FEC techniques are used to find and correct transmission errors over an unreliable and noisy communication channel without asking for retransmission

- *Idea:*
  - Transmitter encodes messages by adding some redundant bits
  - Receiver, using redundant bits, can find and correct errors

- FEC techniques are used:
  - *Broadcast and Multicast:* When it is not possible to send back ACK/NACK to the sender
  - *Long Propagation Delay:* To avoid long inactivity periods of sender for waiting ACK/NACK
  - *High Bit Error Rates:* If 20% of bit stream received is wrong, it is very difficult to communicate using only FEC techniques

Block Code

- Encoder takes k data bits as input and convert them into a codeword of n bits



- Binary logic of encoder works like a function

- Encoder has NO memory: this means that given as input always the same k bits, binary logic of encoder gives as output always the same n bits

Hamming

- Hamming codes are a family of linear error-correcting codes invented by Richard Hamming in 1950
- A typical hamming code is written like this H(n, k, n-k) where

  - *n*: # of bits in a codeword

  - *k*: # of data bits

  - *n-k* = # parity bits
- To DETECT e errors we need e+1 parity bits
- To CORRECT e errors we need 2e+1 parity bits

Hamming Definitions

- Hamming Weight (H_w): is the number of bits = 1 into a string

1011101 → HAMMING WEIGHT = 5

- Hamming Distance (H_d): measures the minimum number of substitutions required to change one string into another one. (# of errors)

1011101 1001001 → HAMMING DISTANCE = 2

Parity Bit Coverage

- All bit positions that are powers of two are Parity Bits!
  All other bit positions are Data Bits!
- Each parity bit “protects” a subset of data bits
- Position 1: cover 1 bit, skip 1 bit, etc. (1,3,5,7,9,11,13,15,...)
- Position 2: cover 2 bits, skip 2 bits, etc. (2,3,6,7,10,11,14,15,...)
- Position 4: cover 4 bits, skip 4 bits, etc. (4,5,6,7,12,13,14,15,...)

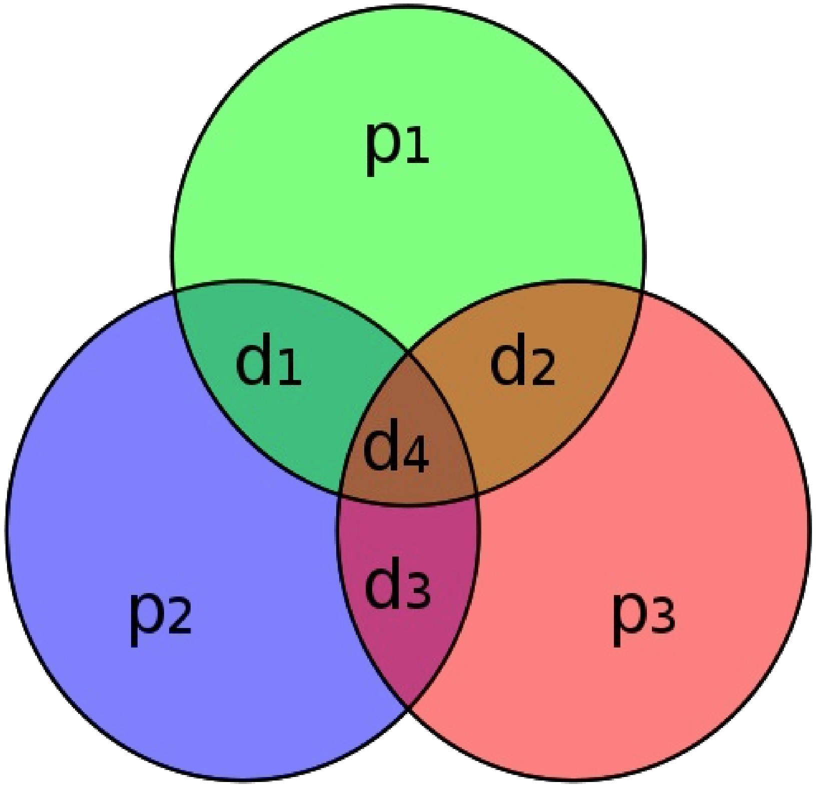
Bit position		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Encoded data bits		p1	p2	d1	p4	d2	d3	d4	p8	d5	d6	d7	d8	d9	d10	d11	p16	d12	d13	d14	d15	
Parity bit coverage	p1	X		X		X		X		X		X		X		X		X		X		
	p2		X	X			X	X			X	X			X	X			X	X		...
	p4				X	X	X	X					X	X	X	X					X	
	p8								X	X	X	X	X	X	X	X						
	p16																X	X	X	X	X	

Parity Bit Coverage

- This is an Hamming (7,4,3) codeword:
  p_1 p_2 d_1 p_3 d_2 d_3 d_4

- A parity bit coverage can also be explained as an Eulero-Venn diagram like in this figure

- In a Hamming (7,4,3) code:
  - p_1 cover d_1 d_2 d_4
  - p_2 cover d_1 d_3 d_4
  - p_3 cover d_2 d_3 d_4



- $\forall$ Parity bit (p_x) | $x \in$ power of 2
  If (H_w of data bits covered by p_x is odd)
  $p_x = 1$
  Else $p_x = 0$

Hamming (7,4,3) Example - Encoding

- Let's suppose that we want to send a bit stream s = 1011
- Hamming (7,4) codeword becomes: p_1 p_2 1 p_3 0 1 1
- $p_1 = H_w$ of its covered bits (**p1** p2 **1** p3 **0** 1 **1**) is **2** → **EVEN** → 0
- $p_2 = H_w$ of its covered bits (p1 **p2** **1** p3 0 **1** **1**) is **3** → **ODD** → 1
- $p_3 = H_w$ of its covered bits (p1 p2 1 **p3** **0** **1** **1**) is **2** → **EVEN** → 0
- Encoded codeword is: **0** **1** 1 **0** 0 1 1

Hamming (7,4,3) Example – Error Correction Algorithm

1 – Set an int variable sum = 0

2 – Repeat encoding algorithm for each parity bit e_i

3 – If its value not correspond with H_w of its covered bits then add its index to variable sum

4 – If sum = 0 means that all parity bits was corrected so there is nothing to do because received codeword is correct

5 – Otherwise something went wrong and the value of variable sum is the index of wrong bit, to correct that error, simply negate that bit

