Digital Communications

Prof.ssa Ernestina Cianca
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Introduction

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Material:
Slides del corso

Advised Books:

Fundamentals of Communication Systems,
J. Proakis, M. Salehi, ©2005, Pearson Prentice Hall

Digital Communication Systems, 1st Edition
Simon Haykin, April 2013, ©2014, Wiley

Objectives

The primary objectives of this course are:

- to introduce the basic techniques used in modern communication systems
- to provide fundamental tools and methodologies in analysis and design of these systems

The course aims to provide the student with fundamental tools and methodologies to understand, design and evaluate the main elements of a modern telecommunication system;

In particolar, student should be able to:

- Understand the principles and technique of modulation, coding and transmission;
- Analyze the performance of a digital communication link when additive noise is present in terms of the signal-to-noise ratio and bit error rate;
- Design digital communication systems, given constraints on data rate, bandwidth, power, reliability and complexity;

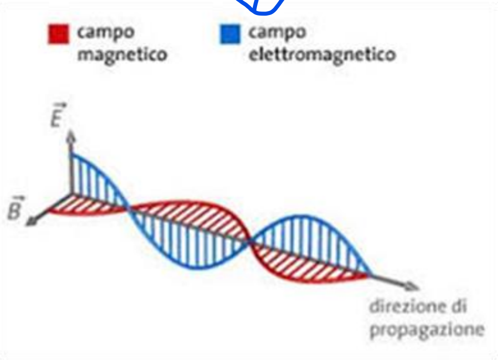
COMMUNICATION SYSTEMS

Communication: it is the process of transmitting information from a source to a destination.
Telecommunication: when this transmission occurs using electromagnetic waves,

Electromagnetic waves are nothing but electric and magnetic fields drifting through free space with the speed of light. A speeding charged particle is when the charged particle oscillates about a symmetry position. If the frequency of oscillation of the charged particle is f, then it yields an electromagnetic wave with frequency f

fumo

luce

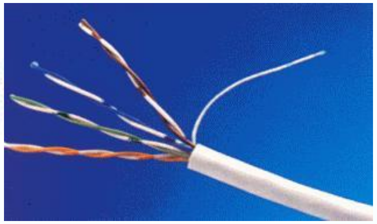


Onda elettromagnetica

COMMUNICATION SYSTEMS

Examples of propagation medium for electromagnetic waves

Guided propagation



fiber

twisted pair

Coaxial cable

Free propagation

Mobile broadcast channel

Mobile radio channel

Satellite channels

DIGITAL COMMUNICATION SYSTEM
Hystorical overview

1838: telegraph (S. Morse)
□1876: telephone (A. Bell)
□1895: radio by Marconi
□1901: trans-atlantic communication

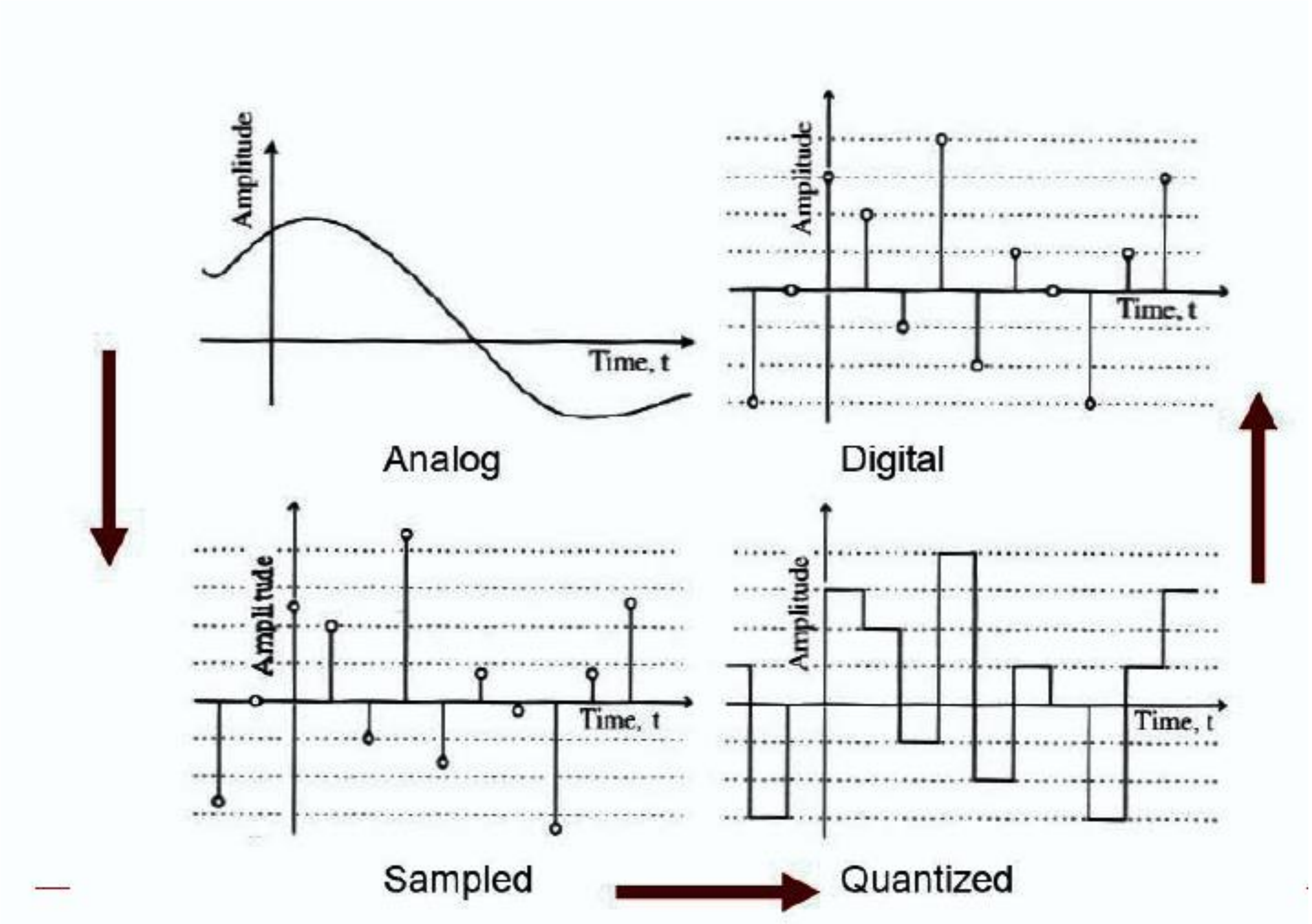
1956 : Narinder Singh Kapany optical fiber

