Wireless Communications

2. Physical Layer

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DIN/CTC/UEM

2018

Periodic Signal

- Periodic signal: repeats itself in time, that is

$$g(t) = g(t + T)$$

in which T (given in seconds [s]) is the **period** of the signal $g(t)$

- The number of cycles (or periods) per second is the **frequency** f of the signal $g(t)$ (given in Hertz [Hz])

$$f = \frac{1}{T}$$

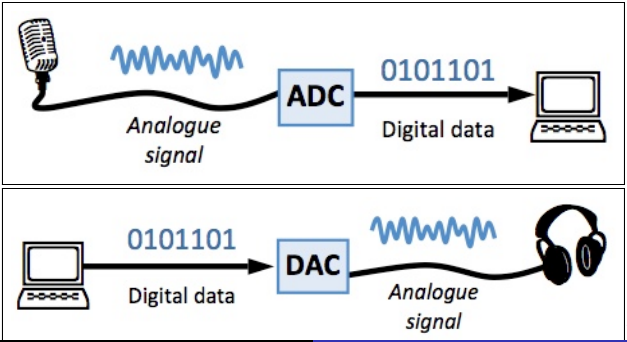
- **Amplitude** is the signal strength
  - Intantaneous amplitude: amplitude at some time t
  - Maximum and minimum amplitudes: maximum and minimum values reached by the signal

Analog Signal

- Can assume any real numeric value
- In general, it is continuous in time, that is, it is defined for any time t
- Maintains direct relationship with expressed magnitude
- Example: electric voltage of a microphone is proportional to the pressure caused by the sound/voice

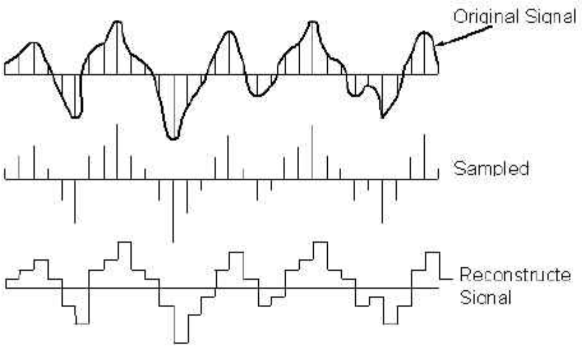
Digital Signal

- Can assume only a finite set of values
- In general, it is discrete in time, that is, it is only defined for some instants of time t_i, $i = 0, 1, \ldots$
- In general, digital signal is obtained from an analog source
  - Analog-to-Digital Converter (ADC)
  - Digital-to-Analog Converter (DAC)

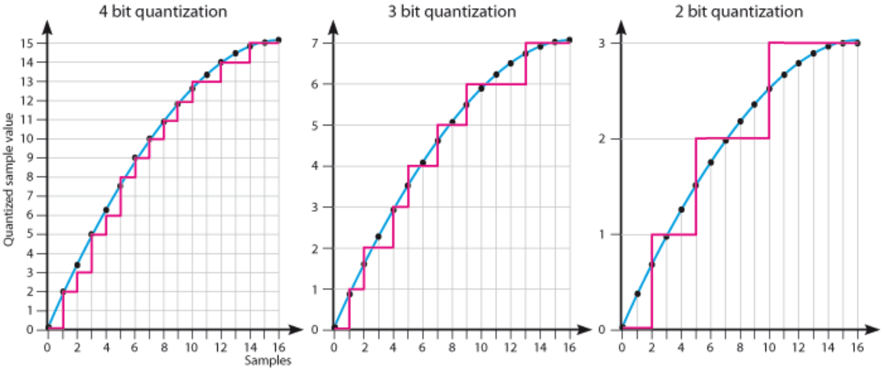


Sampling and Digitalization

- Technique for analog-digital conversion



Digitalization Example



Bit Rate and Baud Rate

- Bit rate
  - Every second produces N samples
  - Each sample uses B bits
  - Therefore:

$$\text{bit rate} = N \times B$$

- Baud rate
  - Each symbol carries b bits
  - Therefore:

$$\text{baud rate} = N \times \frac{B}{b}$$

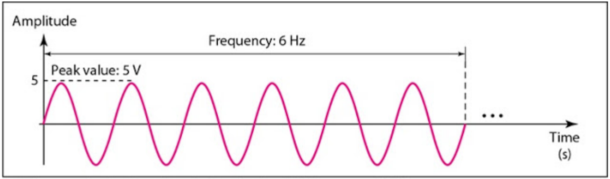
Information in the Digital Format

- Advantages of manipulation in the digital format:
  - Economy: advances in digital circuits
  - Security: easier to encript

- Advantages of transmission in the digital format:
  - Data integrity: increased noise immunity
  - Channel usage: easier to multiplex multiple sources