Hamming (7,4,3) Example – Error Correction

- If, during transmission, something goes wrong (noise, interferences, etc..) receiver will get something different then original bit stream

- Let's suppose receiver get wrong codeword where fifth bit is wrong: 0110111

- Repeating encoding algorithm for each parity bit:

p_1 = 0 - H_w of its covered bits (0 1 1 0 1 1 1) is 3 → ODD → ***WRONG***

p_2 = 1 - H_w of its covered bits (0 1 1 0 1 1 1) is 4 → EVEN → ***OK***

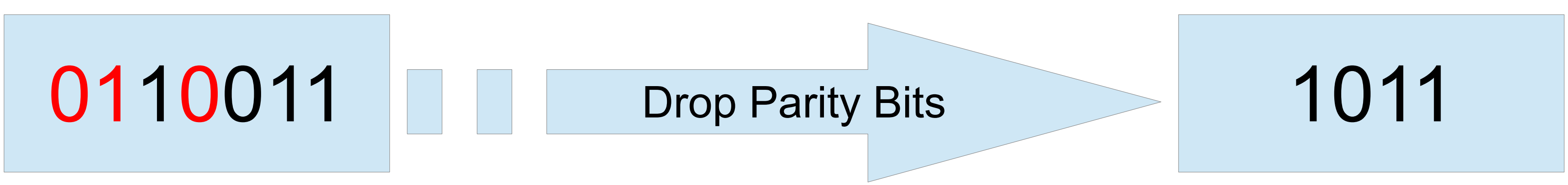
p_3 = 0 - H_w of its covered bits (0 1 1 0 1 1 1) is 3 → ODD → ***WRONG***

- Adding indexes of wrong parity bits 1 + 4, we get the index (5) of bit where error occurs!

- Receiver can then correct that error and get 0110011, the correct codeword!

Hamming (7,4) Example - Decoding

- Finally, to get only data bits from codeword, decoder must only drop parity bits
- Drop every parity bits means drop every bit which have index that are powers of two
- After decoding, data bit stream can be passed up to application level



Galois Field

- A Galois field GF(x): is a finite field that contains a finite number of elements, x specify cardinality of GF

- A GF has these properties:
  - Closing under Addition and Multiplication
  - Associativity, Commutativity and Distributivity
  - Existence of neutral element: 0 for addition and 1 for multiplication
  - Existence for each element u of its opposite -u
  - Existence for each element $u \neq 0$, the inverse element u^{-1}

- In Addition and Subtraction are executed with XOR operand

- In Division, dividend is divisible by divisor only if it is composed by the same number of bits of divisor otherwise not!

- In Multiplication the result must be divided by cardinality of Galois Field considered and take the remainder as right result!

Galois Field

- ADDITION

10110011 +
10001101 =
00111110

← It's the same! →

- SUBTRACTION

10110011 -
10001101 =
00111110

- MULTIPLICATION

111000 x
101 =
111000
000000-
111000--
11011000 mod |GF(x)|

- DIVISION

111000 : 101 = 1101
101
0100
101
0010
00100
101
001

CRC (Cyclic Redundancy Code)

- CRC Code checks if transmission errors occurs but not correct them.
- A bit stream of k bits can be converted in a polynomial of degree k-1
- CRC uses Galois Field to encode messages
- Es. 100110 ($k = 6$) can be converted in a polynomial like this: $x^5 + x^2 + x$. Degree = k-1
- Generator Polynomial g(x) is an algebraic polynomial of degree r (composed by r+1 bits) where FIRST and LAST bits = 1;
- g(x) is always known by transmitter and receiver

CRC – Encoding Algorithm

1. Let's suppose m(x) is message that we want encode

2. Add r zero bits to m(x) (r is degree of g(x))

3. $r(x) = x^r m(x) \bmod g(x)$

4. $m(x) = x^r m(x) - r(x)$ (it is a XOR operation of last r bits)

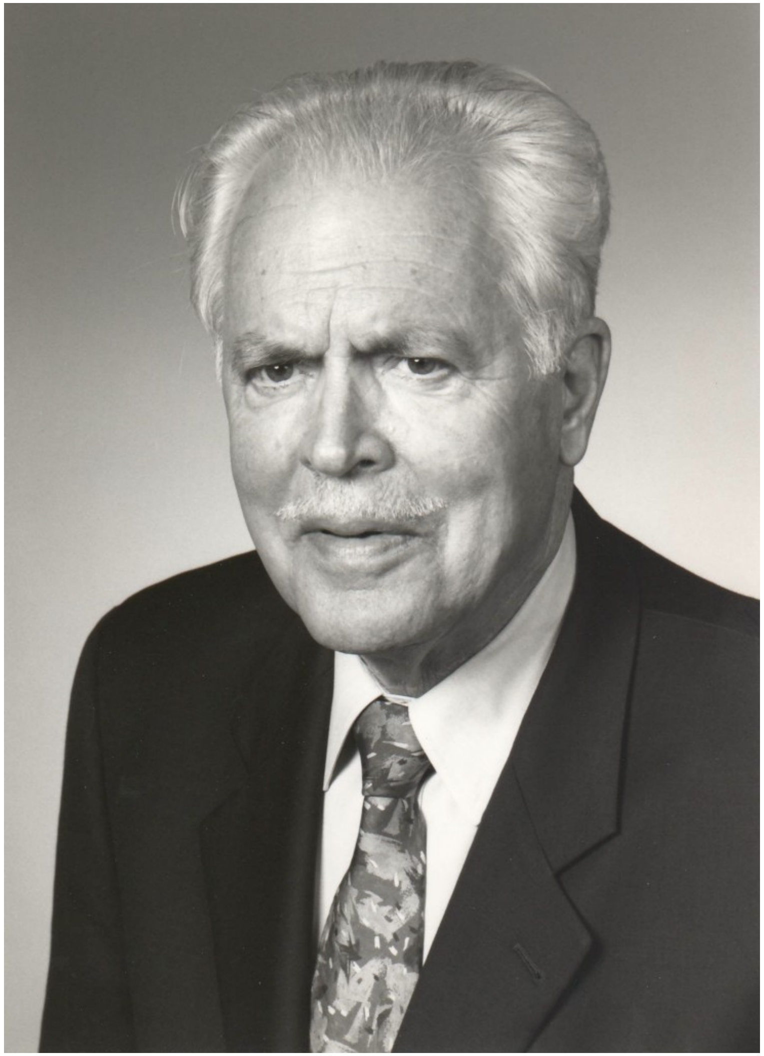
5. Transmit this new polynomial m(x) where first m bits, data bits, are unchanged

