# Sistemas de Comunicaciones

## Master en Ingeniería de Telecomunicación

# Unit 1. The Digital Communications System


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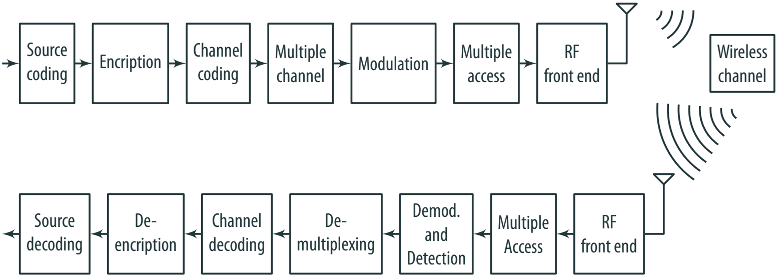
# Digital Communications Systems

# Digital Communications Systems



# Source coding

- If input is analog it is adapted to digital, where big issues are
  - *Sampling*
  - *Quantization*
- Information is compressed
  - Shannon proved that if long enough words (packets) are sent channel source and channel coding could be designed independtly
- The *rate* is the averaged number of bit per sample used
- Algorithms should achieve the lowest rate (maximum possible compression) but bearing in mind complexity and latency
- Compression can be *lossless or lossy*
  - data files or text is usually lossless compressed: Huffman LZ77, LZ78,
  - voice, image or video are usually compressed with loss: GIF, BNP, JPEG, MP3, H.264/MPEG-4,...
- In lossy compression perception we aim at discarding data not affecting perception.
- Important to bear in mind throughputs $R_{b,s}$ ...

# Not Compressed Sources

## Examples of Sources

| Source | sampling and bits | output rate |
|---|---|---|
| Telephony (200-2400 Hz) | 8000 samples/s $\times$ 12 bits/sample | 96 kbps |
| Wideband speech (50 - 7000 Hz) | 16,00 samples/s $\times$ 14 bits/sample | 224 kbps |
| Wideband audio (20-20,000 Hz) (CD) | 44,100 samples /s $\times$ 2 channels $\times$ 16 bits/sample | 1.41 Mbps |
| Images | 512 $\times$ 512 pixel color image $\times$ 24 bits/pixel | 6.3 Mbits/image |
| Video | 640 $\times$ 480 pixel color image $\times$ 24 bits/pixel $\times$ 30 images/s | 221 Mbps |
| HDTV | 1280$\times$ 720 pixel color image $\times$ 60 images/s $\times$ 24 bits/pixel | 1.3 Gbps |

Storage and transmission of *uncompressed* video is unfeasible

# Once compressed

- for video:

| Resolution | Minimum Upload Speed* | |
|---|---|---|
| | H.264 | H.265 |
| 480p | 1.5 mbps | 0.75 mbps |
| 720p | 3 mbps | 1.5 mbps |
| 1080p | 6 mbps | 3 mbps |
| 4K | 32 mbps | 15 mbps |

*These values are rough estimates based on stable network environments, calculating upload requirements is very subjective and depends on a number of factors

**mpbs: Megabits per second**

BOXCAST

Source: `https://www.logitech.com/assets/45120/logitechh.pdf`

- for audio, MP3 is between 96 kbps and 256 kbps
- for speech, modern codecs (used in mobiles) are below 6 kbps

# Encription

- Encription is needed if we wish the information to be kept secret.
- There are several methods to encript information.
- Communication can be encripted using, e.g., SSL/TSL
  - SSL, "Secure Socket Layer" is the predecesor of the TLS "Transport Layer Security".
  - They are based upon *certificates*.
  - They check also for the *integrity* of the message.
  - They are based on RSA/DSA/ECC public/private keys.
  - Public/Private key: every body knows the *public key* and can encrypt information with it, but just the one with the *private key* can desencrypt it.
- With just one key, to encrypt a document, the *Advanced Encryption Standard (AES)* algorithm can be used, e.g. AES-256.
- No redundancy is usually added: throughput at the output is the same as at the input.