Nobel Prize for Physics (1909)

Beginning last century **most communication systems are ANALOG**
Engineering designs are ad-hoc, tailored for each specific application

DIGITAL COMMUNICATION SYSTEM

DIGITAL COMMUNICATION SYSTEM



DIGITAL COMMUNICATION SYSTEM
Why Digital Communications?

- ❑Robustness to channel noise and external interference

- ❑Security of information during its transmission

- ❑Integration of different source information in a single format

- ❑Low cost DSP chips by very cheap VLSI designs

DIGITAL COMMUNICATION SYSTEM
Fundamental Questions

Is there a general methodology for designing communication systems?

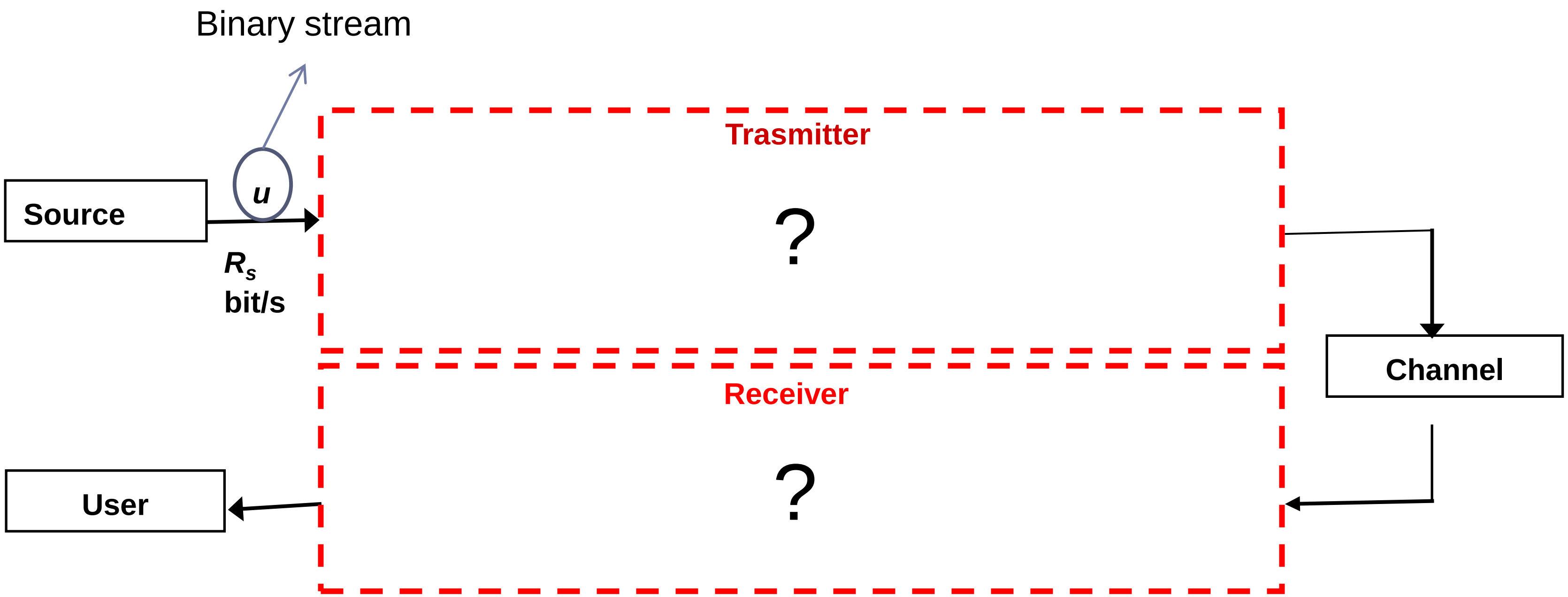
Is there a limit to how fast one can communicate?