CRC (Cyclic Redundancy Code)

- Message is another polynomial m(x) of degree m-1 where $m > r$
- IDEA: Append at m(x) a control bit string of r bits to get a polynomial divisible by g(x)
- If transmission works, decoder divide m(x) by g(x) and get no rest. This means that codeword is correctly received
- To decode m(x), decoder must divide m(x) by x^r to get only data bits.
- Otherwise, if transmission errors occurs, with very high probability, that polynomial will not be more divisible by g(x)
- Decoder must ask for a retransmission of that wrong packet using ARQ

Reed Solomon – RS Code

- RS-codes are non-binary cyclic error-correcting codes invented by Irving S. Reed and Gustave Solomon
- Like CRC it see a bit stream like a polynomial
- RS-Code use algebraically properties of Galois Field to encoding
- RS-Code purpose is to find greater number of packets that contains errors.
- RS-Code are used in our Digital TV



Reed Solomon - RS Code

- RS-Code uses an alphabet of q symbols (not only 0 or 1)
- A symbol represent many bits (16 or more..)
- RS-Code are used to find burst of errors (multiple errors)
- Codeword contains n symbols, k are data symbols and n-k are redundancy symbols
- $0 < k < n < 2^m$
- RS-Code can find and correct until $t = (n-k) / 2$ errors in a codeword
- The most common form for RS-codes is $RS(2^m-1, 2^m-1- 2t)$ where: 2t is the number of redundancy symbols

RS-Code – Encoding Algorithm

- Define a generator polynomial g(x) known by transmitter and receiver: $g(x) = (x + \alpha)(x + \alpha^2)\ldots(x + \alpha^{2t})$ where α, α^2.. are roots

$$= g_0 + g_1 x + g_2 x^2 + \ldots + g_{2t-1} x^{2t-1} + x^{2t}$$

- Convert a bit stream of k bits into a polynomial:

  $d(x) = d_0 + d_1 x^1 + \ldots + d_{k-1} x^{k-1}$

- Multiply d(x) with x^{2t-1} (2t = n-k) to get a polynomial of n symbols and degree n-1
- $p(x) = x^{2t-1} d(x) \bmod g(x)$, is the rest of division by g(x)
- $a(x) = x^{2t-1} d(x) / g(x)$, is the result of division by g(x)
- Finally $c(x) = x^{2t-1} d(x) + p(x)$ (it is a XOR operation)
- Now we get c(x) that is a polynomial which is exactly divisible by g(x)

RS Code – Decoding

- Let's suppose some errors in transmission: $e(x) = r(x) – c(x)$, where $r(x)$ is the received codeword
- More generally $e(x)$ will be something like this: $e(x) = e_0 + e_1 x + e_2 x^2 + \ldots + e_{n-1} x^{n-1}$
- Codewords, where $c(x) \bmod g(x) \neq 0$, surely contains some errors, but we don't know in which position and what is the right symbol (because we are in a NON binary code)
- Firstly we must calculate the syndrome polynomial $s(x)$ $s(x) = r(x) \bmod g(x) = (a(x)\, g(x) + e(x)) \bmod g(x)$
- If syndrome is null, this means that codeword is correctly received
- Otherwise we have to calculate errors polynomial $e(x)$ $e(x) = s(\alpha^i)$, where each α^i is a root of $g(x)$ at position i

RS Code – Decoding

- Otherwise we have to calculate errors polynomial e(x):
  $e(x) = s(\alpha^i)$ i=1..2t, where each α^i is a root of g(x) at position i

- Finally to get correct codeword c(x) we simple:

$$c(x) = r(x) - e(x)$$

- *Important*: Some operations may seem very strange, it is correct because we are using properties of a Galois Field(2^x)

- To get more informations about RS Code visit:

  - Stefano Rinauro - Codifica RS (Italian)

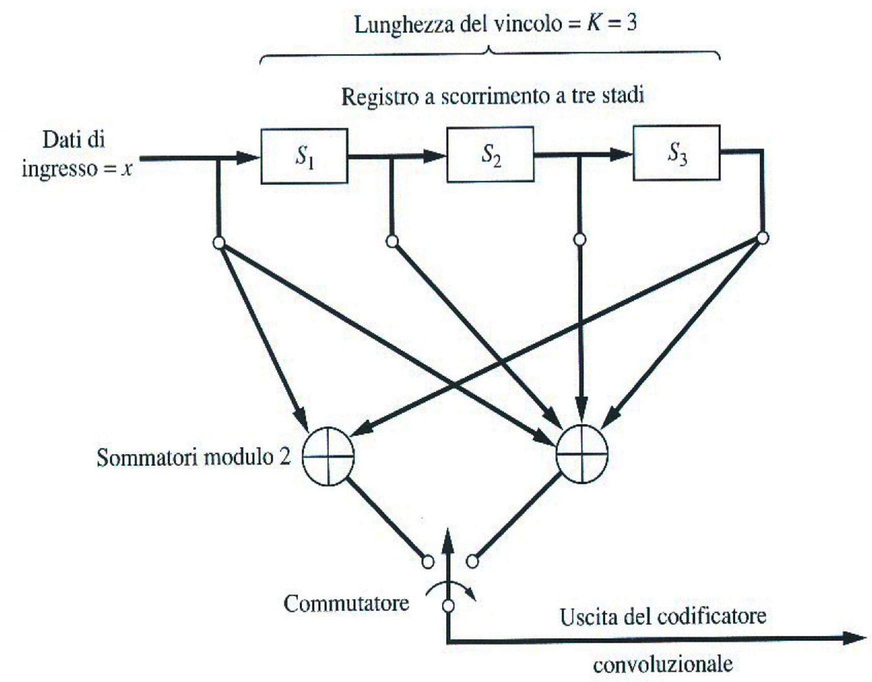
  - Bernard Sklar (English)

Convolutional Code

- Encoder has a little memory to remind previous states
- Encoder use a scrolling register to store until K bit stream blocks past
- *Constraint Length:* Number of bit stream blocks (K) stored into the scrolling register
- From these K-1 blocks plus the new one, binary logic calculate the new codeword
- *Infinite Memory:* Because a convolutional encoder can remember K previous states, we say that it remember infinite previous states because each state depends by K before, and so on