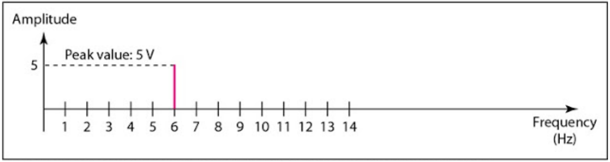
Time and Frequency Domains

- Time domain: independent variable is the **time**
- Frequency domain: independent variables are **frequency** and **phase**
- Example: sine wave (fundamental wave)



a. A sine wave in the time domain (peak value: 5 V, frequency: 6 Hz)

time domain:
$s(t) = A \sin(2\pi f t)$
$s(t) \in \mathbb{R}$



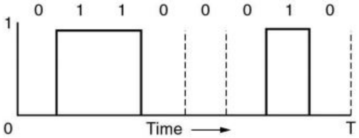
b. The same sine wave in the frequency domain (peak value: 5 V, frequency: 6 Hz)

frequency domain:
$S(f) = A\,\delta(f)$
$S(f) \in \mathbb{C}$
$\delta(.)$ is the impulse function

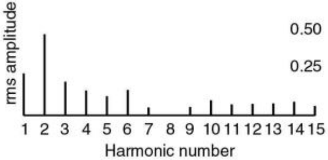
Decomposition of Periodic Waves

- **Any** periodic signal of frequency f can be expressed as a summation (often infinite) of sine waves
- Component sine waves have frequencies that are multiple of the frequency of the orginal signal and are known as harmonics:
  - sine wave with frequency f is the first harmonic
  - sine wave frequency $2 \times f$ is the second harmonic and so on
- Each sine wave represents a component (an impulse) in the frequency domain

<u>time domain</u>:

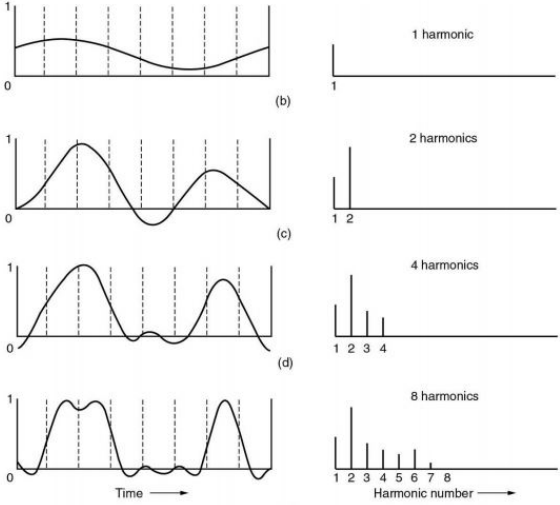


<u>frequency domain</u>:



Decomposition of Periodic Waves

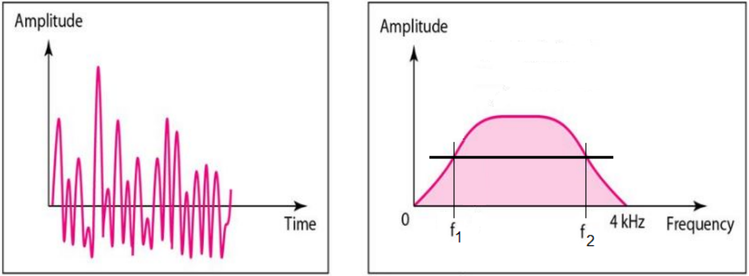
time domain: frequency domain:



- The more harmonics are added to the summation, the more the resulting signal resembles the original signal
- If the mean value of the periodic wave is nonzero, this value is represented with a zero frequency component ($f = 0$)

Spectrum Non-Periodic Signals

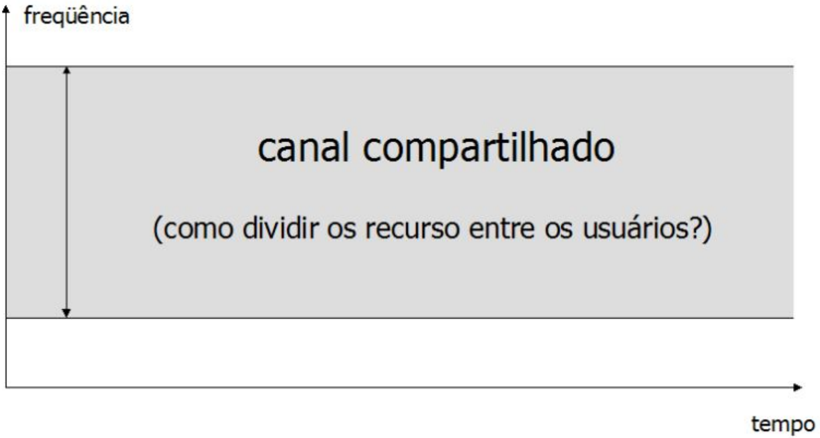
- When the signal is non-periodic, the spectrum ceases to be formed by discrete frequencies and becomes continuous
- The bandwidth of the analog signal is delimited by the two frequencies (f_1 and f_2 in the figure below) where the signal power is half the maximum power



a. Time domain
b. Frequency domain

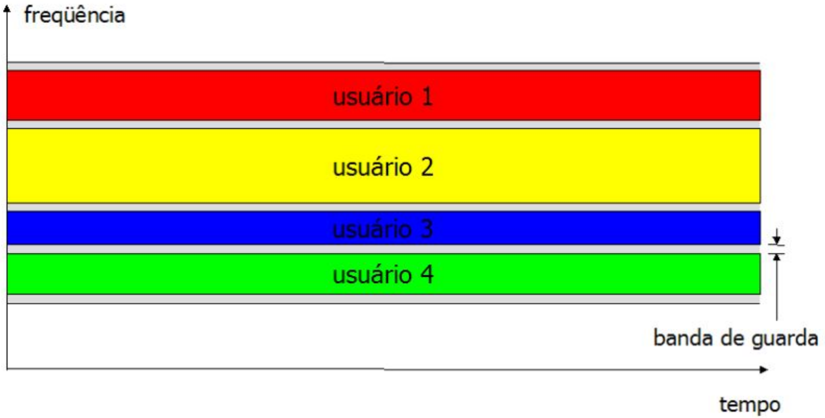
The Multiplexing Problem

- How to divide the channel among all users?



