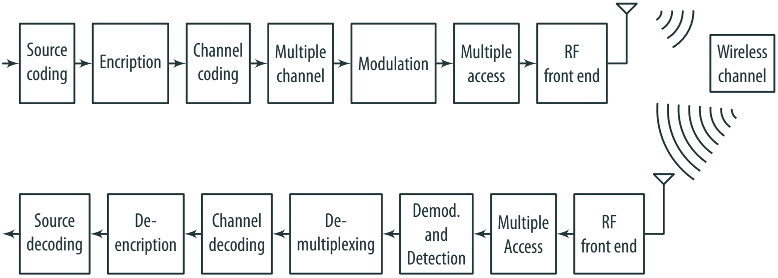
Digital Communications Systems



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	Minimum Upload Speed* 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

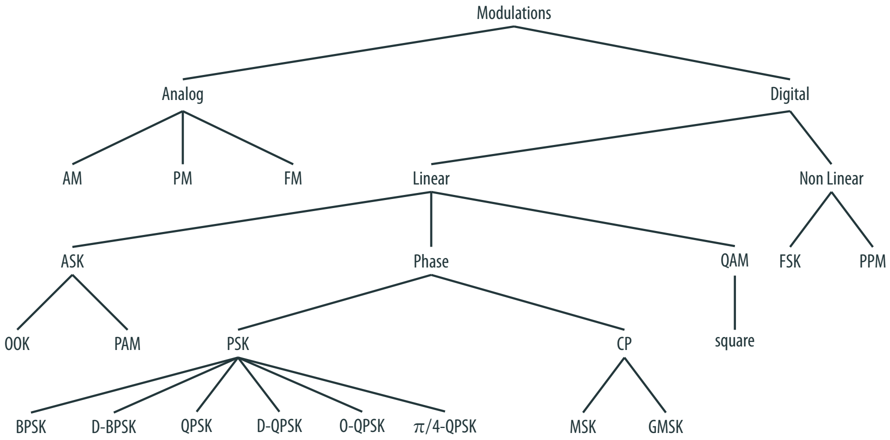
- We usually have several types of information
  - Control
  - Voice
  - Video
  - Photographs
  - Info from sensors,...
- In the Multiple Channels block we pack them to be sent
- This packing can be performed in several ways
  - we could send them sequentially (*time division multiplexing, TDM*)
  -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



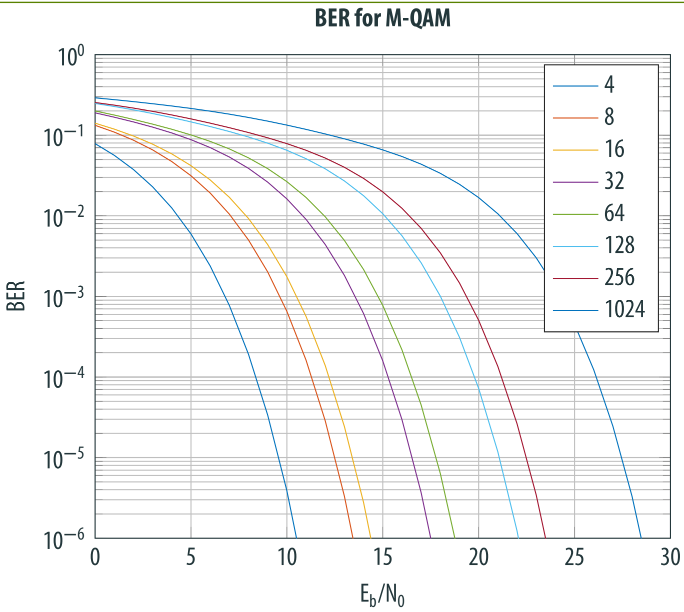
Modulations: Notes

- *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 $T = \log_2 MT_b$ symbol time, $T_b = 1/R_{b,c}$ and β 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)**	η**((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	$\frac{M}{2T} = \frac{MR_b}{2 log_2 M}$	$\frac{2 \log_2 M}{M}$	$P_M \approx (M-1)Q\left(\sqrt{\gamma_b \log_2 M}\right)$

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 (β) 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

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.

λ		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

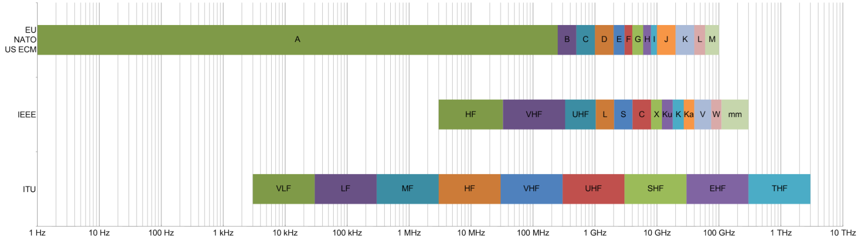


Figure: IEEE Spectrum Division

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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

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*,...