Convolutional Code – Encoding Example

- Example:
  - Constraint Length (K) = 3
  - #bits of codeword (n) = 2
  - #data bits as input (k) = 1
- To make a codeword, a commutator rotate clockwise between some mod 2 adders concatenating their output
- R = redundancy rate = ½ because each 1 bits of data as input, we get 2 encoded bits as output

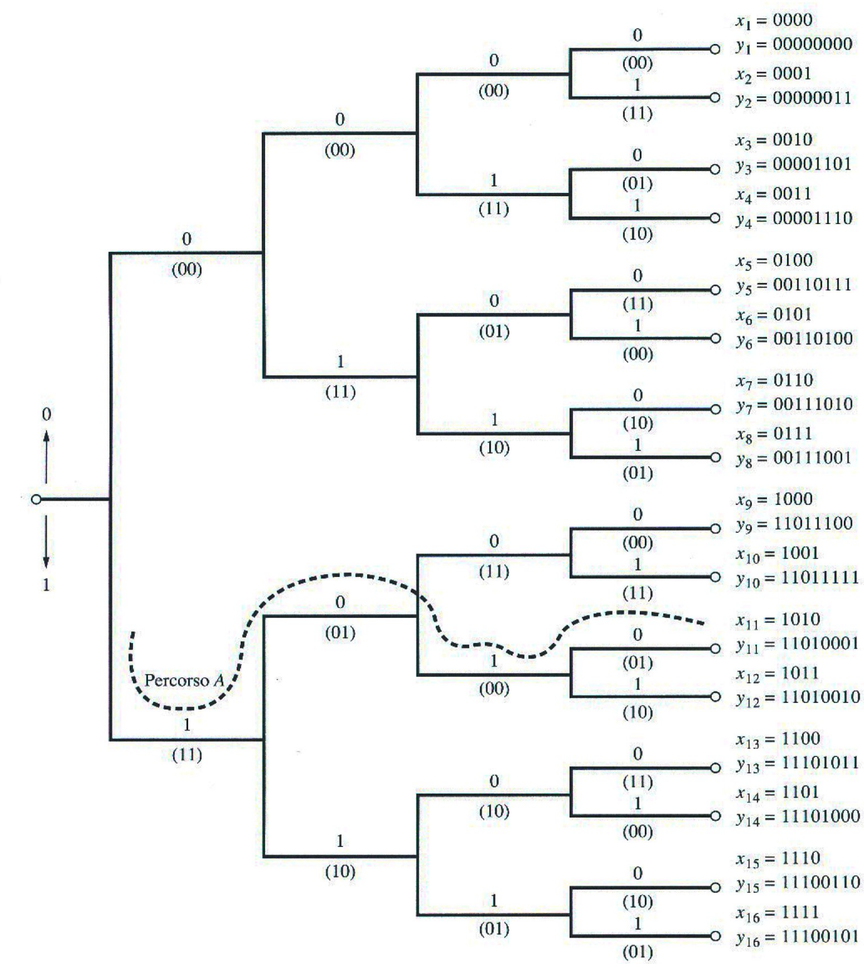


Convolutional Code – Encoding Example

- Encoder make a code tree like in this figure
- To move within a code tree, we have to move:

  - Up if source bit is 0
  - Down if source bit is 1

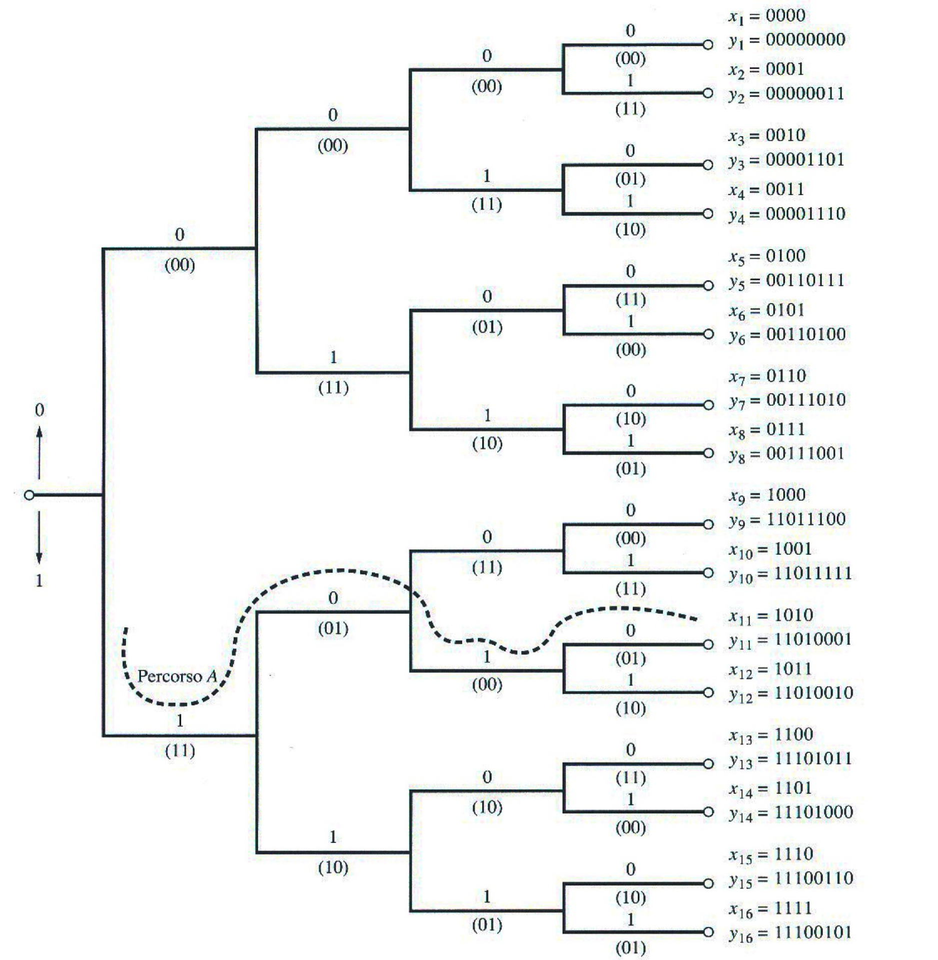
- Taking bits contents in each node which is crossed by our path, we get encoded string
- Let's suppose source bits are: s = 1010, following code tree, we get encoded string: y_{11} = 11010001