Harry Nyquist (1928)

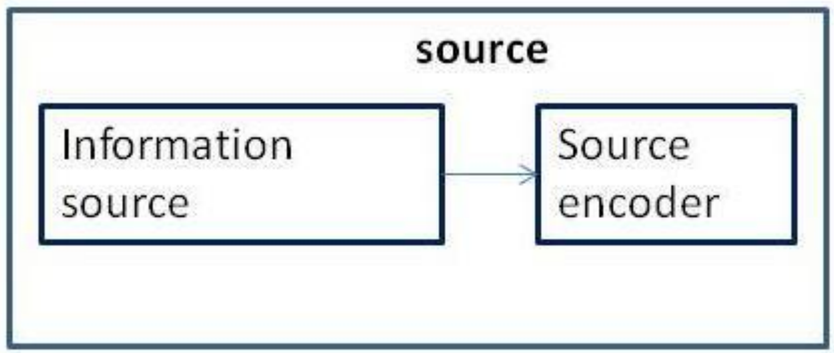
Sampling Theorem
"Certain topics in telegraph transmission theory", Trans. AIEE, vol. 47, pp.617–644, Apr. 1928
13

Claude Shannon (1948)
"A Mathematical Theory of Communication", *Bell System Technical Journal. 1948*
<u>He is the founder of Information Theory</u>

DIGITAL COMMUNICATION SYSTEM



DIGITAL COMMUNICATION SYSTEM
Digital Source

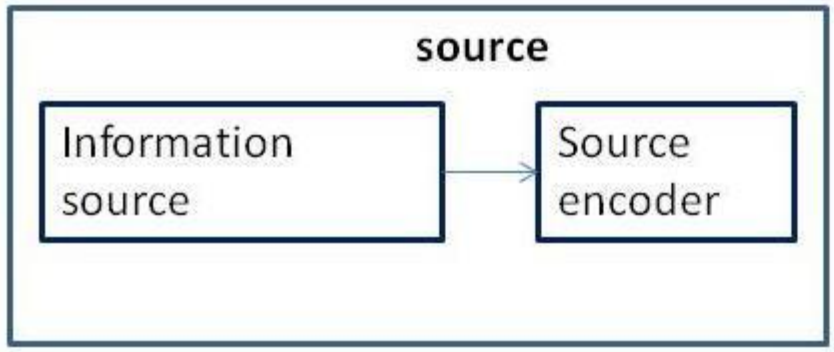


The digital source in the figure includes:

- the information source;
- the source encoder;

Information source
This is the device producing information to be communicated by means of DCS.
Information source can be **analog or discrete**.
The output of an **analog source** can have any value in a continuous range of amplitudes.
Examples: voice signal from a microphone, the output of a sensor, a video waveform

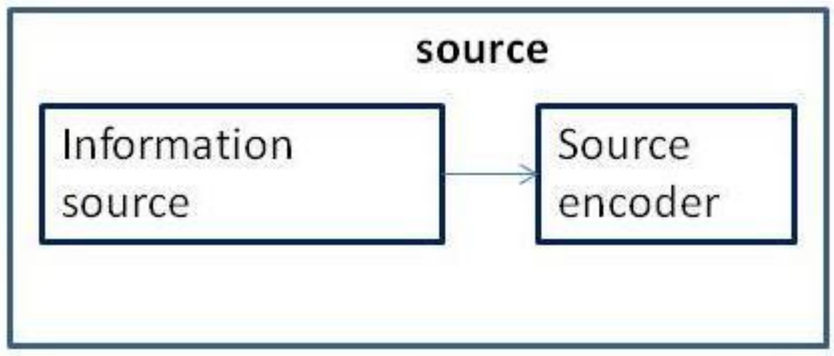
DIGITAL COMMUNICATION SYSTEM
Digital Source



<u>Information source</u>.
The output of an **discrete source** takes its value from a finite set.

<u>Examples:</u> sequence of symbols such as letters from the Italian or Chinese alphabet, binary symbols from a computer file

DIGITAL COMMUNICATION SYSTEM
Digital Source



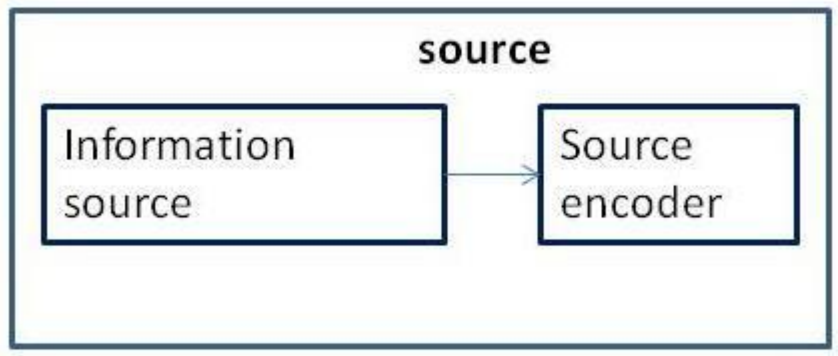
Source Enconder has the function of converting the input from its original form (analog or digital) into a sequence of bits.

The simplest source coding techniques involve simply representing the source signal by a sequence of symbols from some finite alphabet, and then coding the alphabet symbols into fixed-length blocks of bits.

Examples:

- Letters from the 27-symbol English alphabet (including a space symbol) may be encoded into 5-bit blocks.
- Upper-case letters, lower-case letters, and a great many other special symbols may be converted into 8-bit blocks (“bytes") using the standard ASCII code.