# Channel Coding

- Information Theory provide the limits to transmission speeds (in bits per second -bps-), aka throughput, free of error
- To reach these limits we include redundancy
- We use a channel encoder to include the redundancy
- At reception we use a channel decoder to retrieve the useful information
- While the bit error rates at the entry of the channel decoder may be high (10%-0.1%), at the output of the channel decoder we have a residual error (below $10^{-8}$)
- We say that for each $k$ bits entering the channel encoder there are $n$ bits at the output where $r = k/n$ *is the rate of the code*
  - If the *throughput* at the input of the channel encoder is $R_{b,s}$ (bps),
  - at the output we have a throughput of $R_{b,c} = R_{b,s}/r$
- There are several types of channel coding schemes: *convolutional, turbo codes, BCH, Reed-Salomon or LDPC* are well known and used.

# Multiple Channels or Multiplexing

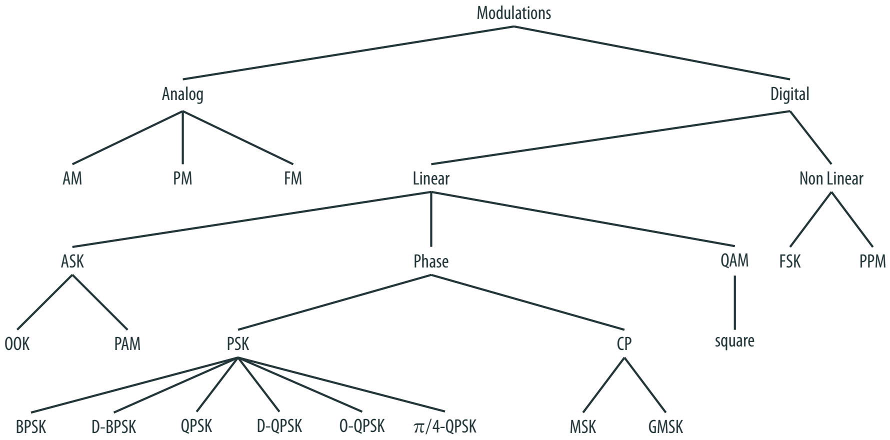
- We usually have several types of information
  - Control
  - Voice
  - Video
  - Photographs
  - Info from sensors,...
- In the Multiple Channels block we pack them to be sent
- This packing can be performed in several ways
  - we could send them sequentially (*time division multiplexing, TDM*)
  - we could send them in different channels (*frequency division multiplexing, FDM*)
  - ...
- Also, information going to or coming from the device has to be scheduled

# Modulation and Demodulation

- Digital Modulation
  - The *Modulator* transforms a sequence of bits into a wave form occupying a given bandwith, $B$, at a given carrier frequency, $f_c$ in two steps
    - First it translates $\log_2(M)$ bits into a symbol, $M$ is the order of the modulation
    - Then it generates a signal within $B$ at $f_c$ that depends on this symbol
  - Demodulation
    - First, the signal is down-converted to low frequency, it can be done *coherently or non-coherently*, if the carrier is recovered and used to demodulate or not, respectively.
    - Then the transmitted symbol is detected
- Analogue Modulation
  - *Analog modulations* directly modify the
    - amplitude (AM)
    - frequency (or phase) (FM)

    of a sine proportionally to the input (analog signal).
  - AM modulations are still used in airplanes (e.g. airband 108-137 MHz) and FM in commercial radio broadcasting.

