

Computer Networks - Xarxes de Computadors

Outline

- Course Syllabus
- Unit 1: Introduction
- Unit 2: IP Networks
- Unit 3: Point to Point Protocols -TCP
- Unit 4: Local Area Networks, LANs
- **Unit 5. Data Transmission**

Unit 5. Data Transmission

Outline

- **Introduction**
- Attenuation
- Spectral Analysis
- Modulation (or Symbol) Rate
- Noise
- Baseband Digital Transmission
- Bandpass Digital Transmission
- Error Detection

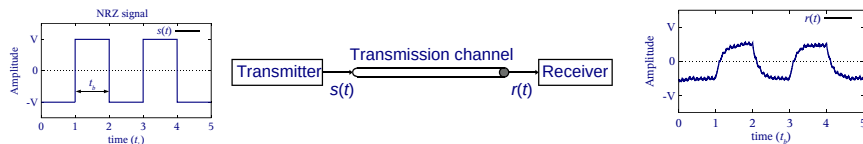
Unit 5. Data Transmission

Introduction

- The received signal, $r(t)$, differs from the transmitted signal $s(t)$ ($r(t)$ and $s(t)$ are measured in Volts):

$$r(t) = f[s(t)] + n(t)$$

- $f[s(t)]$ represent the modifications introduced by the transmission media:
 - Attenuation
 - Distortion
- $n(t)$ represent the interference and noise.



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Attenuation

- Every channel introduces some *transmission loss*, so the power of the signal progressively decreases with increasing distance.
- We measure the “quantity of signal” in terms of average power (Watts). The power of a signal is proportional to the square of the voltage (Volts), or to the square of the current intensity (Amperes):

$$P = 1/T \int_T p(t) dt \propto 1/T \int_T s(t)^2 dt$$


- The attenuation is defined as the rate of the average power of the transmitted signal (P_{Tx}), to the average power of the received signal (P_{Rx}). P_{Rx} does not include interference or noise:

$$\text{Attenuation, } A = \frac{P_{Tx}}{P_{Rx}}$$

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Attenuation - deciBels (dBs)

- Typically relation between powers is given in deciBels (in honor of Alexander Graham Bell, inventor of the telephone):

$$\text{Power relation expressed in dBs} = 10 \log_{10}\{\text{Power relation}\}$$

- For instance, the attenuation expressed in dBs is:

$$\text{Attenuation (dBs), } A \text{ (dBs)} = 10 \log_{10} \frac{P_{Tx}}{P_{Rx}}$$

$$\log(a \times b) = \log(a) + \log(b)$$

$$\log(a/b) = \log(a) - \log(b)$$

$$\log_a(x) = \log_b(x) / \log_b(a)$$

Properties of logarithms

P_{Tx}	P_{Rx}	$10 \log_{10}\{P_{Tx}/P_{Rx}\}$
1	1	0
2	1	3
10	1	10
100	1	20
1000	1	30
10^n	1	$n \times 10$

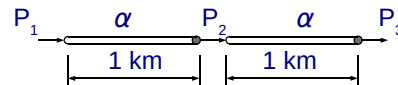
dBs, numerical example

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Attenuation – why deciBels (dBs)?

- Assume a cable with attenuation:

$$\alpha = \frac{P_1}{P_2} = \frac{P_2}{P_3}, \quad \frac{P_1}{P_3} = \frac{P_1}{P_2} \frac{P_2}{P_3} = \alpha^2$$



- Thus, the attenuation for n km is α^n . In dBs:

$$\text{Attenuation of } n \text{ km} = 10 \log(\alpha^n) = n 10 \log(\alpha) = n \alpha \text{ (dBs/km)}$$

- The manufacturer gives the parameter α (dBs/km).