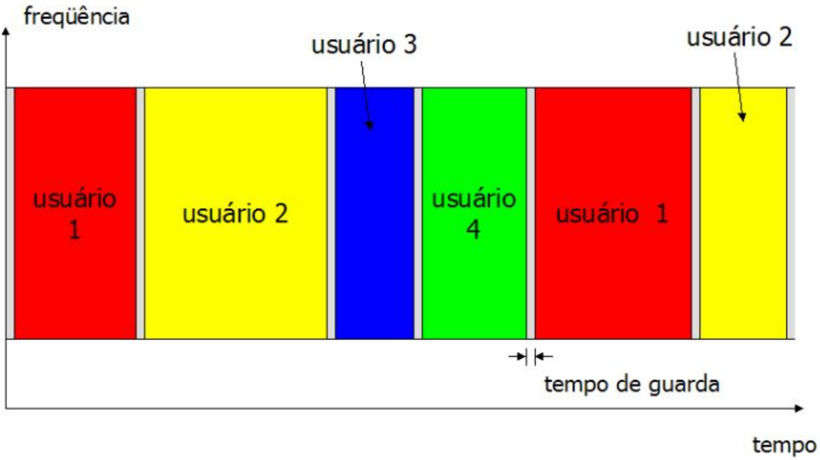
FDM

- *Frequency Division Multiplex*

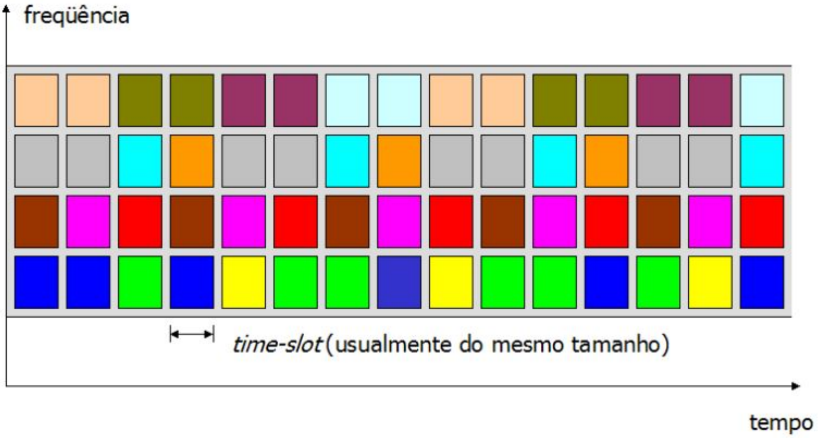


TDM

- *Time Division Multiplex*

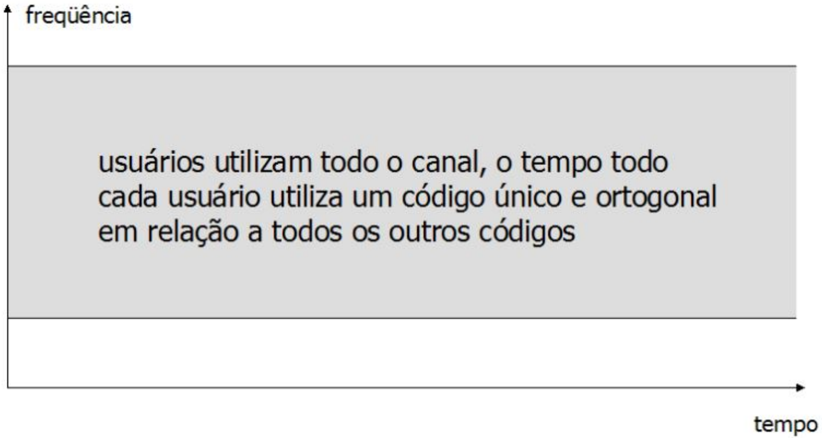


Combination of FDM and TDM



CDM - Direct Sequence

- *Code Division Multiplex, Direct Sequence*



Example CDM - Direct Sequence

- 4 users (A, B, C and D), each with his/her own spreading code
- Codes are orthogonal (i.e., $A \cdot B = A \cdot C = \ldots = C \cdot D = 0$)
- Sending of information uses the spreading code
  - For example:
    - User C transmits code C to send bit "1"
    - User C transmits code $\bar{C}$ to send bit "0"
- In the channel occurs the sum of the transmitted signals (S_1 to S_6 in the figure)
- For decoding, the receiver must multiply the received signal and the desired spreading code (in the figure, the C code)

Example CDM - Direct Sequence

A: 0 0 0 1 1 0 1 1	A: (−1 −1 −1 +1 +1 −1 +1 +1)
B: 0 0 1 0 1 1 1 0	B: (−1 −1 +1 −1 +1 +1 +1 −1)
C: 0 1 0 1 1 1 0 0	C: (−1 +1 −1 +1 +1 +1 −1 −1)
D: 0 1 0 0 0 0 1 0	D: (−1 +1 −1 −1 −1 −1 +1 −1)
(a)	(b)

