

# TAF STAR – TAF OPE

## UE Cœur 1 (CPC & PCPO)

Cours 1

*Physical channels of  
propagation: introduction*

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Département Optique

Septembre 2023

- Historical approach to (physical) communications
- Communication media and channels
- Signal and information

# Structure de l'UE « CPC » (Canaux Physiques de Propagation)

- Fiche UE consultable sur l'intranet (via l'application PASS)
- Page Moodle : <https://moodle.imt-atlantique.fr/course/view.php?id=450>
- Volume horaire global (face-à-face) : 41h + 1h15 examen
- Equipe pédagogique :
  - ▶ Département Optique : B. Fracasso, K. Heggarty, M.-L. Moulinard, L. Anet Neto
  - ▶ Département Micro-Ondes : F. Le Pennec, F. Gallée, P. Pajusco
  - ▶ Département Mathematics and Electrical Engineering : C. Laot
  - ▶ Département Image et traitement de l'information : F. Maussang

# Historical approach to communications



« On ne connaît pas complètement une science tant qu'on n'en sait pas l'histoire ».

Cours de philosophie positive, Auguste Comte (1798-1857).

*"You don't know a science completely until you know its history"*

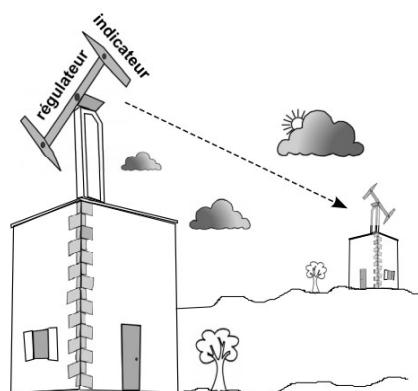
- 1. Birth of telecommunications**
- 2. The emergence of radio communications**
- 3. Sources of information**
- 4. Transmission media**
- 5. From telecommunications to networks**

# « Birth » of telecommunication

## The origins

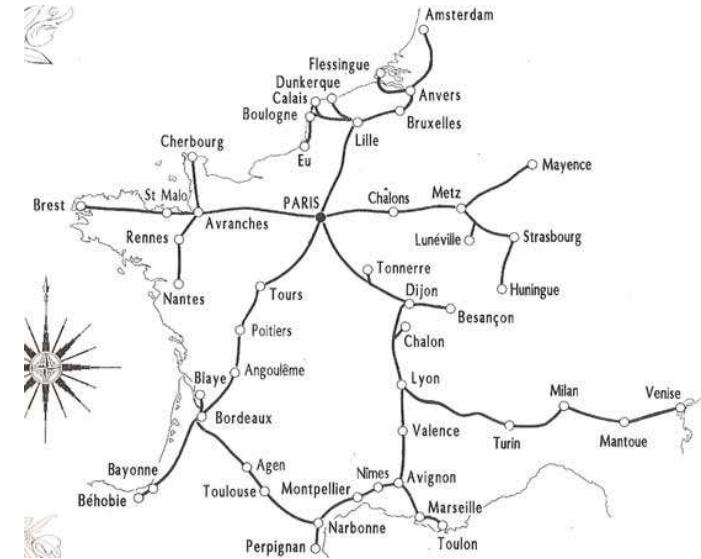
- ▶ **Acoustic signals:** shouts, whistles, bells, horns
- ▶ **Optical signals:** flames, smoke, lighthouses

## Chappe's optical telegraphy (1792-1850)



Extrait du vocabulaire - Télégraphe Chappe Page 50

|                       |              |                   |
|-----------------------|--------------|-------------------|
| 1 Absenter            | Enrôlé       | HUDSON (baie)     |
| 2 Astif               | Équivalent   | HUDSON (déroit)   |
| 3 Age                 | Ettoffe      | Huée              |
| 4 Antipathie          | Sur eux      | Huer              |
| 5 Assesseur           | Extorqué     | HUESCA            |
| 6 Aumône              | Félicitation | HULST             |
| 7 Après avoir         | Fois         | HONDURAS          |
| 8 Baisse              | Friche (en)  | Hune              |
| 9 Bénéficier          | Général      | Hunier            |
| 10 Bouclier           | GRAVELINES   | HUMINGE           |
| 11 Buisson            | HESSERS      | HUMMINGUE (pont)  |
| 12 Céravane           | HIESCA       | HUNTINGTON        |
| 13 Avec celui         | HILDELSHEIM  | HURON             |
| 14 Chargement         | Historien    | Hussard           |
| 15 Civiliser          | Hivernage    | Escadron          |
| 16 Commodité          | HOCHSTET     | Hydraulique       |
| 17 Conduire           | HOGUE (Cap)  | Hymne             |
| 18 Conternation       | Hollandais   | Hypocrisie        |
| 19 Conviction         | Hollande     | Hypothèque        |
| 20 Craintre           | HOLSTEIN     | Idée              |
| 21 Débaucher          | Honfleur     | Identifier        |
| 22 Défense            | Hongrie      | Identité          |
| 23 Démontez           | Hopinois     | échapper          |
| 24 Devenir            | Horaire      | échapper          |
| 25 Domine             | HORN (Cap)   | Idiotie           |
| 26 Domination         | Hortel       | Idle              |
| 27 Donner une idée de | Hospice      | Ignorance         |
| 28 Echouer            | Hottentots   | Ignorant          |
| 29 Electriser         | HOTWIEL      | Ignoré            |
| 30 Empoisonnement     | HOUNDEL (le) | IGNORER           |
|                       |              | ILANTE            |
|                       |              | ILDEFONSE (Saint) |