Convolutional Code – Decoding Example

- Using Viterbi's Algorithm decoder find a path which have minimum Hamming distance from received sequence to each possible sequence path in code tree

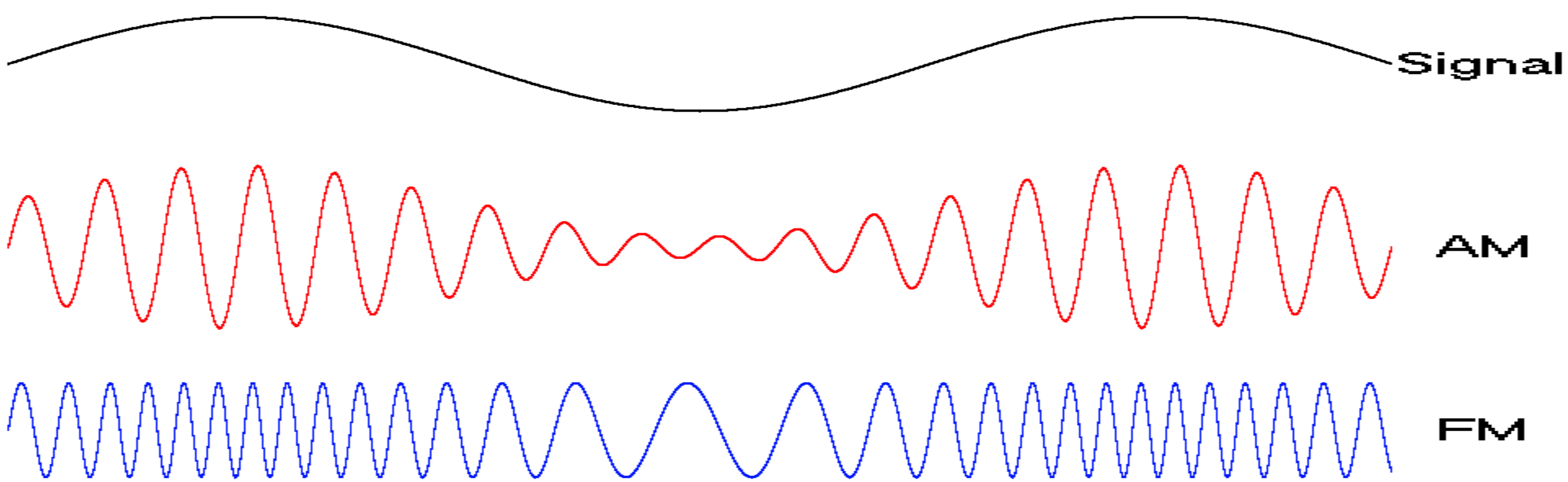
- Works only if there are almost 1 error for each codeword



Chapter 4 – Modulation

Modulation

- *Modulation:* varying one or more properties of a high-frequency sinusoidal waveform, called the "carrier" signal, with a modulating signal which contains information to be transmitted.
- *Modulator:* is an hardware circuit that accept a sequence of data bits and applies modulation to a carrier wave according to the bits to transmit data over that carrier wave



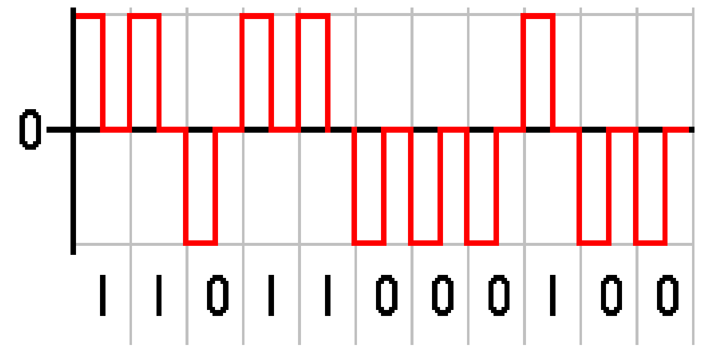
Demodulator

- *Demodulator:* Hardware circuit that accepts a modulated carrier wave and recreates the sequence of data bits that was used to modulate the carrier wave
- To support full-duplex communication each location need both modulator and demodulator
- Manufactures combine both circuits into a single device called MODEM (MOdulator-DEModulator)

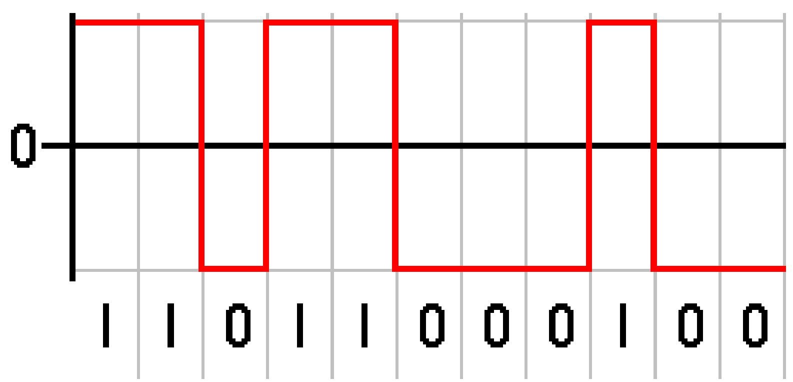
Baseband Modulation (Line Code)

- Line coding is a representation of the digital signal by an amplitude variation in time-discrete
- Signal that is optimally tuned for the specific properties of the physical channel

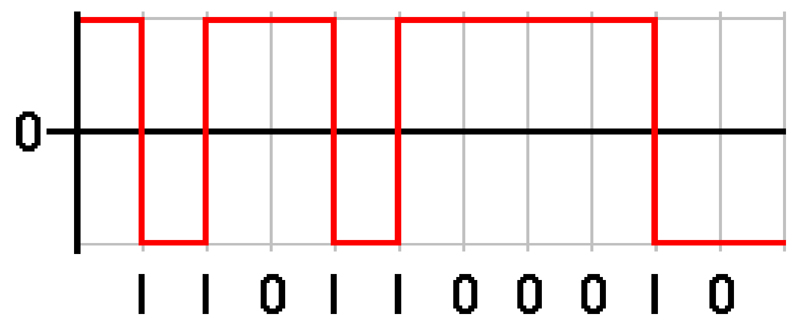
- RZ (Return to Zero)