Six examples:

– – 1 –	C	S_1 = (−1 +1 −1 +1 +1 +1 −1 −1)
– 1 1 –	B + C	S_2 = (−2 0 0 0 +2 +2 0 −2)
1 0 – –	A + $\overline{B}$	S_3 = (0 0 −2 +2 0 −2 0 +2)
1 0 1 –	A + $\overline{B}$ + C	S_4 = (−1 +1 −3 +3 +1 −1 −1 +1)
1 1 1 1	A + B + C + D	S_5 = (−4 0 −2 0 +2 0 +2 −2)
1 1 0 1	A + B + $\overline{C}$ + D	S_6 = (−2 −2 0 −2 0 −2 +4 0)

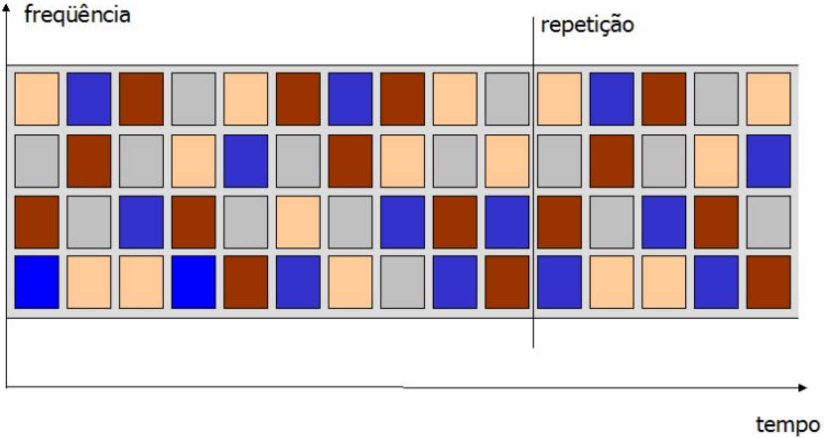
(c)

$S_1 \bullet C$ = (1 +1 +1 +1 +1 +1 +1 +1)/8 = 1
$S_2 \bullet C$ = (2 +0 +0 +0 +2 +2 +0 +2)/8 = 1
$S_3 \bullet C$ = (0 +0 +2 +2 +0 −2 +0 −2)/8 = 0
$S_4 \bullet C$ = (1 +1 +3 +3 +1 −1 +1 −1)/8 = 1
$S_5 \bullet C$ = (4 +0 +2 +0 +2 +0 −2 +2)/8 = 1
$S_6 \bullet C$ = (2 −2 +0 −2 +0 −2 −4 +0)/8 = −1

(d)

CDM - Frequency Hopping

- *Code Division Multiplex, Frequency Hopping*

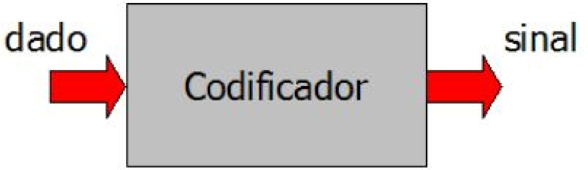


Conversion of Bits into Signals

- Source of information produces bits
  - In general bits are not good for data transmission
  - It is necessary to convert bits into a better signal, appropriate to the channel
- Objectives:
  - Reduce the bandwidth of the encoded signal
    - Concentrate the encoded signal spectrum in the channel bandwidth, thus reducing attenuation and distortion
    - Eliminate high-frequency components, thus reducing interference between physically close channels
  - Eliminate low frequency components of the encoded signal
    - Enable AC coupling, which ensures better insulation and the possibility of remote power supplying (repeaters, terminals) with transformers
  - Shape the spectrum of the encoded signal in a way to facilitate the extraction of a clock signal for the synchronizing function

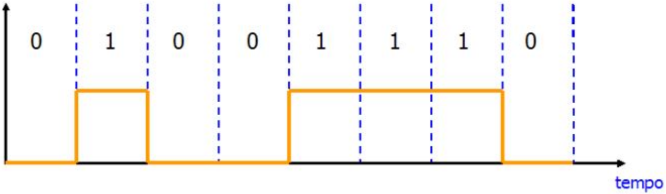
Conversion of Bits into Signals

- Conversion of bits into digital signals
  - Digital encoder and decoder
- Conversion of bits into analog signals
  - Modem (modulator e demodulator)



Unipolar Coding

- Uses presence/absence of polarity; for example:
  - Bit 0: absence of polarity
  - Bit 1: presence of polarity
- Easy implementation
- Reasonable spectral efficiency
- Does not allow AC coupling (signal contains DC component and low frequency)
- Does not allow self-synchronism (difficult to extract clock from signal)