DIGITAL COMMUNICATION SYSTEM
Digital Source



How to convert an analog waveform to a bit sequence?

This operation is called **analog to digital (A/D) conversion** an consist in first to sample the source at a suffciently high rate (called the Nyquist rate), and then to quantize it sufficiently finely for adequate reproduction.

In standard voice telephony, the source encoding rate is the number of bits per second that are used to represent the voice signal. To calculate the source encoding rate, you can use the following formula:
Source encoding rate = (bandwidth in Hz) * (sample rate in samples/sec) * (bits per sample)

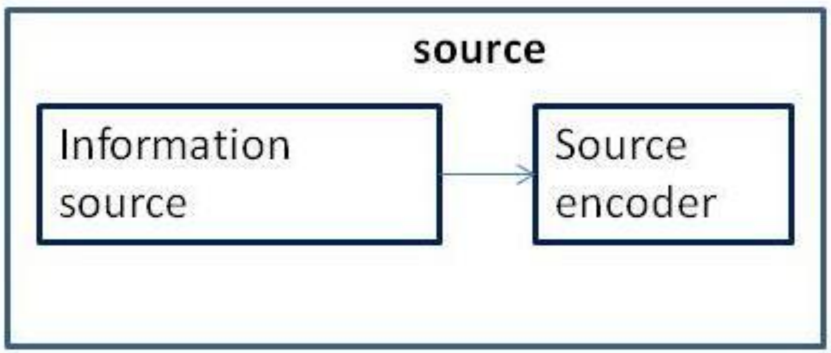
Example:

in standard voice telephony, the voice waveform is filtered to a bandwidth of less than 4 KHz and sampled 8000 times per second; each sample is then quantized into one of 256 levels and represented by an 8-bit byte.

This yields a source coding bit rate of 64 kb/s.

correct 32kbps

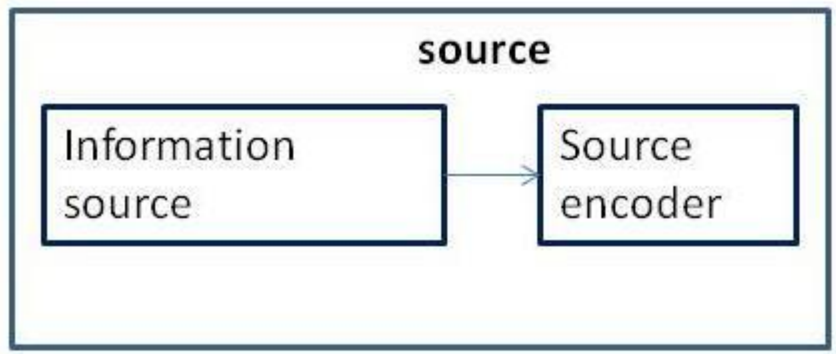
DIGITAL COMMUNICATION SYSTEM
Digital Source



Beyond the basic objective of conversion to bits the source encoder often has the further objective of doing this **as efficiently as possible**, i.e., transmitting as few bits as possible, subject to the need to reconstruct the input adequately at the output.

In this case source encoding is often called **data compression**. For example, modern speech coders can encode telephone-quality speech at bit rates of the order of 6-16 kb/s rather than 64 kb/s.

DIGITAL COMMUNICATION SYSTEM
Digital Source



The digital source is responsible for producing the message $u = \{a_k\}$, whose a_k symbols takes values in a finite message set or alphabet A of cardinality M.

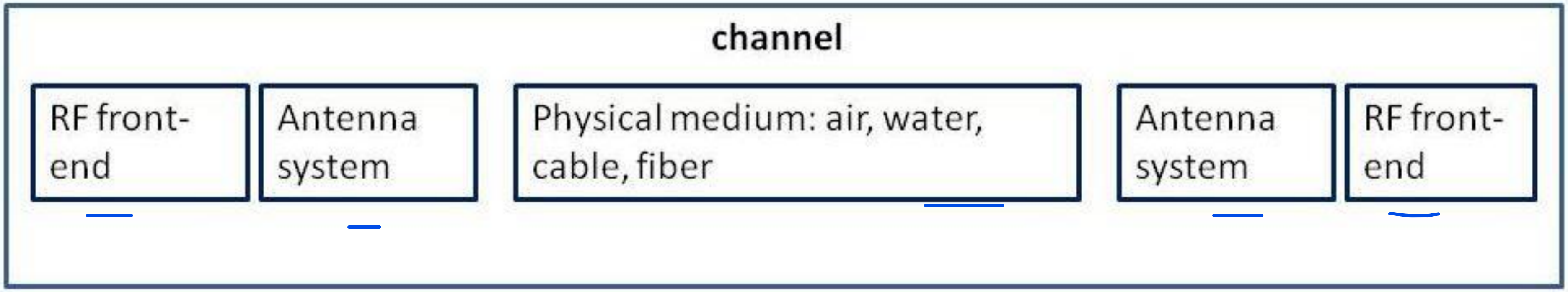
In many cases, the symbol a_k is a binary symbol, i.e. is a group of k=$log2M$ bits