# Classification

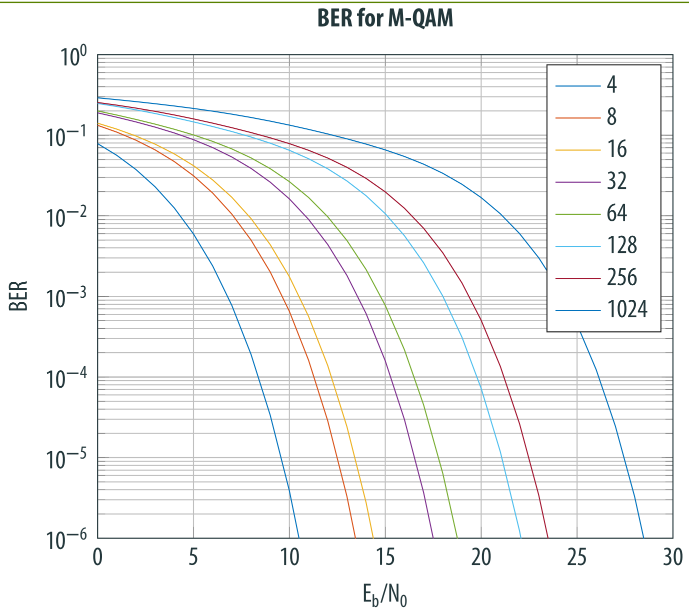


# Modulations: Notes

- *Linear modulations* can be expressed as a sequence of symbols, from a given constellation, multiplied by a pulse.
    - In wireless communication *root raised cosine* pulses are quite extended: bandwith for BPSK, M-QAM, M-PSK, M-ASK,.... yields
      $$B = \frac{1+\beta}{T} = \frac{(1+\beta)R_{b,c}}{\log_2 M}$$
      with $T = \log_2 M T_b$ symbol time, $T_b = 1/R_{b,c}$ and $\beta$ the *roll-off factor*, aka excess bandwidth.
- *OFDM* (orthogonal frequency division multiplexing/modulation): downlink of WiMAX, LTE, 5G, IEEE 802.11,...,DSL
    - Used to avoid multipath effect (ISI, inter-symbol interference)
    - A set of $N_c$ subcarriers (typically around $W_c = 7.5 - 15$ kHz) are modulated: bandwith is this width by the number, $B = N_c W_c$
    - Usually *M-QAM* is used in every subcarrier (Used in WiFi IEEE 802.11)
    - when using with channel coding: COFDM
- *DS-SS* (direct sequence spread spectrum): GPS
- *PPM*: (pulse-position modulation) different pulses are transmitted depending on the data
- *UWB* (ultra wide band): wireless sensors
    - A pulse of huge bandwith (GHz) and no carrier

# BER for M-QAM


BER for M-QAM
BER
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
0
5
10
15
20
25
30
$E_b/N_0$
4
8
16
32
64
128
256
1024

# Comparison between modulations

- We focus on three parameters: *bandwith, spectral efficiency and BER* (or SER, after symbol error rate), that depends on the
  - $E_{bav}/N_0$: the ratio bit energy (averaged energy per bit period) to power spectral noise (how much noise we have per bandpass unit bandwith, i.e. 1 Hz)
- Assuming coherent MFSK modulation we have the following table, with $\gamma_b = E_{bav}/N_0$:

| | $B$, (Hz) | $\eta$((bit/s)/Hz) | SER |
|---|---|---|---|
| **M-PSK** | $\frac{1}{T} = \frac{R_b}{log_2 M}$ | $\log_2 M$ | $P_M \approx 2Q\left[\sqrt{2\gamma_b \log_2 M} \sin\left(\frac{\pi}{M}\right)\right]$ |
| **M-QAM** | $\frac{1}{T} = \frac{R_b}{log_2 M}$ | $\log_2 M$ | $P_M \approx 4Q\left(\sqrt{\frac{3 \log_2 M}{(M-1)} \gamma_b}\right)$ |
| **M-FSK** | $\frac{M}{2T} = \frac{MR_b}{2log_2 M}$ | $\frac{2 \log_2 M}{M}$ | $P_M \approx (M-1)Q\left(\sqrt{\gamma_b \log_2 M}\right)$ |

Note: $\beta = 0$, $R_b$ is throughput at the input of the modulator.

# Further notes on modulation

## Throughput and bandwith

Suppose we have $R_b = 1$ Mbps ($10^6$ bits per second) at the input of the modulator and and excess bandwidth ($\beta$) of 0.2

- if we transmit a BPSK, what the bandwith is?
- and if we transmit a QPSK, 16-QAM, 64-QAM?
- how does it change the needed $E_b/N_0$?

## ACM, adaptive coding and modulation

*ACM*: Depending on the channel conditions a pair of coding scheme modulation is selected

- If the channel is good: high $M$ (for a M-QAM) and high rate $k$
- In WiFi 6 (IEEE 802.11ax) the MCS (modulation and coding scheme) indicates the value of the rate and modulation used.