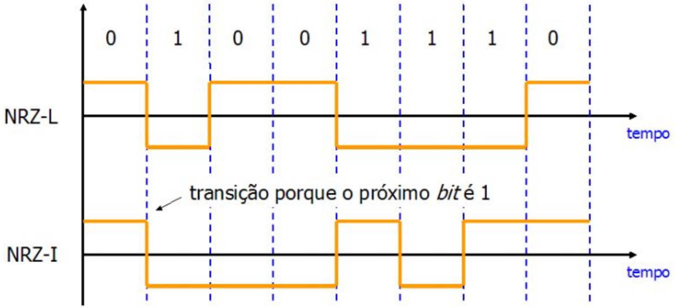


Bipolar Coding

- It uses two different polarities
- Non-return-to-zero (NRZ)
  - Polarity remains the same during the period of a bit
  - Examples:
    - NRZ-Level (NRZ-L): signal follows change of bit
    - NRZ-Inverted (NRZ-I): signal changes if next bit is 1
- Return-to-zero (RZ)
  - Bits represented by pulses that occupy only part (50% in general) of the period of a bit
  - Signal remains at zero for the remainder of the bit time

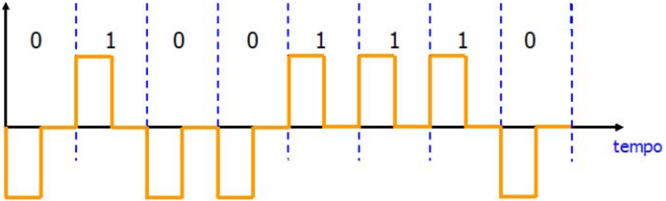
NRZ Encoding

- Advantages and disadvantages similar to unipolar coding
- However, it allows AC coupling



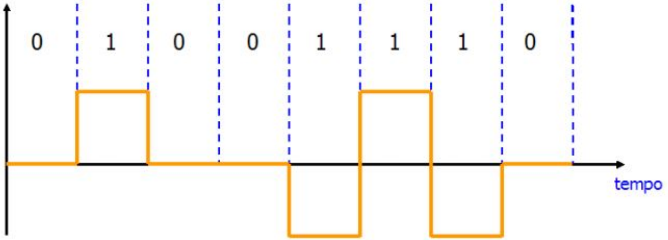
RZ Encoding

- Worse spectral efficiency than NRZ
- However, it allows easy synchronization



Alternate Mark Inversion (AMI) Encoding

- Bipolar coding:
  - Bit 0: no polarity
  - Bit 1: alternate polarities
- Immunity to inversions of polarities
- Absence of low frequency components
- Good spectral efficiency
- Used by the American T1 (1.544 Mbps)



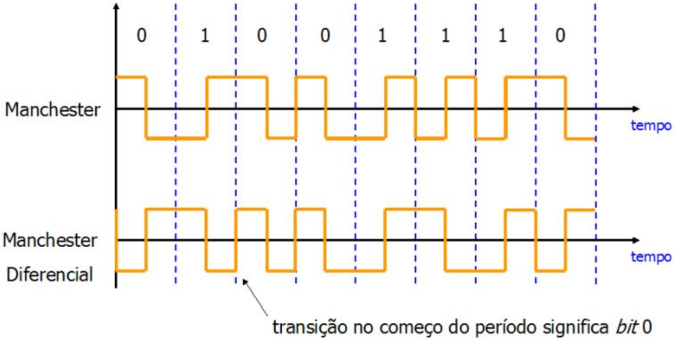
Manchester Encoding

- Manchester: transition in the middle of each bit
  - Bit 0: downward transition
  - Bit 1: upward transition
- Used by IEEE 802.3 (Ethernet)

- Manchester Differential
  - Bit 0: transition at the beginning of the bit
  - Bit 1: no transition at the beginning of the bit
- Used by IEEE 802.5 (Token Ring)

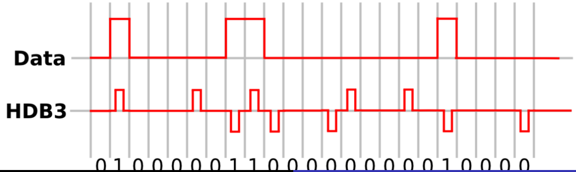
- Advantages
  - Easy implementation
  - Easy synchronization
  - No CC component
- Disadvantages
  - The baud rate is twice the bit rate
  - Requires greater bandwidth than NRZ

Manchester Encoding

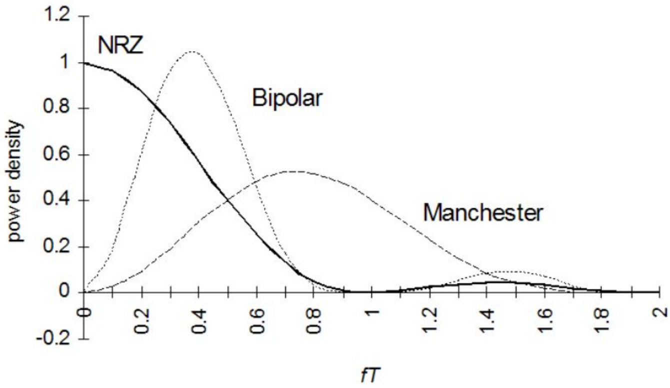


Other Coding Schemes

- Bipolar with 8 Zeros Substitution (B8ZS)
  - Based on AMI
  - Sequency of 00000000 is replaced by
    - 000+−0−+ if previous pulse is positive
    - 000−+0+− if previous pulse is negative
- High Density Bipolar 3 Zeros (HDB3)
  - Based on AMI
  - Forth zero in the sequency 0000 is always transmitted with a pulse that violates the rule of alternation
  - First zero in the sequency 0000 may be transmitted with a pulse in accordance to the rule of alternation
  - Used by the European E1 (2.048 Mbps)