- ▶ 5000 km of line
- ▶ 534 stations
- ▶ 29 major cities
- ▶ 700 km travelled in 20 minutes
- ▶ Alphabet:  $2 \times 7 \times 7 = 98$  messages

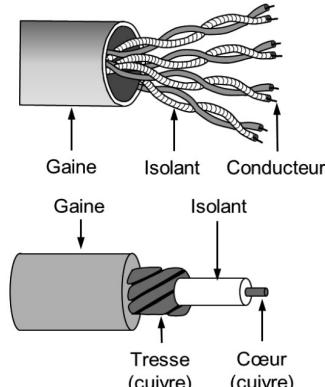
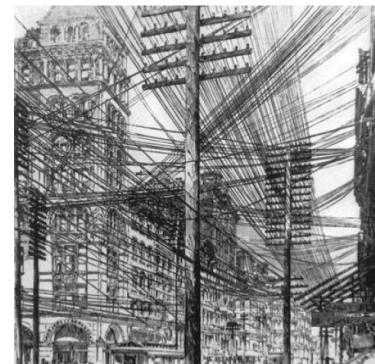
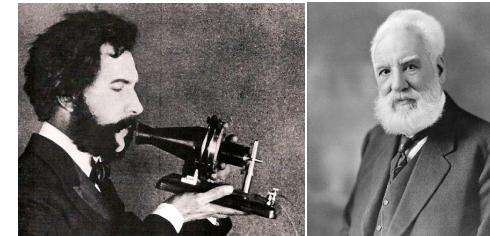
# Development of the electric telegraph

- **1820** : Oersted (DK) and Ampère (F): first remote transmission (magnetic field created by a current and action of a magnetic field on a wire)
- **1831** : Faraday (UK) discovers induction currents in a conductor
- **1833** : Gauss and Weber (D) demonstrate the first 10 km needle telegraph
- **1835-1840** : Morse (USA) Cooke and Wheatstone (UK): development of the first efficient telegraph ("20 words per minute")
- **1841** : Joule (UK) demonstrates resistive losses in a conductive material
- **1844** : First electric telegraph link between Baltimore and Washington, using the "Morse" code.
- **1848** : Von Siemens (D) develops the insulation of copper wires with a latex-based gum (called "Gutta-Percha")
- **1858** : Transatlantic link (by submarine cable) between Ireland and Newfoundland (100 words in 67 minutes, message from Queen Victoria to the American President)



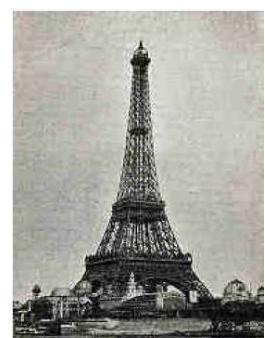
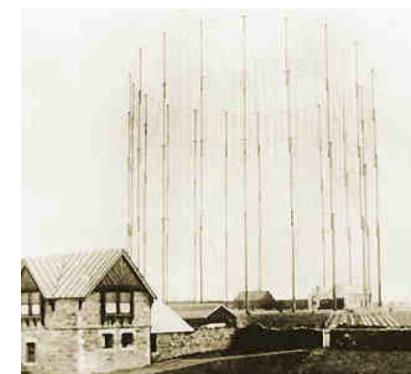
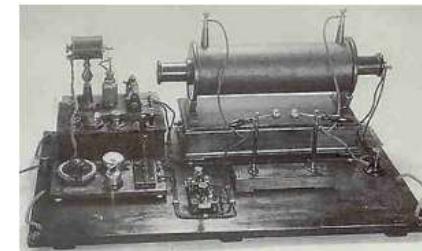
# The « talking » telegraph