- NRZ (Non Return to Zero)



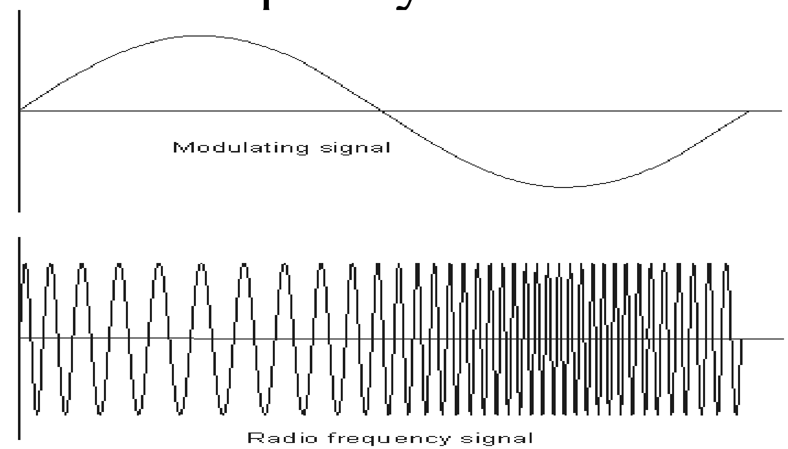
- NRZI (Non Return to Zero Inverted) – USB



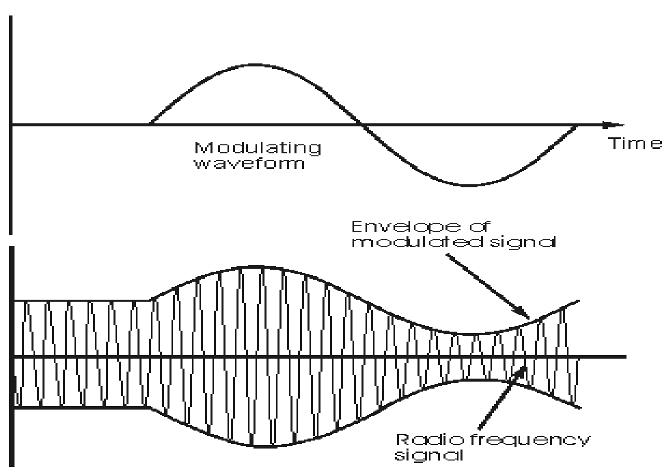
Typical Modulation

- Conveys information over a carrier wave by varying its instantaneous frequency, amplitude or phase
- In digital transmission that modulations are called respectively FSK, ASK, PSK

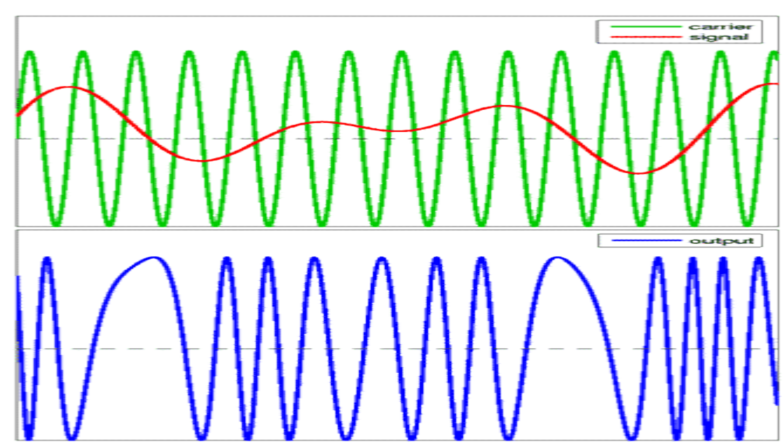
- FM: Frequency modulation



- AM: Amplitude modulation



- PM: Phase modulation



Q-AM Quadrature Amplitude Modulation

- Q-AM modulation permits to transmit symbols and not only a bit stream.

- Data Bits are modulated as symbol

- A Symbol is identified by:
  - Amplitude Value
  - Phase Value

- This means that it is possible to transmit a lot of bits with a single symbol

- In 16Q-AM (as in figure) each symbol transmitted conveys 4 data bits

OFDM

- OFDM (Orthogonal Frequency Division Multiplexing) is a modulation used in our digital television to transmit and receive tv channels

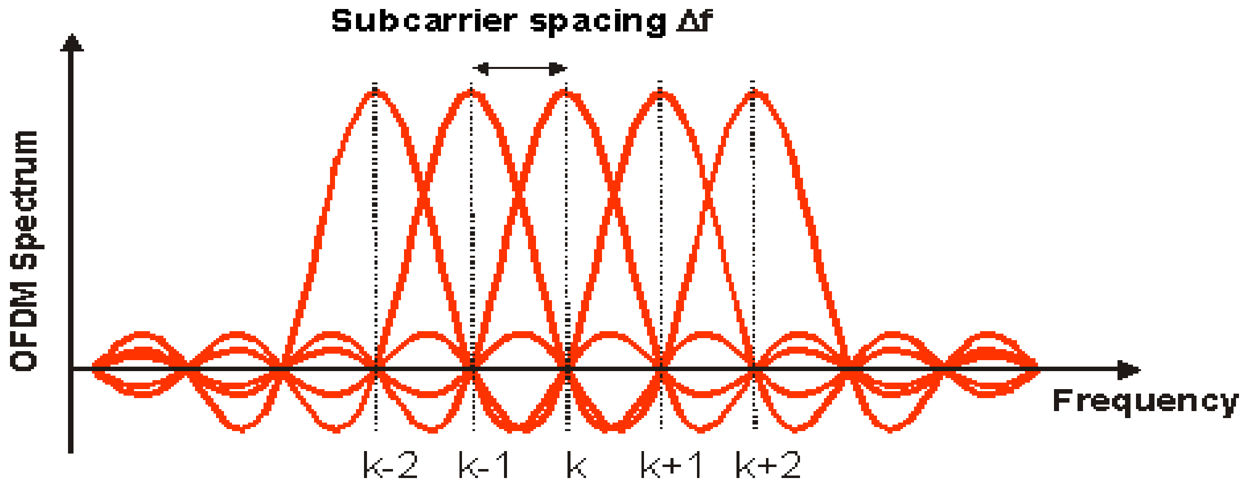
- OFDM is a multi carrier wave modulation, this means that uses a lot of carrier, each orthogonal with other