Frequency (MHz)	Attenuation (dB/km)
1	7,9
10	27
30	48
100	94
200	135
2000	550

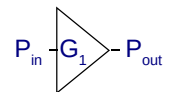
Commercial coaxial cable RG-62

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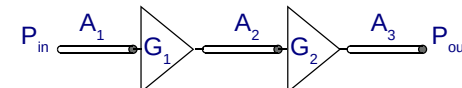
Attenuation – Amplifiers and Repeaters

- Transfer energy from a power supply to the signal.
- Repeaters: “regenerate” and amplify the signal.
- We define the gain:

$$\text{Gain (dBs), } G \text{ (dBs)} = 10 \log_{10} \frac{P_{out}}{P_{in}}$$



- If we operate in dBs, attenuation and gain add with opposite sign:



$$G_{tot}(\text{dB}) = 10 \log_{10} \frac{P_{out}}{P_{in}} = G_1(\text{dB}) + G_2(\text{dB}) - A_1(\text{dB}) - A_2(\text{dB}) - A_3(\text{dB})$$

$$P_{out} = 10^{G_{tot}(\text{dB})/10} P_{in}$$

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Spectral Analysis

- At the beginning of XIX Fourier showed that any signal can be decomposed in a series (periodic signal) or integral (aperiodic signal) of sinusoidal signals.
- E.g. for a periodic signal of period T :



Jean Baptiste Joseph Fourier

$$f(t) = a_0 + \sum_{n=1}^{\infty} v_n \sin(2\pi n f_0 t + \phi_n)$$

- $f_0 = 1/T$ is the fundamental period. Each sinusoid is called harmonic, with amplitude v_n , frequency $n f_0$ and phase ϕ_n
- The function $F(f)$ that gives the amplitude and phase of each harmonic for every frequency is called the Fourier Transform or Frequency Spectra of the signal.
- $F(f)$ is in general a complex function, where the module and phase of each complex value are the amplitude and phase of the harmonic.
- $|F(f)|^2$ is called the Power Spectral Density of the signal, and it is also defined for random signals (is the Fourier transform of the *autocorrelation function*).

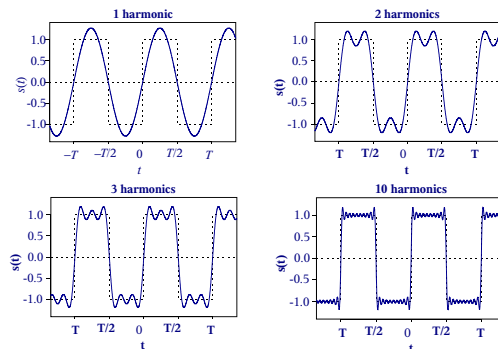
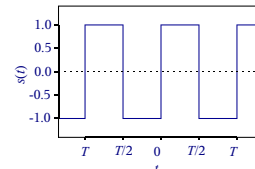
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Spectral Analysis

- The Fourier series of a rectangular signal is:

$$f(t) = \sum_{n=0}^{\infty} \frac{4}{(2n+1)\pi} \sin((2n+1)2\pi f_0 t)$$

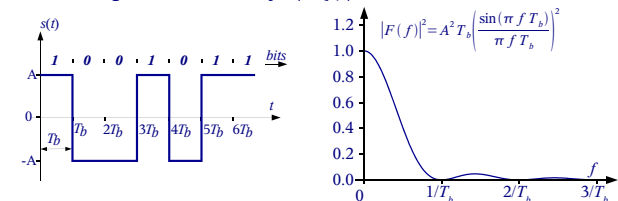
$$= \frac{4}{\pi} \left\{ \sin(2\pi f_0 t) + \frac{1}{3} \sin(3 \times 2\pi f_0 t) + \frac{1}{5} \sin(5 \times 2\pi f_0 t) + \dots \right\}$$



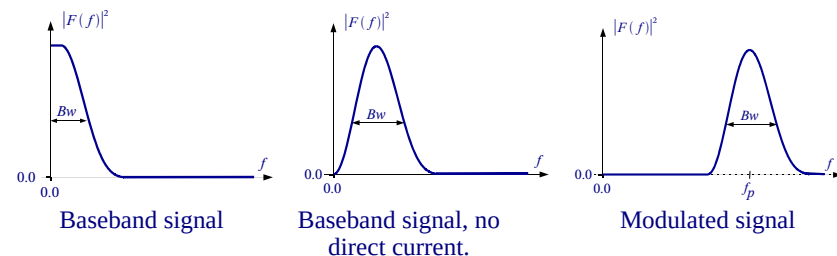
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Spectral Analysis – Signal Bandwidth

- Band of frequencies where most of the signal power is concentrated. Typically, where the Power Spectral Density, $|F(f)|^2$, is attenuated less than 3 dBs.