In anycase, it is modeled by a random variable a taking values on a finite alphabet A and described by its probability mass function

$$P_a(i) \quad \text{with } i \in A$$

In most cases of interest to us, *a* is uniformly distributed

DIGITAL COMMUNICATION SYSTEM
Channel



Channel

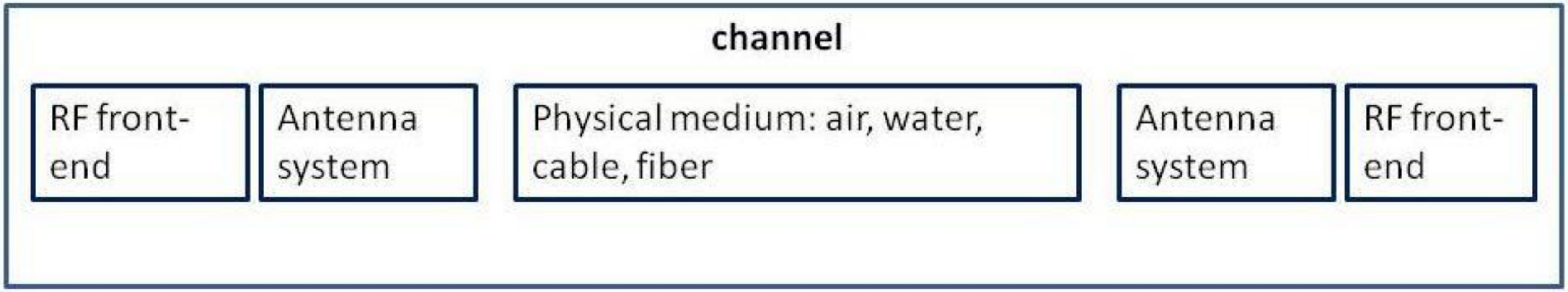
In general, the channel is that part of the communication medium that is given and not under the control of the designer.

❑For an antennas designer, the channel is the physical medium (air, water,)

❑For a RF-front-end designer is the physical medium + the distorsions introduced by the antenna.

❑For a digital communication designer, it include the physical medium, antennas, RF front-end (amplifier, filter, up and down converter, D/A e A/D).