# Multiple Access

- Several terminals could be accessing to the same central system
  - The terminal could use each one a different channel: *frequency division multiple access (FDMA)*
  - The terminal could use the same channels but different time slots: *time division multiple access (TDMA)*
  - ...
- The info coming and outgoing to the terminal has also to be scheduled
  - If they share the same channel, the channel is used in both senses: *time division duplexing (TDD)*
  - If they are transmitted in different channels: *frequency division duplexing (FDD)*
- Usually a central node (base station, access point,...) transmit information to terminals (*uplink, UL*) using multiplexing while terminals access back (*downlink, DL*) with multiple access

## GSM

In GSM it is used NB-TDMA, narrow band TDMA, a mixture of FDMA and TDMA: each carrier of 200 kHz has 8 slots of TDMA.
Voice is encoded into 6.5 or 13 kbps to provide, after channel coding, a throughput of 22.8 kbps. After including control data, each user transmit 156.25 bits per TDMA frame of 120/(26) ms: 270.8 kbps

# Conclusions

- *Source coding* used to convert to digital (if needed) and compress.
- *Encription* is important to secure information. It can also ensure integrity.
- *Channel coding* is important to reduce and check for transmission errors.
  - They introduce redundancy: output bit error rate is $kR_{b,s}$, where $k$ is the rate.
- *Time and frequency multiplexing* allows packing different information sources into a channel, providing $R_{b,m}$.
- *Digital Modulations* are widely used
  - however there exists some uses of AM and FM in aircrafts
- The *bandwith* of the linear modulations such as M-QAM is

$$B = \frac{(1+\beta)R_{b,m}}{\log_2 M}$$

  for some $\beta \leq 1$
- Hence, the bandwith decreases with the number of bits used to generate a symbol, however the needed energy increases.
- *COFDM/OFDM* uses several transmissions of narrow bandwithds
  - It is widely used because is robust to multipath (superimposed delayed copies of the transmitted signals)
  - usually, every sub-transmission (subcarrier) can be modulated with a M-QAM
- *Multiple access* of terminals to the channel must be considered

# Questions

1. Private and public key algorithms
   a) are channel coding algorithms
   b) are source coding algorithms
   c) are encryption methods
2. In channel coding, if $R_b$ is the throughput at the output of the source coding,
   a) the throughput at the output of the channel coding block is equal to $R_b$
   b) the throughput at the output of the channel coding block is lower or equal to $R_b$
   c) the throughput at the output of the channel coding block is larger or equal to $R_b$
3. In time division multiplexing
   a) the errors are discarder along time
   b) information from different sources within the system are transmitted sequentially in time
   c) information from different sources withing the system are transmitted sequentially in frequency

# Questions

4. The bandwith of a M-QAM, if $R_b$ is the throughput at its input,
   a) is roughly the inverse of the symbol time $T = \log_2(M)/R_b$
   b) is a fixed constant multiplied by $T_b = 1/R_b$
   c) does not depend on $R_b$
5. In a OFDM system with 180 subcarriers of 15 kHz, the bandwith is *roughly*,
   a) 180/15 kHz
   b) 15/180 kHz
   c) $180 \times 15$ kHz
6. In TDMA
   a) each terminal access the channel in a different given time slot
   b) each terminal access the channel in a different given frequency slot
   c) each terminal access the channel using a different given code
7. A voice codec of GSM, providing 13 kbps, after channel coding and including control/signaling information generates
   a) a 22.8 kpbs transmission over 1/8 of the time
   b) a 270.8 kbps transmission over 1/8 of the time
   c) a 2 Mbps transmission over 1/8 of the time

# The RF part

# RF equipment

- We have the Tx and the Rx,
  - both of them may be jointly implemented in a *transceiver (TRX)*
- Devices involved are: up/down converters, mixers, oscillators (including VCO), amplifiers, duplexors, feeders, connectors, filters, ...
- The design of the Tx is less involved than the one of the Rx
- In the Tx
  - we mainly focus on power, nonlinear distortion and out-band transmission
- In the Rx
  - we face *nonlinear distortion, selectivity (of the desire bandwidth) and sensitivity (to low signals, facing noise)*,...
- *Software defined radio (SDR)* permits programming part of the overall chain.
- *Antennas* play an important role: *gain and bandwidth* are important
- Then *propagation* ...