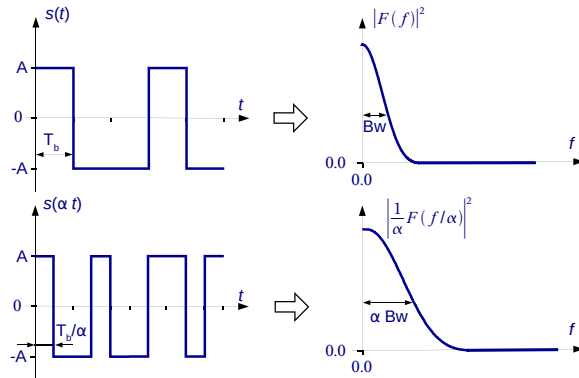
NRZ signal and its Power Spectral Density



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Spectral Analysis – Time-Frequency Duality

- A main Fourier Transform property is: $s(t) \leftrightarrow F(f)$, then $s(\alpha t) \leftrightarrow 1/\alpha F(f/\alpha)$. In other words: If a signal is time-scaled by α , the spectra is scaled by $1/\alpha$.
- Consequence: Increasing the transmission rate α times by reducing the duration of the symbols α times, increases the signal bandwidth by α times:



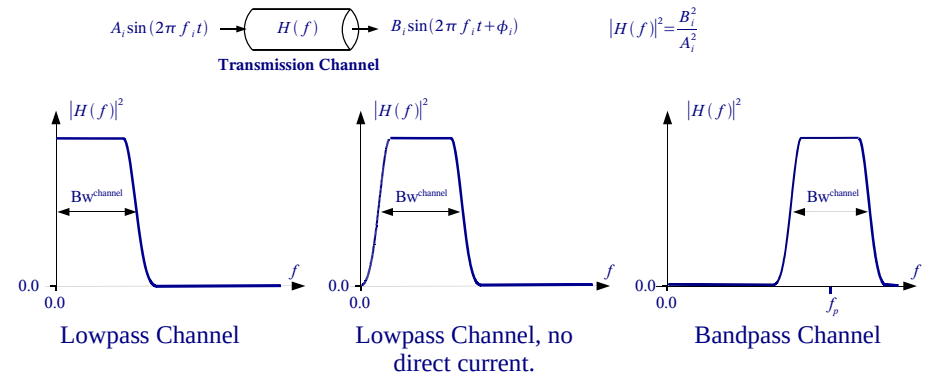
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Spectral Analysis – Transfer Function

- We will consider linear systems: multiply the signal by a factor, and derivate and integrated the signal (resistors, capacitors and coils).
- We characterize the transmission media by the *Transfer Function*:



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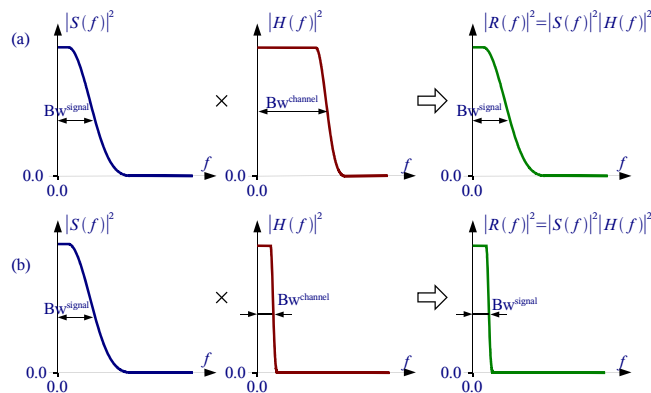
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Spectral Analysis – Distortion

- In a linear system the following relation holds:

$$s(t) = \sum A_i \sin(2\pi f_i t) \xrightarrow{|H(f)|^2 = \frac{B_i^2}{A_i^2}} r(t) = \sum B_i \sin(2\pi f_i t + \phi_i) = \sum A_i |H(f)| \sin(2\pi f_i t + \phi_i)$$

$$R(f) = S(f)H(f)$$



(a) $R(f) = S(f) \rightarrow$ No distortion, (b): $R(f) \neq S(f) \rightarrow$ distortion.