DIGITAL COMMUNICATION SYSTEM
Channel

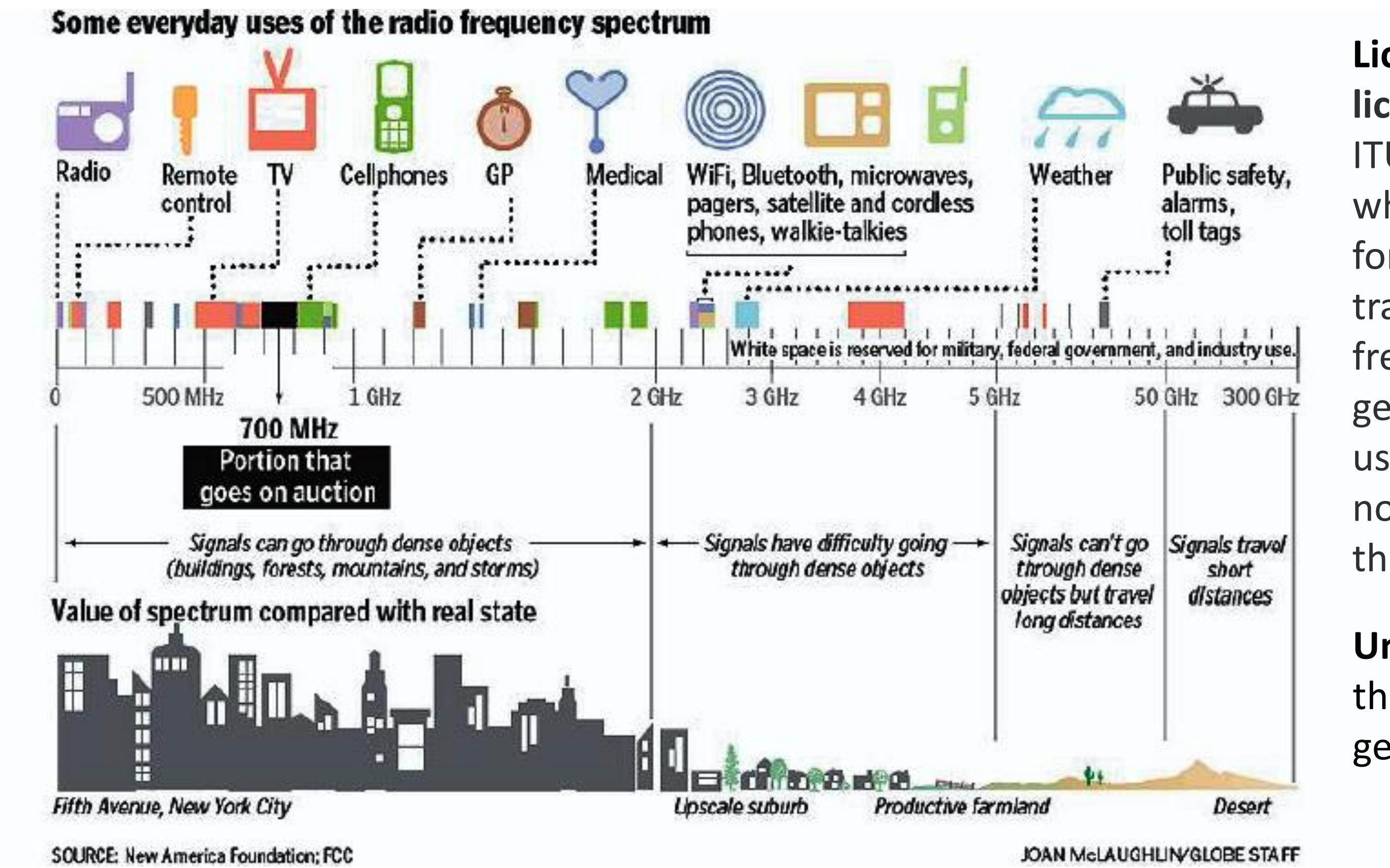


<u>Channel</u>

How to model it?
It is usually modeled as a linear time-invariant system (e.g., a filter), completely characterized by its impulse response or frequency response.
However, the channels that we look at here (and channels in practice) always have an extra ingredient: **the noise** (disturbance that is **statistically independent** from the signal)

<u>It was Shannon in 1948 who realized that noise provides the fundamental limitation to performance in communication systems</u>

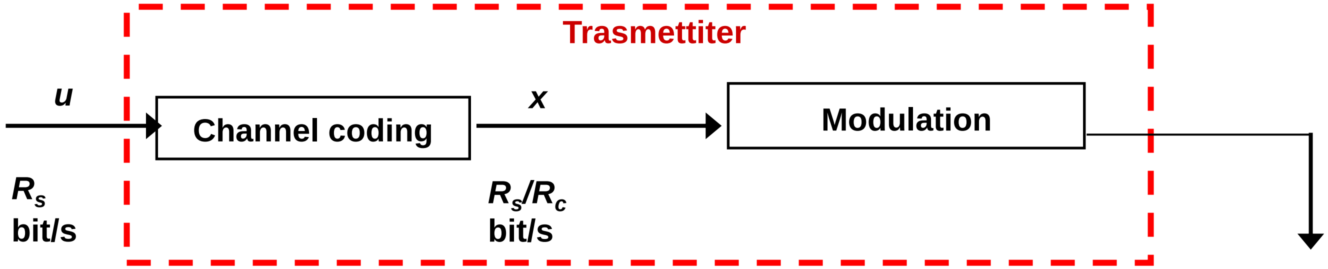
FREQUENCY SPECTRUM



Licenced frequency: they are **licensed** by authorities (FCC, ITU etc.) to certain users, who might pay a licensing fee for the exclusive right to transmit on an assigned frequency within a certain geographical area. Those users can be assured that nothing will interfere with their transmission.

Unlicenced frequencies:. they can be used without getting permission

DIGITAL COMMUNICATION SYSTEM
Transmitter



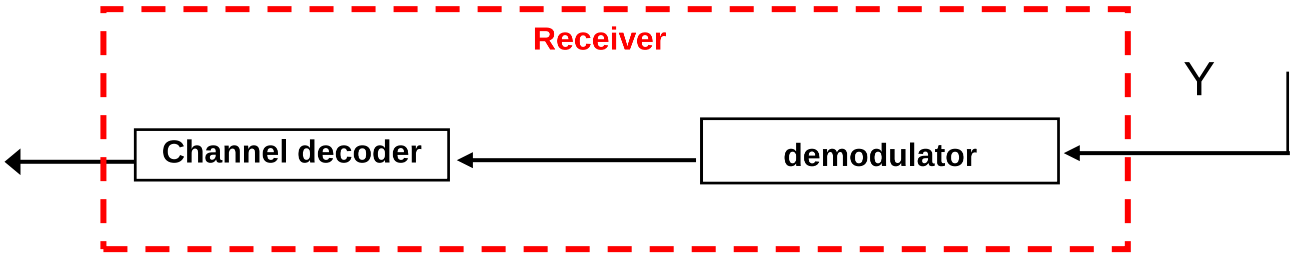
Transmitter

The transmitter has the objective to transform the input signal (which is digital in a DCS) in a signal that is adapted to be transmitted over a specific physical medium (fiber, cable, wireless).
This "adaptation" is performed by the **MODULATION**.
However, the transmitter also includes other blocks to make the transmission over the channel, such as the **channel coding**
The transmitter performs a mapping from the message set A to the signal set S

with
$$S = \{s_0, s_1, \ldots\ldots, s_{m-1}\}$$

s_i are in general complex number REPRESENTING real waveforms

DIGITAL COMMUNICATION SYSTEM
Receiver



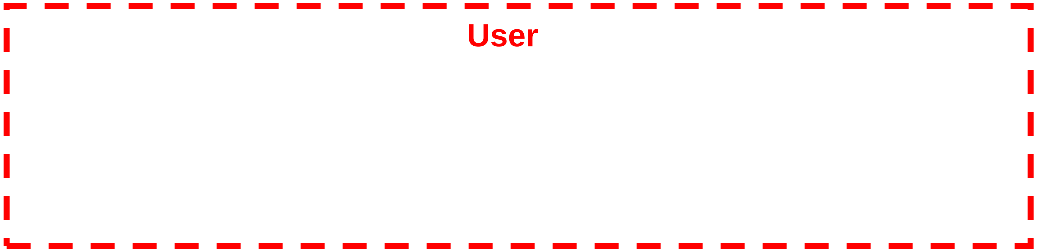
Receiver

The receiver's task is to “guess“ a (random variable) from Y . The decision made by the receiver is denoted by $\hat{a}$.