- OFDM main properties:

  - Splits information flow on multiple carriers
  - Each carrier is modulated using QAM modulation
  - In QAM modulation is used a low symbol rate

OFDM

- Maintain low symbol rate reduce interferences because permits to use guard intervals of duration acceptable
- OFDM can be used also in bad channel conditions because orthogonality of carriers and its properties permit avoid transmission problems



Chapter 5 - Channels

Channel

- *Channel:* refers either a physical transmission medium such as a wire, or to a logical connection over a multiplexed medium such as a radio channel

- A channel is used to convey an information signal from one or several transmitters to one or several receivers

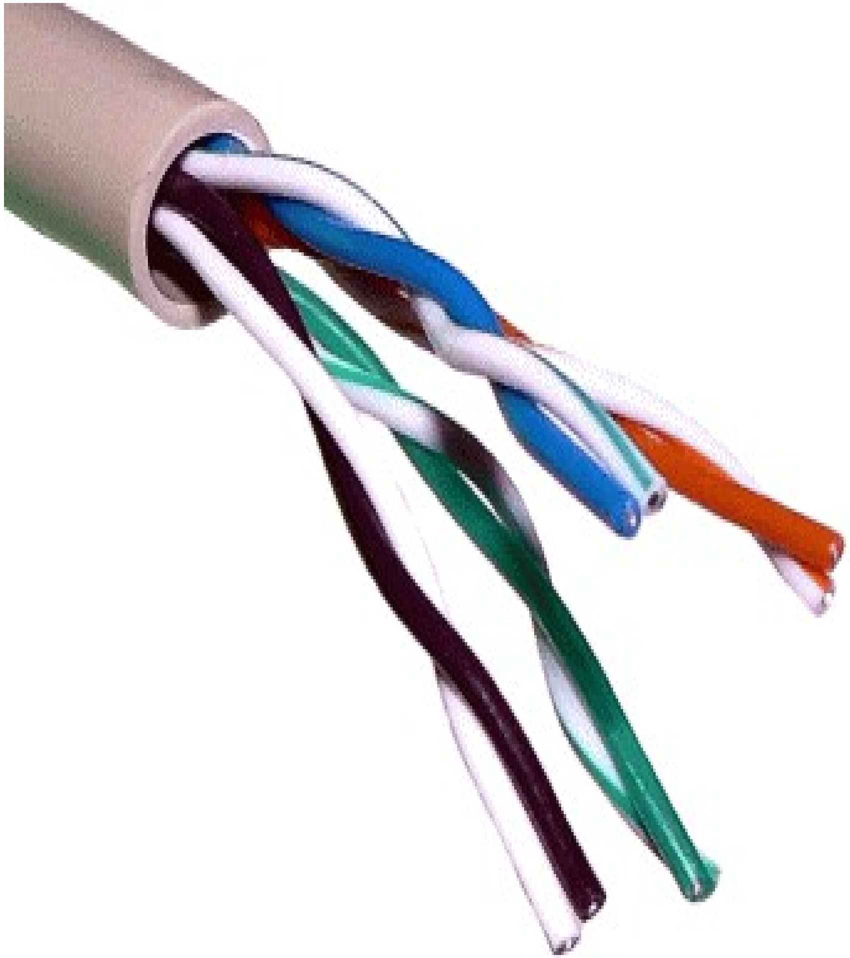
- *Channel capacity*: is the maximum quantity of information that can be reliably transmitted measured in:

  - Bandwidth (Hz)

  - Data rate (bits / second)

Copper Wires

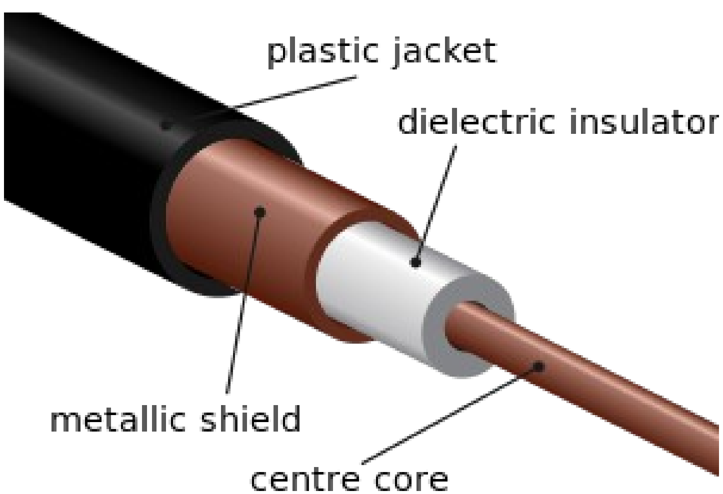
- *Unshielded Twisted Pair (UTP)*: Primary medium to connect computers because it is inexpensive and easy to install
- Twist limit interferences emitted and prevent interferences from other wires
- Used for computer networks because it have a low resistance to electric current and signals can travel farther

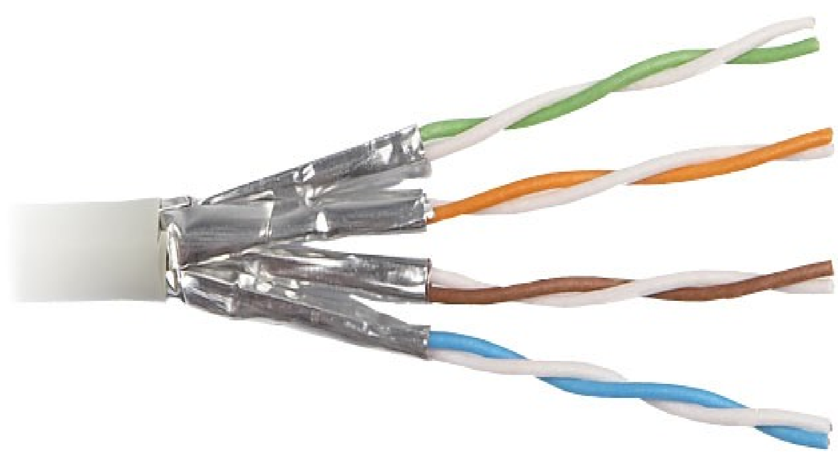


Copper Wires

- *Coaxial Cable*: is single wire surrounded by a heavy metal shield that prevent interferences from itself and to other wires (better then UTP cable).
- Can be placed in parallel to other cables