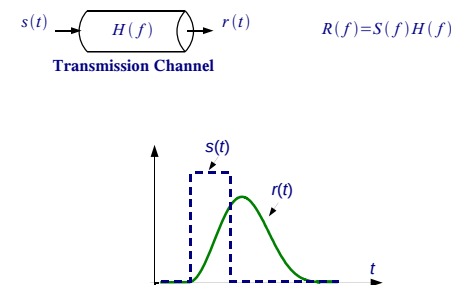
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Spectral Analysis – Inter-Symbol Interference (ISI)

- If the harmonics are reduced, by the time-frequency duality, the duration of the received signal will increase. This provokes Inter-Symbol Interference (ISI).



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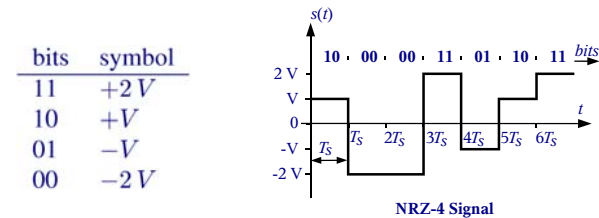
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Modulation (or Symbol) Rate

- How can we increase the line bitrate if the channel bandwidth is limited?



- Define the Modulation (or Symbol) Rate as:

$$\nu_m = \frac{1}{T_s}, \text{ symbols per second or bauds}$$

- Clearly, with N symbols we can send at most $\log_2(N)$ bits, thus:

$$\nu_t [bps] = \frac{\text{bits}}{\text{symbol}} \times \frac{\text{symbol}}{\text{second}} = \log_2(N) \times \nu_m [bauds]$$

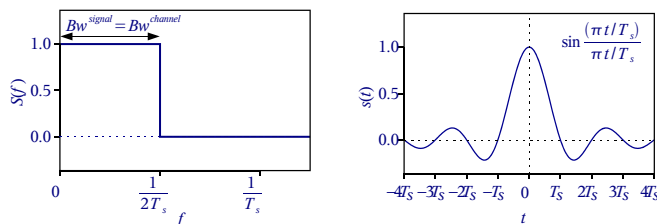
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Modulation (or Symbol) Rate - Nyquist Rate

- What is the maximum number of symbols per second we can send into a frequency limited channel, Bw^{channel} ?
- Nyquist Rate. To avoid distortion it must be:

$$\nu_m \leq 2 Bw^{\text{channel}}$$

- The only symbols where the relation holds as equality ($1/T_s = 2 Bw^{\text{channel}}$) are:



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Noise

- Thermal noise: Due to the random thermal agitation of the electrons. The power (N_0) is given by: $N_0 = k T Bw^{\text{channel}}$, where k is the Boltzmann constant ($1,38 \cdot 10^{-23}$ Joules/Kelvin) and T is the temperature in Kelvins.
- Impulsive noise: Short duration and relatively high power. Due to atmospheric storms, activation of motors, etc.
- Interferences: Due to other signals.
- Echo: Reflections of the high frequency signals in electric discontinuities.
- etc.
- The Signal to Noise Ration (SNR) measures the amount of noise present in the signal:

$$SNR \text{ (dBs)} = 10 \log_{10} \left(\frac{\text{Average signal power}}{\text{Average noise power}} \right)$$