Unless specified otherwise, the receiver will always be designed to minimize the probability of error defined as the probability that $a \neq \hat{a}$.

Guessing a from Y when a is a discrete random variable is the so-called **hypothesis testing problem** that comes up in various contexts (not only in communications).

DIGITAL COMMUNICATION SYSTEM
User



<u>User</u>

The objective of the receiver is to re-generate the original signal, with an "acceptable" quality degradation.

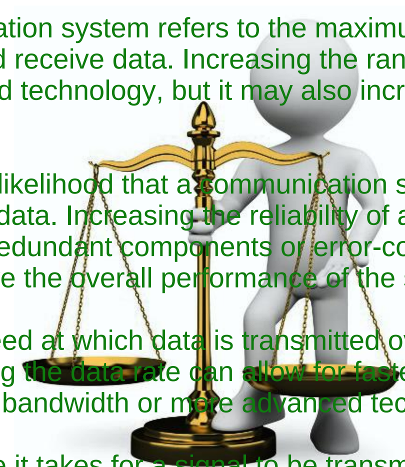
What means "acceptable" depends from the user, i.e. type of signal (voice or data), specific applications (listening music or just understanding a dialog)

*How to measure the quality degradation depends from the communication system? In other words, what the **performance metrics**?*

DIGITAL COMMUNICATION SYSTEM

Requirements of a DCS

- Range (m)
- Reliability
- Data Rate (bps)
- Latency (s)
- Power Consumption
- Security and Privacy



Range: The range of a communication system refers to the maximum distance over which the system can transmit and receive data. Increasing the range may require more power and/or more advanced technology, but it may also increase the cost and complexity of the system.

Reliability: Reliability refers to the likelihood that a communication system will successfully transmit and receive data. Increasing the reliability of a system may require more resources, such as redundant components or error-correction techniques, but it may also improve the overall performance of the system.

Data rate: The data rate is the speed at which data is transmitted over a communication channel. Increasing the data rate can allow for faster transmission of data, but it may also require more bandwidth or more advanced technology.

Latency: Latency refers to the time it takes for a signal to be transmitted from the sender to the receiver. Reducing latency may require more advanced technology or more efficient communication protocols, but it can also improve the performance of the system.

Tradeoff

Power consumption: The power required to transmit a signal can impact the range and reliability of the communication system. Reducing power consumption may improve the efficiency of the system, but it may also limit the range and performance of the system.

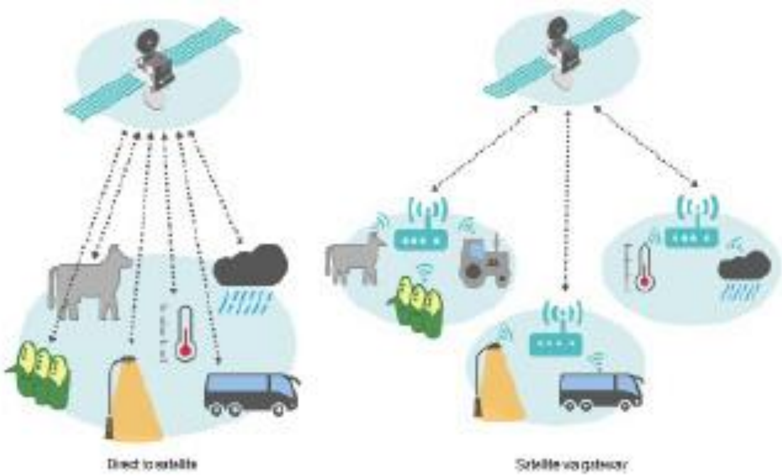
Security and privacy: Ensuring the security and privacy of a communication system can protect against unauthorized access or tampering with the data. However, implementing security measures can also increase the complexity and cost of the system.

Balancing these tradeoffs can be a complex task, and the optimal solution will depend on the specific requirements and constraints of the system.

DIGITAL COMMUNICATION SYSTEM

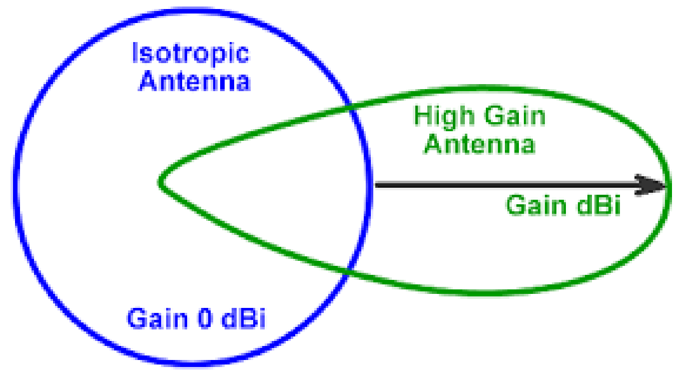
Range

Centimeter distance



Thousands kilometers distance

Range



P_{tx} transmit power (W)
P_{rx} receive power (W)
$\boldsymbol{r}$ range
f carrier frequency
c light speed
RX_sensitivity receiver sensitivity
g_{tx} transmit antenna gain
g_{rx} receive antenna gain

1/free space loss

$$P_{rx} = P_{tx}\, g_{tx}\, g_{rx} \left(\frac{\lambda}{4\pi r}\right)^2 = P_{tx}\, g_{tx}\, g_{rx} \left(\frac{c}{4\pi r f}\right)^2 > RX\_sensitivity$$