Power Spectrum



Digital Modulation

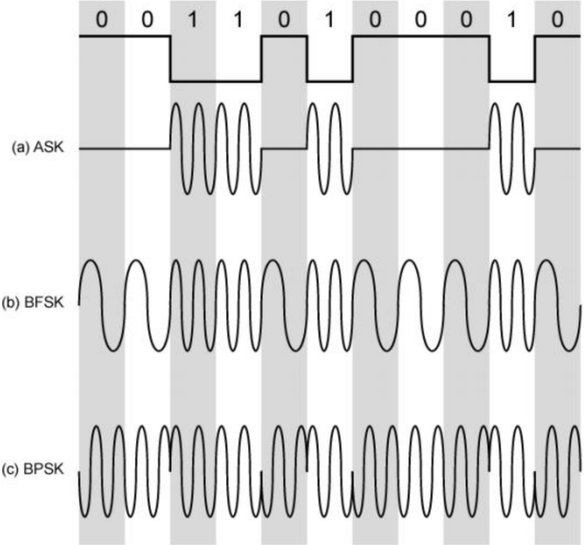
- Carrier:

$$y(t) = A\cos(2\pi ft + \phi)$$

  in which A is the amplitude, f is the frequency and ϕ is the phase

- Frequency Shift Keying (FSK)
  - Modulate (change) the frequency f
  - Amplitude A and phase ϕ remain unchanged
- Amplitude Shift Keying (ASK)
  - Modulate (change) the amplitude A
  - Frequency f and phase ϕ remain unchanged
- Phase Shift Keying (PSK)
  - Modulate (change) the phase ϕ
  - Amplitude A and frequency f remain unchanged

Digital Modulation



digital signal

ASK

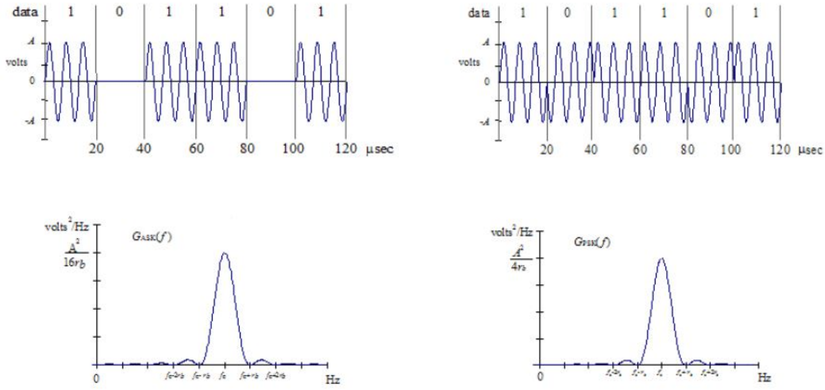
FSK

PSK

Digital Modulation

- ASK
  - Encode bits wiuth different carrier amplitudes
  - Inefficient and not immune to noise
  - Up to 1200 bps on phone lines; most popular with fiber optics
- FSK
  - Encodes bits with different carrier frequencies
  - More robust than ASK
- PSK
  - Encodes bits with different carrier phases
  - Binary PSK (BPSK) uses 2 phases (0^o e 180^o, for example) to represent bits 0 and 1
  - Quaternary PSK (QPSK) uses 4 phases (0^o, 90^o, 180^o e 270^o, for example) to represent the pairs of bits 00, 01, 10 and 11

Spectral Density ASK and PSK



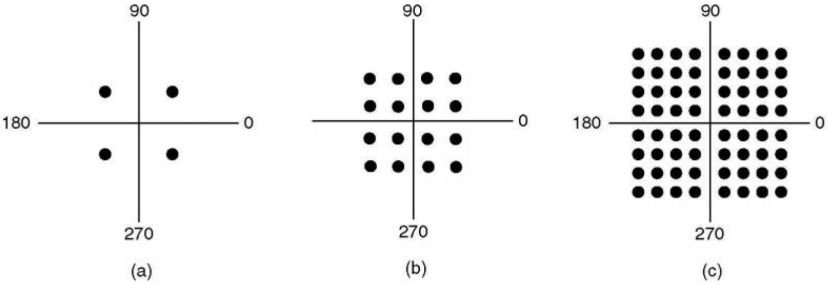
f_c = carrier frequency

Quadrature Amplitude Modulation (QAM)

- Generalization of PSK that combines phase and amplitude modulations
- Encodes bits with different pairs of amplitude/phase of the carrier
  - For example, Modem V.29 (9600 bps) uses 16-QAM with eight phases and two amplitudes totaling 16 symbols
  - Each symbol carries 4 bits and therefore the symbol rate (baud rate) is 2400 baud
- Allows higher spectral efficiency because it can pack more bits by symbol.