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Noise - Shannon Formula

- The channel bandwidth imposes a limit on the modulation rate ($v_m \leq 2 Bw^{\text{channel}}$).
- Beyond this limit, the line bitrate can be increased by increasing the number of symbols. The noise imposes a limit on the number of symbols that can be used (given that the Tx power is limited).
- The Shannon Formula establishes a bound on the amount of error-free bps that can be transmitted over a communication link with a specified bandwidth in the presence of *white* noise (flat power spectral density over the channel bandwidth). This is referred to as the Channel Capacity (C):

$$C \text{ [bps]} = Bw^{\text{channel}} \log_2 \left(1 + \frac{\text{Average signal power}}{\text{Average noise power}} \right)$$

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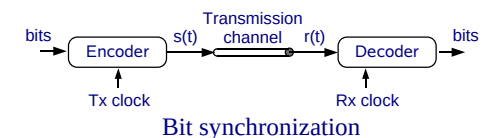
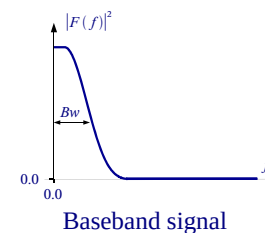
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Baseband Digital Transmission

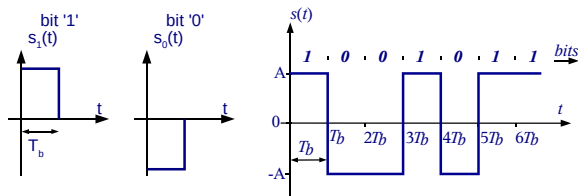
- Different criteria are used to chose among different baseband coding:
 - Bandwidth efficiency: Measure of how well the coding is making use of the available bandwidth. We shall consider that the efficiency is good if there is only one transition per symbol.
 - Direct current: Lowpass Channels with $H(f)=0$ at $f=0$ require signals with no direct current component.
 - Bit synchronization: Allow using the signal transition for synchronizing the Tx and Rx clocks.



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Baseband Digital Transmission - Non Return to Zero (NRZ)

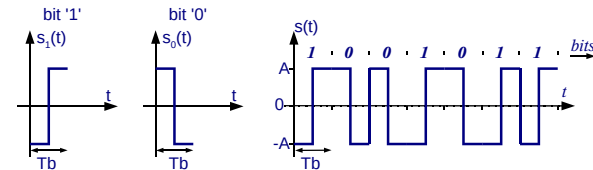
- Bandwidth efficiency: good.
- Direct current: yes.
- Bit synchronization: no.



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Baseband Digital Transmission - Manchester

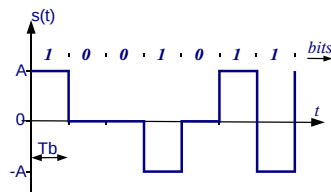
- Bandwidth efficiency: poor.
- Direct current: no.
- Bit synchronization: yes.
- Used in all 10 Mbps Ethernet standards.



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Baseband Digital Transmission - Bipolar or AMI (Alternate Mark Inversion)

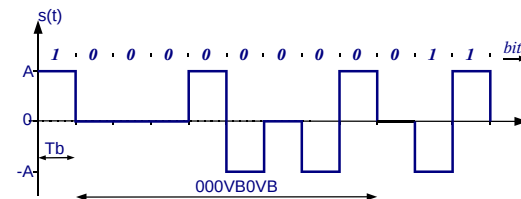
- The codification consists of alternating between A and -A when the bit '1' is sent.
- Bandwidth efficiency: good.
- Direct current: no.
- Bit synchronization: no.
- Used in all 56k digital lines in USA (very popular in the 70s).



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Baseband Digital Transmission - Bipolar with 8 Zeros Substitution (B8ZS)

- The codification consists of an AMI encoding changing 8 bit zero sequences by 000VB0VB, to allow bit synchronization.
- Bandwidth efficiency: good.
- Direct current: no.
- Bit synchronization: yes.
- Used in all ISDS lines in USA (in Europe a similar encoding is used: HDB3).