# Spectrum Classification (I)

- A well known classification starts at 3-30 kHz and goes up with a $\times$10 factor.

| $\lambda$ | | $f$ | Band |
|---|---|---|---|
| 100-10 km | Miriametric waves | 3-30 kHz | VLF |
| 10-1 km | kilometric waves | 30-300 kHz | LF |
| 1-.1 km | hectometric waves | 0.3-3 MHz | MF |
| 100-10 m | decametric waves | 3-30 MHz | HF |
| 10-1 m | metric waves | 30-300 MHz | VHF |
| 1-.1 m | decimetric waves | 0.3- 3 GHz | UHF |
| 10-1 cm | centrimetric waves | 3-30 GHz | SHF |

*Tropospheric Propagation*

**Bandwiths increase**

Figure: Spectrum Division in SH/UH/VH/H/M/L/VL Frequencies

# Spectrum Classification (II)

- Another quite used classification is that using letters (IEEE):
  - Quite used in satellite communications

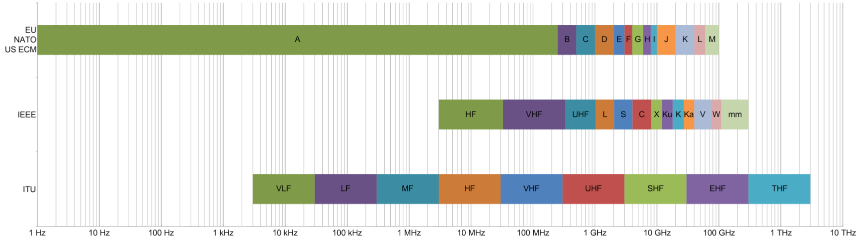



Figure: IEEE Spectrum Division

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# Spectrum

- In general, lower frequencies have better propagation:
  - the "*dividendo digital*" tries to compress TV channels free frequencies near 800 MHz while
  - the "*refarming*" reassigned frequencies in the 900 MHz to the operators.
- Who can use every part of the spectrum is suggested by the ITU and then, in SPAIN, detailed in the *CNAF (cuadro nacional de atribución de frecuencias)*
- There are some *ISM (industrial, scientific and medical bands)* where WiFi operates
  - at $f = 2.4GHz$ is $\lambda = 12.5$ cm

# Systems

# Standarization and Consortiums

- In the development of systems the standardization organism play a central role:
  - IEEE (EEUU-worldwide)
  - ETSI (Europe)
  - ARIB Association of Radio Industries and Business (Japan)
  - TTC Telecommunication Technology Committee (Japan)
  - ANSI T-1 American National Standards Institute (EEUU)
  - TTA telecommunications technology association (South Corea)
  - Chinese Wireless Telecommunication Standard (CWTS) (China).
- There are also groups of them for particular projects: *3GPP*
- But equipment companies also propose changes to the protocols of the systems: Nokia, Ericcson, Motorota, Siemens, Nortel, Lucent-Alcatel (<Nokia<Microsoft 2015), Cisco, Huawei, Andrew, Kathrein, Galgus, Moyano.
- Consortiums or Alliances are key to favor compatibility between equipment from different companies:
  - *WiFi, WiMAX, ZigBee, Lora*

# IEEE

IEEE: The Institute of Electrical and Electronics Engineers

- Born in USA in 1884
- Within their standards we underline the following
  - IEEE 802.10 – Security
  - *IEEE 802.11* – Wireless networks (WiFi)
  - *IEEE 802.15* – Bluetooth, wireless sensor netwoks,. . .
  - IEEE 802.16 - WPAN (WiMAX)
  - IEEE 802.20 – Mobile Broadband Wireless Access
  - IEEE 802.22 – Wireless Regional Area Network

# Regulation

- At international level the *ITU* is a major reference
  - It is divided in several groups
  - It is in charge of organizing the spectrum
- In USA the *FCC* (federal communications commision) regulates the communications
- In Spain we have the Secretaría de Estado de Telecomunicaciones e Infraestructuras Digitales
  - One of their duties is spectrum managment: CNAF See `https://avancedigital.mineco.gob.es/espectro/Paginas/cnaf.aspx`