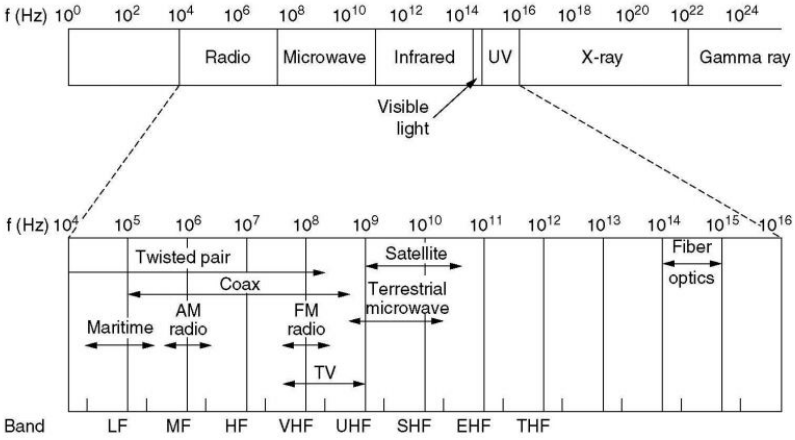
PSK/QAM Constellation

- Symbols in PSK and QAM modulations are represented by pairs (amplitude, phase), as if they were complex numbers in polar form
- Graphically, symbols are represented by points in the complex plane



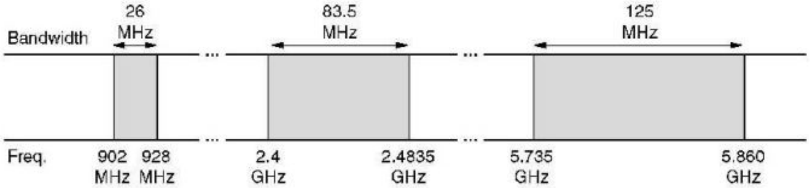
(a) QPSK (ou 4-PSK) (b) 16-QAM (12 fases e 3 amplitudes) (c) 64-QAM

Electromagnetic Spectrum



ISM band in the USA

- Industrial, Scientific, Medical
- 902 - 928 MHz:
  - transmitter up to 1 W
  - microwave oven up to 750 W
  - industrial heater up to 100 kW
  - radar up to 1000 kW
- 2.4 - 2.4835 GHz:
  - transmitter up to 1 W
  - microwave oven up to 900 W
- 5.725 - 5.850 GHz
  - transmitter up to 1 W



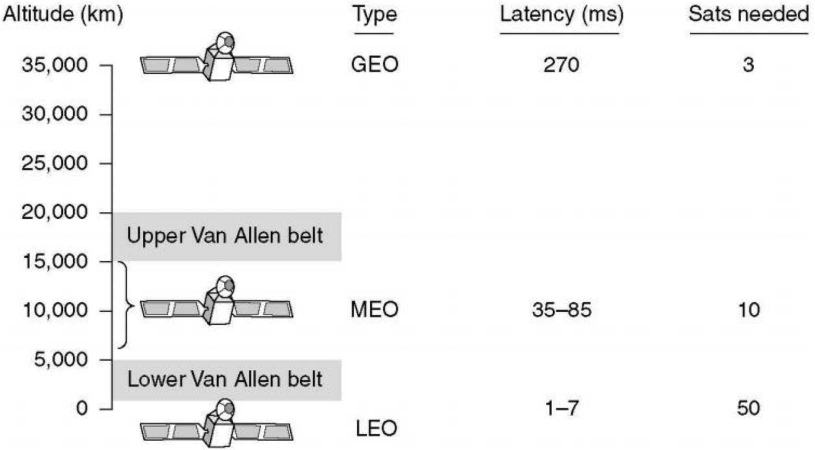
ISM Band in Brazil

- 6.765 - 6.795 MHz (30 kHz band)
- 13.563 - 13.567 MHz (4 kHz band)
- 26.957 - 27.283 MHz (326 kHz band)
- 40.660 - 40.700 MHz (40 kHz band)
- 902 - 928 MHz (26 MHz band)
- 2.4 - 2.5 GHz (100 MHz band)
- 24 - 24.25 GHz (250 MHz band)
- 61 - 61.5 GHz (500 MHz band)
- 122 - 123 GHz (1 GHz band)
- 244 - 246 GHz (2 GHz band)

Communication Satellites

- Used for
  - Telephone
  - Television
- Disadvantages:
  - Orbit congestion (GEO satellites)
    - Each GEO satellite occupies 2 degrees of the circumference
  - High cost, high risk, high delay, low privacy
  - Limited life (fuel)

Communication Satellites



Satélites GEO (Geostationary), MEO (Medium Earth Orbit) and LEO (Low Earth Orbit)

Sats needed is the number of satellites for planetary coverage

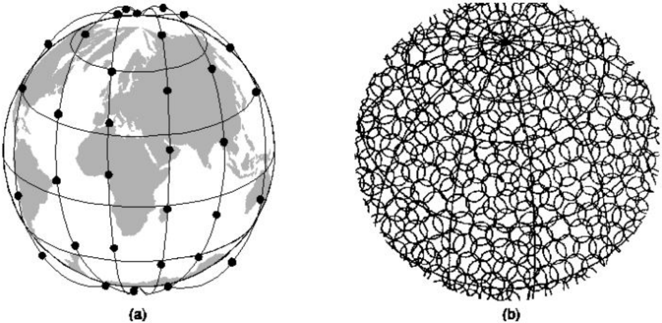
Communication Satellites

- Bands used

Band	Downlink	Uplink	Bandwidth	Problems
L	1.5 GHz	1.6 GHz	15 MHz	Low bandwidth; crowded
S	1.9 GHz	2.2 GHz	70 MHz	Low bandwidth; crowded
C	4.0 GHz	6.0 GHz	500 MHz	Terrestrial interference
Ku	11 GHz	14 GHz	500 MHz	Rain
Ka	20 GHz	30 GHz	3500 MHz	Rain, equipment cost