The range is a function of the transmit power, frequency, antenna gains, receiver's sensitivity
But also LOS or NLOS, presence of abstacles/atmospheric precipitation

Range

- Range

P_{tx}		= 100mW
f		2.4GHz
c		$3 \cdot 10^3$
$RX\_sensitivity$		10µW
g_{tx}	1	
g_{rx}	1	

Range = (Ptx * Gtx * Grx) / (4 * pi * f * C * RX_sensitivity)

Range = (100mW * 1 * 1) / (4 * pi * 2.4GHz * 3 * 103 * 10mW)

Range of 10meters

Reliability

❑Reliability is usually expressed in terms of minimum:

- **Signal-to-Noise Ratio (SNR)** for analog systems
- **Bit Error Rate/Packet Error Rate (BER/PER)** for digital systems (which also depends from the SNR, and the dependance is related to the specific modulation/coding etc.)

that are needed to get the desired Quality of Service

In Analog systems, the receiver must deal with an infinite number of waveforms and the figure of merit is a fidelity criterioon, such as signal-to-noise ratio, percent of distorsion, or expected mean-square error between the transmitted and received waveforms

In Digital systems, the set of transmitted waveforms is finite and knows a priori and a figure of merit is the probability of incorrectly detecting a digit, or probability of error PE

Note: Even if no other impairments are present, the **channel is noisy** (thermal noise is always there)

Reliability

- Examples of requirements

Communication service	BER requirement
Voice service	10(-3)
Video Broadcasting	10(-10)
Data Communications	10(-13) «error free»

Reliability

- Reliability can also be expressed in terms of outage probability, i.e. the probability that SNR is lower than a threshold:

$$P_{outage} = P(SNR < SNR_{tr})$$

or in terms of percentage of time in which $(SNR > SNR_{tr})$

For instance, in case of 5G Ultra Reliable Low Latency Communications (URLLC) in 5G a reliability of 99.999% is required

DATA RATE

- Usually expressed in bit/seconds (bps), it related to how much information I can transfer in the unit time.

Capacity of a channel

$$C = B\log_2\left(1+\frac{P}{N}\right) = B\log_2\left(1+\frac{E_b R}{N_0 B}\right) \quad \text{(bit/s)}$$

B Channel bandwidth in Hertz

P Signal power

$N = N_0 B$ Noise power

E_b = Energy per bit

N_0 = power spectral density of the thermal noise

R = data rate (bit/s)

<u>Maximum data rate for reliable transmission over the noisy channel</u>

$$\boxed{R<C}$$

DATA RATE

.

- Let us calculate the capacity C of a Gaussian channel with bandwidth B = 2500 Hz e SNR=30 dB

<u>*Solution:*</u> $B = 2500$ and $P/N_0B = 10^3$ by applying the formula:

C = B * log2(1 + SNR)

$C = 24918$ bps around 25 kbps

11875 bps

How much is the channel capacity of the power is double?

C= 27,416 kbps a little bit higher than 27kbps

C = 2500 Hz * log2(1 + 60 dB)

= 12500 bps

What about is the bandwidth is double?

C= 49836 bps about 50kbps

C = 5000 Hz * log2(1 + 30 dB)

= 23750 bps

DATA RATE

.

- ❑ Increasing the bandwidth is the more efficienct way to increase the channel capacity or to reduce the transmit power

In GSM the bandwidth per channel is 200kHz, in UMTS is 5MHz
In LTE is 20MHz and it can arrive to 100MHz with carrier aggregation

Nevertheless, the bandwidth availability it limited!

Power Consumption

- ❑ Power consumption must be kept low in several scenarios.
- ❑ For instance, in case of an Internet of Thingd scenario:

1) Sensors cannot be recharged or replaced often (sensors in remote areas, implanted sensors etc.)
2) Batteries must be small (e.g., wearable devices, coins-size sensors) or even not existing (energy harvesting solutions)

The required lifetime of sensors could be of years……

Latency

- The **latency** of a **communications** network is **defined** as the time needed to transport information from a sender to a receiver.
It is related to the propagation delay (e.g., in case of geostationary satellite the one-way propagation delay is 250ms)
BUT it does NOT depend only from the propagation delay but also from the communication protocol.

For instance, if the propagation is bad, I might need many retransmissions before receiving the data correctly and this increases the latency.

*5G Ultra-Reliable Low Latency Communication (URLLC) needs to support latencies as low as **5ms***

DIGITAL COMMUNICATION SYSTEM

summary

Classification of signals (analog, digital, quantized, energy, power, deterministic, random)
Importance of theoretical studies
Basic scheme of a DCS
Why Digital?
Source encoder
What do we mean for channel in this course?
Performance metrics and tradeoffs

Syllabus

- ❑Introduction (1 week)
- ❑Signal, random processes and spectra (1 week)
- ❑Channel and noise: (1 week)
- ❑Transmission system and overview on analog modulation (1 week)
- ❑Complex Representation of bandpass signals (1week)
- ❑Analog to digital conversion (1 week)
- ❑Pulse modulation (1 week)
- ❑Digital transmission through baseband channels (2 weeks)
- ❑Signal space representation (1 week)
- ❑Optimal receivers (2 weeks)
- ❑Digital modulation techniques (2 weeks)

Lab exercises with the URSP platform