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Baseband Digital Transmission - mBnL

- every group of m bits is transmitted using n symbols of L levels. Typically, L is referred to as B: 2 symbols; T: 3 symbols; Q: 4 symbols.
- A table (and maybe some rules) are used to specify the symbols that must be transmitted for each group of bits.
- Typically, more combinations of symbols are available, and only the interesting ones are used, e.g. to achieve bit synchronization.
- Used in FDDI and several Ethernet standards.
- Example: 2B3B with two symbols indicated as + and -

bits	symbols
11	+ - +
10	+ + -
01	- - +
00	- + -

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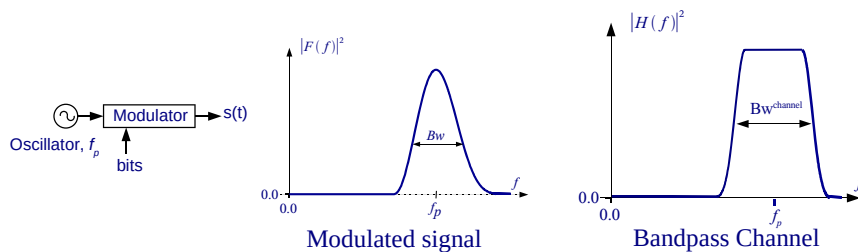
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Bandpass Digital Transmission

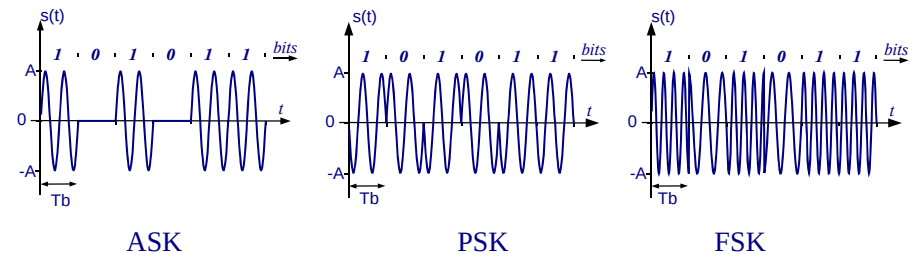
- Used in bandpass channels, e.g. radio Tx.



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Bandpass Digital Transmission

- Basic types:
 - Amplitude Shift Keying, ASK: $s(t) = x(t) \sin(2 \pi f t)$
 - Phase Shift Keying, PSK: $s(t) = A \sin(2 \pi f t + x(t))$
 - Frequency Shift Keying, FSK: $s(t) = A \sin(2 \pi (x(t)+f) t)$



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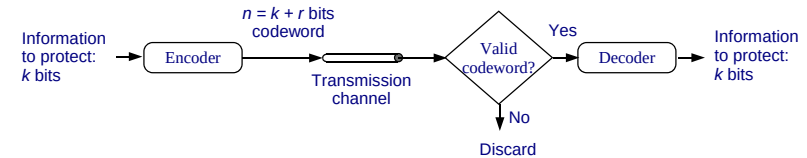
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Error Detection

- Objective: Detect erroneous PDUs, these are normally discarded.
- Model:



- The information to protect is k bits long.
- The encoder adds r bits (redundancy bits).
- There are 2^n codewords: 2^k valid and $2^n - 2^k$ non valid.
- There is a bijection between valid codewords and possible informations to protect.
- Upon receiving a valid codeword, it is assumed that no errors occurred.
- Upon receiving a no valid codeword, errors occurred with probability 1.

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Error Detection

- The goal minimize the non detected error probability.
- Non detected error probability is in general very difficult to measure, therefore, the robustness of the error detection code is given in terms of:
 - Hamming distance.
 - Burst detecting capability.
 - Probability that a random codeword is a valid codeword.

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Error Detection - Hamming distance

- Define the Hamming distance between two codewords as the number of different bits. The Hamming distance of the code is the minimum distance between any two valid codewords.
- Consequence: If the Hamming distance of the code is D , then, the code detects a number of erroneous bits $< D$ with probability 1.

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Error Detection - Burst Detecting Capability

- Define the error burst as the number of bits between the first and last erroneous bits of a codeword.
- The Burst Detecting Capability is the maximum integer B such that all error bursts of size $\leq B$ are detected with probability 1.