Iridium

- 66 LEO satellites, each with up to 48 cells
- Transmission between satellites
- Voice and data up to 2.4 kbps and Internet up to 10 kbps
- Company still in business (check www.iridium.com)



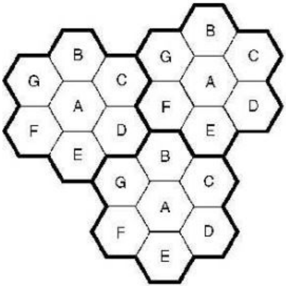
(a) Satellites (b) Cells

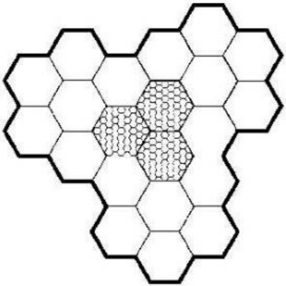
Mobile Phone System

- 1st Generation (1G), 1985
  - analog voice
  - AMPS, TACS, NMT, etc.
- 2nd Generation (2G), 1992
  - digital voice
  - D-AMPS, GSM, CDMA (IS-95), etc.
- 2nd Generation Transitional (2.5G, 2.75G)
  - packet switching and data communication
  - GPRS/EDGE, CD2000-1x, etc.
- 3rd Generation (3G), 2003
  - digital voice + data
  - UMTS, CDMA2000, etc.
- 4th Generation (4G), 2013
  - digital voice + multimedia, IP network
  - LTE, WiFi, etc.

AMPS

- Advanced Mobile Phone System
- Area of coverage divided into cells
  - Allow frequency reuse
  - Transmission using lower power





AMPS

- Some components
  - Mobile station (MS) or mobile terminal
  - Base Station (BS)
  - Mobile Switching Center (MSC)
- A little bit of jargon
  - Camping: MS camps in a cell
  - Handoff or handover: MS changes cell during call
  - Paging: sent by BS to MS for call search and alert
  - Cell Info: broadcasted by BS, informs cell identification and characteristics
- Uses TDM-FDM on radio link with channel bandwidth of 30 kHz
- 832 channels in the 800 MHz band, plus channels added in the 1800-1900 MHz band

AMPS

- Cell Selection (initial camping)
  - When turned on, MS searches for a cell to camp, usually the strongest of a list of preferred carriers
- Cell Reselection (cell change with no call in progress)
  - Continuously MS checks the intensity of all the cells it can receive
  - A report with this list is sent to BS
  - The cell change occurs when a cell becomes better than the current one
- Handoff (cell change during a call)
  - MS sends to BS values about call quality in progress and the strengths of neighboring cells
  - System decides when handoff should occur and informs MS

Digital AMPS (D-AMPS)

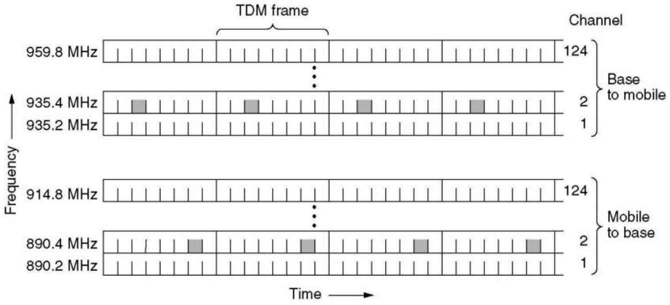
- North American system of 2nd generation, specified by IS-136
- Co-existence with the analog AMPS standard (maintains same channel structure in the radio interface)
- Each analog channel divided into 3 digital channels
- Compatibility requirement with AMPS impaired system

GSM

- Global System for Mobile Communication, European system of 2nd generation
- Uses TDM-FDM in radio link with 200 kHz channels
- System with the largest number of subscribers worldwide
- Improved for data communication (the generation 2.5G)
  - General Packet Radio Service (GPRS): up to 60 kbps
  - Enhanced Data Rates for GSM Evolution (EDGE): up to 380 kbps

GSM

- GSM Structure: Combination of TDM and FDM with TDM frame with 8 slots and separate channels for uplink and downlink



CDMA (IS-95)

- North American 2nd generation system specified by IS-95
- Uses CDM instead of TDM or FDM, with channel bandwidth of 1.25 MHz

Third/Forth Generations

- 3G
  - Voice, messaging, multimedia and Internet access
  - Rates up to 2 Mbps
  - System with global access
  - UMTS
    - Uses W-CDMA with channel bandwidth up to 20 MHz
    - Allow handoff with GSM
  - CDMA-2000
    - Uses W-CDMA with channel bandwidth up to 20 MHz
    - Based on IS-95
- 4G
  - Mobile broadband Internet access, high-definition mobile TV, video conferencing, etc.
  - Rates up to 100 Mbps (peak rate in mobile environment) and 1 Gbps (peak rate in indoor environment)
  - All IP network
  - Uses CDMA or OFDM with channel bandwidth up to 20 MHz