# Systems

- We cannot list every communication system
- Nowadays systems are mostly digital ones
  - Commercial radio broadcasting public services are still AM and FM modulated
  - In airplanes, some channels remains as AM systems, as they are easy to demodulate for everyone.
  - Walkie-talkies have been mostly analog (FM with digital signaling) but in recent years digital systems are being used (*DMR*, digital mobile radio)
- A main classification of communication systems is based on the propagation mechanism:
  - Optical guided/not-guided (e.g. *FTTH, Li-Fi*, inter-satellite)
  - Infrared
  - Radio, guided or not
  - Wired (electrical)

  where in radio communication the number and applications of systems is quite large

# Systems as services or networks

- Other classification of the communication systems is based on the coberture area
  - *PAN*: personal network, 10 m range. Device interconnection.
  - *LAN*: local area network, 100 m range. Short range data networks. Usually, but not limited, to indoor.
  - *WAN*: wide area network, km range (countries).
  - *MAN*: metropolitan networks. Large distance access. Usually outdoor/indoor. Mostly thought to solve the *last mile connectivity problem*

  If wireless, they are named WPAN, WLAN, WWAN or WMAN. If low power is needed, LP- is used (e.g. LP-WAP).
- A recent new WAN is IoT, that can use public mobile infrastructure (LTE, 3GPP: *LTE-M, NB-IoT*) or dedicated one (*SigFox (The world's largest IoT network (2021)?, Redexia (Says uses LoRa but not in web of LoRa Alliance in 2021),Everynet (LoRaWAN)*)
- In the classification of communication systems the service is quite used in the ITU documents (`https://life.itu.int/radioclub/rr/art1.pdf`). *A service can be:*
  - Fixed or mobile (terminal changes position)
  - Land, maritime, or aeronautic (position of the terminal)
  - Broadcasting, radionavigation,...
  - Satellite or terrestrial (Note: terrestrial (terrenal o terrestre) is used for not space infrastructure while earth (terrena) is used for space)
  - Public or private

 

# Examples of systems

- Public land terrestial mobile servicie a.k.a. PLMN (Public Land Mobile Network) ó TMA (Telefonía Móvil Automática)
  - 1G analogue (digital signaling): AMPS, ETACS ó NMT,
  - 2G of ETSI: *GSM, GPRS (2.5G) y EDGE (2.75G)*
  - 3G of 3GPP (including ETSI): *UMTS, HSPA (3G+ ó 3.5G)*
  - 4G of 3GPP (including ETSI): *LTE*
  - 5G of 3GPP (including ETSI)
- Private land terrestrial mobile service a.k.a. *PMR* (Private Mobile Radio):
  - Analogue: several vendors, some license exempt (e.g. *PMR466*) frequencies.
  - 2G: *TETRA, DMR, DEC*
  - 4G: *LTE-PMR*
- Maritime and land space services: last generations include connection to satellite, others are specific systems: *Globalcom, Iridum, Inmarsat*,....
- Land terrestrial broadcasting services: *TDT* (Televisión Digital Terrestre based on the *DVB* standard), RDT (Radio digital terrestre based on DAB), AM and FM commercial radio, . . .
- Land/maritime/aeronautical broadcasting-satellite services: *SES-GLOBAL, Hispasat, Eutelsat*,...
- Radionavigation-satellite service, a.k.a. (*GNSS*): *GPS, GLONASS, Galileo, BeiDou*,...

 

# Questions

8. The refarming,
   a) denotes the 4.0 farming paradigm where NB-IoT will be key infrastructure
   b) is used to denote the reassignment of frequencies from TV to Mobile coms.
   c) is used to denote the reassignment of frequencies within a banda, usually from old PLMN generations to new ones.
9. SigFox, Everynet and Redexia,
   a) are companies for equipment used in wireless sensor networks
   b) are operators of wide area networks for IoT
   c) are consortiums for WiFi systems
10. SES-Global
    a) is a GNSS
    b) is a broadcasting satellite-service
    c) is a WiMAX system