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Error Detection - What if errors exceed the Hamming distance and burst detecting capability?

- If the number of erroneous bits is large, we can do the approximation:

$$P \left\{ \begin{array}{l} \text{non detected} \\ \text{error} \\ \text{probability} \end{array} \middle| \begin{array}{l} \text{the number of erroneous bits is} \\ \text{large, exceeding the Hamming dis-} \\ \text{tance and the burst detecting capa-} \\ \text{bility} \end{array} \right\} \approx P \left\{ \begin{array}{l} \text{A random code-} \\ \text{word is valid} \end{array} \right\} = \frac{2^k}{2^{k+r}} = \frac{1}{2^r}$$

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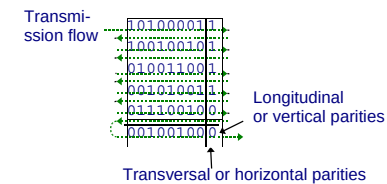
Error Detection - Parity bit

- Even: the number of 1's codeword bits is even (XOR of the bits to protect).
- Odd: the number of 1's codeword bits is odd.
- We deduce that the detection code detects a number of odd erroneous bits.
- If we change 1 bit, we need to change the parity bit to obtain another valid codeword. Thus, the Hamming distance is 2.
- Two consecutive erroneous bits are not detected. Thus, the burst detecting capability is 1.

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Error Detection - Longitudinal Redundancy Check, LRC

- The parity bit is improved by sending a longitudinal parities every block of bits.



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Error Detection - Longitudinal Redundancy Check, LRC

- A non detected error occurs when the number of erroneous bits is even simultaneously in all rows and columns.
- If we change 1 bit, 3 additional bits need to be change to obtain another valid codeword. Thus, the Hamming distance is 4.
- The minimum non detected error burst occur when 4 erroneous bits are adjacent: The burst detecting capability is the number of bits of a row + 1.

1	0	1	0	0	0	0	1
1	0	0	1	0	0	1	0
0	1	0	0	1	1	0	0
0	0	0	0	0	0	1	1
0	1	0	0	1	0	1	0
0	0	1	0	0	1	0	0

Example of a non detected error.

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Error Detection - Cyclic Redundancy Check, CRC

- Define the polynomial representation of a sequence of k bits:

$$s(x) = s_{k-1} x^{k-1} + s_{k-2} x^{k-2} + \dots + s_1 x + s_0$$

- The CRC is computed using a generator polynomial, $g(x)$:

$$c(x) = \text{Remainder} \left[\frac{s(x) x^r}{g(x)} \right]_{\text{module } 2}$$

- Where sums and subtractions using the module 2 operations are given by the binary XOR.

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Error Detection - Cyclic Redundancy Check, CRC

- Example:

- $g(x) = x^3 + 1$
- $s(x) = x^4 + x^3 + 1$
- $s(x) x^r = x^7 + x^6 + x^3$

$$\begin{array}{r}
 x^7 + x^6 + x^3 \quad | \quad x^3 + 1 \\
 \underline{x^7 + x^4} \quad x^4 + x^3 + x \\
 x^6 + x^4 + x^3 \\
 \underline{x^6 + x^3} \\
 x^4 \\
 \underline{x^4 + x} \\
 x
 \end{array}$$

- Therefore, $c(x) = x$, thus, CRC = 010

Unit 5. Data Transmission

Error Detection - Cyclic Redundancy Check, CRC

- For a properly chosen $g(x)$ of degree r , the following hold:
 - Hamming distance ≥ 4
 - The burst detecting capability is $\geq r$
- CRC generator polynomials are standardized. Examples:

$$\begin{aligned}
 g(x) &= x^{16} + x^{15} + x^2 + 1 \\
 g(x) &= x^{16} + x^{12} + x^5 + 1 \\
 g(x) &= x^{32} + x^{26} + x^{23} + x^{22} + x^{16} + x^{12} + x^{11} + x^{10} + x^8 + x^7 + x^5 + x^4 + x^2 + x + 1
 \end{aligned}$$