- *Shielded Twisted Pair (STP)*: is a twisted pair copper wires surrounded by a metal shield
- This shield avoid interferences





Glass Fiber

- This medium uses light to transport data.
- The glass fiber is encased in a plastic jacket which allows the fiber to bend without breaking.
- It is more reliable then copper wire, because it uses light, so:

  - It doesn't emit electrical interference

  - It is no susceptible to electrical interference
- Glass fiber can carry a pulse of light much farther than a copper wire because is manufactured to reflect most of light inside of cable

Radio - Wireless

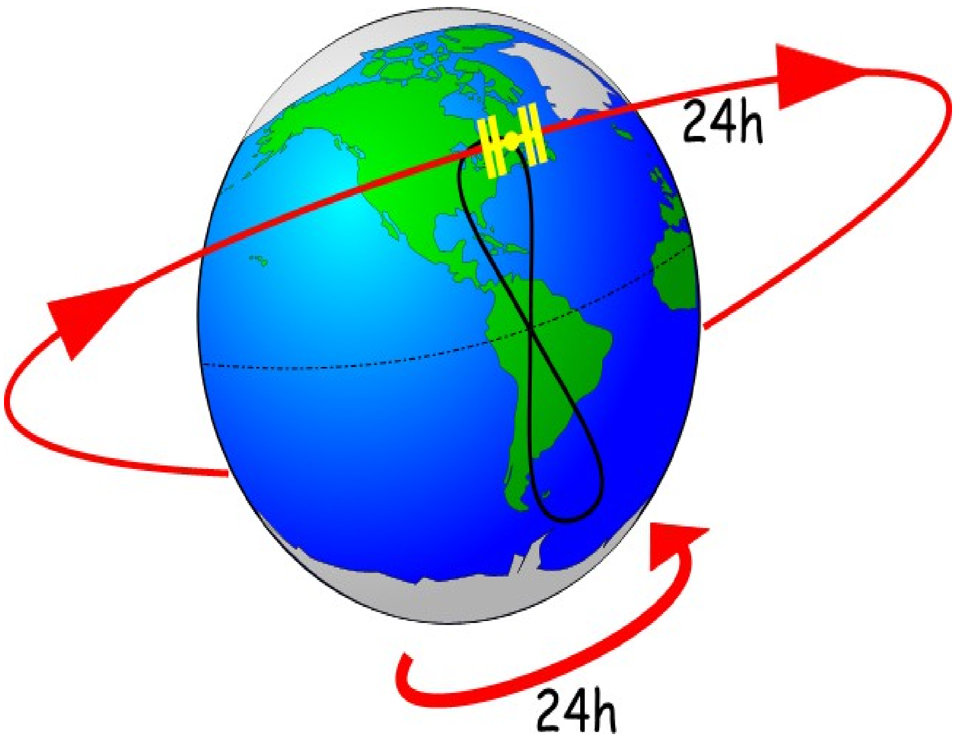
- Electromagnetic radiation can be used to transmit computer data
- Each participating computer attaches to an antenna which can both transmit and receive RF (Radio Frequency)
- Antenna may be large or small, depending on the range desired.
- Large to communicate at several miles or small within a building.

Satellite

- Satellite contains a transponder that consist of a radio receiver and transmitter
- Transponder accepts an incoming radio transmission, amplifies it, and re-transmits, amplified signal, back to the ground at a different angle than it arrived.
- A single satellite contains multiple transponders that operate independently because place a satellite in orbit it is very expensive

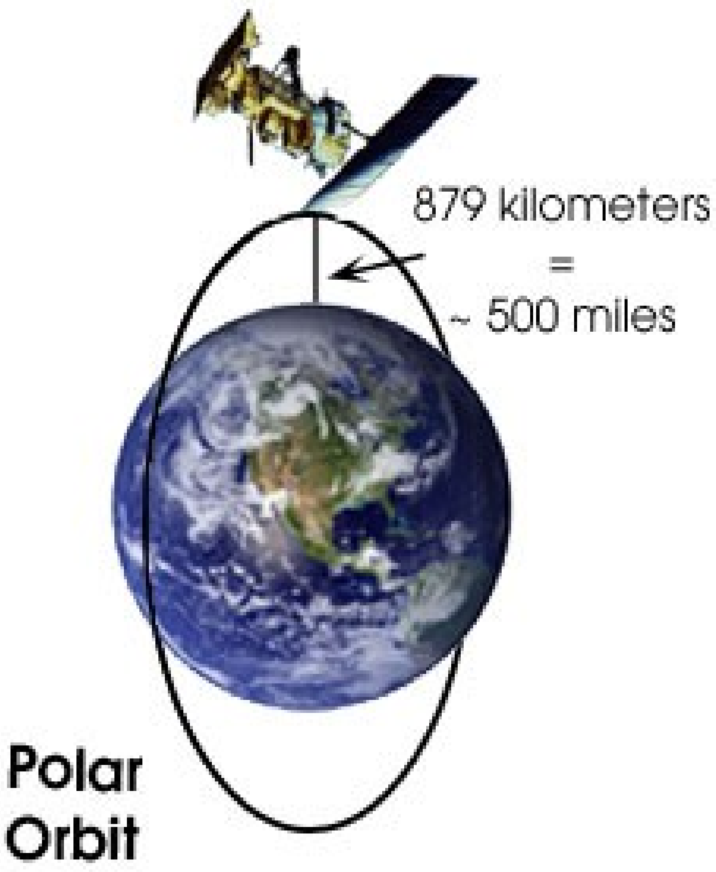
Geosynchronous Satellite (GEO)

- These satellites are placed in an orbit that is exactly synchronized with the rotation of the earth. (also called Geostationary satellites)
- From the ground these satellites appears to remain at exactly the same point in the sky at all times
- The distance required for a geosynchronous orbit is 35.785 km



Low Earth Orbit Satellites (LEO)

- These satellites orbit a few hundred miles above the earth so their period of rotation is faster than the rotation of earth and they don't stay in a fixed point as geostationary.
- A satellite can only be used during the time that its orbit passes between two ground stations.
- Requires complex control system that continuously move the ground pointer to find new reachable satellites



Summary

- Signals
- Transmission
- Encoding
- Hamming Codes and Example
- CRC Codes
- RS - Codes
- Modulation
- Channels

Thanks!

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