- **1854** : Bourseul (F) demonstrates that the acoustic vibrations of the human voice can be transmitted in the same way as the telegraph. No one took him seriously... he had to wait until 1889 to be recognised.
- **1876** : Bell (USA) patented the invention of the telephone, which had been developed by one of his colleagues (Meucci (I)) shortly before ... Meucci was recognised as the "father" of the telephone in 2002
- **1880** : First telephone exchange (USA) and telephone lines
- **1890** : Heaviside (UK) models the distributed constant transmission line
- **1890-1900** : Kaup (DK) and Pupin (SB) propose line impedance matching to increase range (the so-called "Pupin coils")
- **1929** : First "regional" Paris-Bordeaux cable in 1929. Development of twisted pair telephone links
- **1931** : Patent of the coaxial cable by Haffel (USA), based on an idea launched in 1880 by Heaviside. Telephone links were developed on this physical medium until the 1960s



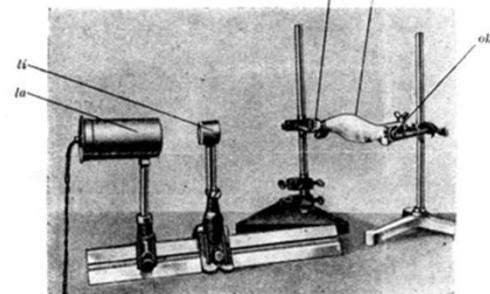
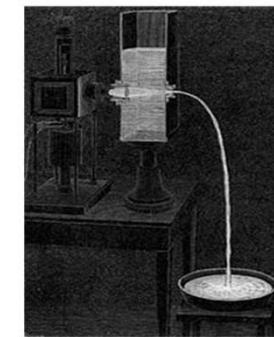
# Emerging of radio-communications

- **1860-1887:** Maxwell (UK) and Hertz (D) synthesise studies on electromagnetism and the propagation of electromagnetic waves
- **1890:** Branly (F) and Lodge (UK): filings coherer to detect waves
- **1896:** First antenna by Popov (R) to transmit and receive waves
- **1897:** Marconi makes the first radio transmission over 12km in Salisbury (UK) (telegraphic signal, TSF)
- **1901:** First transatlantic radio link by Marconi between southern England and Newfoundland (3400 km)
- **1906:** Lee de Forest (USA) invents the triode tube to amplify signals
- **1915:** Campbell (USA) invents the electrical "filter"
- **1917:** Levy (F) and Armstrong (USA) develop the "super-heterodyne" radio reception
- **1925:** Marconi makes the first intercontinental radio communication (shortwave)
- **1926:** Yagi and Uda (JP) invent the "rake" antenna
- **1924-39:** Development of high power RF sources
- **1940-50:** Development of radar, microwave and radio navigation



# Fibre optic transmission (1/3)

- **Ancient Greece:** transport of light in glass cylinders
- **Italian Renaissance:** "millefiori" of Venetian craftsmen
- **1854:** John Tyndall's light fountain
- **1880:** Alexander G. Bell's photophone
- **1888:** Roth and Reuss use glass tubes to illuminate the human body
- **1926:** Hansell transmits images and faxes with glass or plastic fibres
- **1930:** Lamm transmits the image of a light bulb filament in a bundle of quartz fibres
- **1954.** Van Heel (NL) proposes the first optical fibre, with a core (index  $n_c$ ) and a cladding of index  $n_g < n_c$ .
- **1957:** Cutiss and Hirschowitz develop the endoscope



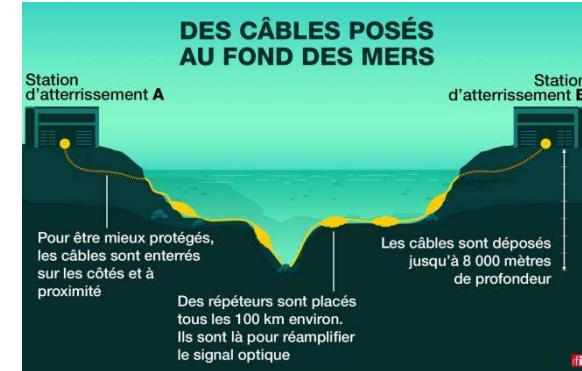
# Fibre optic transmission (2/3)

- **1960** : Invention of the laser by Maiman (US) with a ruby crystal. Optical fibres have losses of 100 dB/km
- **1966** : Kao (UK/US) predicts that the combination of single-mode optical fibre and laser will be the basis for very long distance and very high speed communications (Nobel Prize in Physics 2009)
- **1970** : First "single mode" optical fibre developed by Corning: losses of 17 dB/km
- **1975** : First telecommunications system on optical fibre by British Telecom.
- **1982** : Achievement of single mode optical fibre with minimum losses of 0.2 dB/km at  $\lambda = 1.55 \mu\text{m}$
- **1987** : Payne (UK), Désurvires (F) and Giles (USA) invent the fibre optic amplifier (5000 GHz bandwidth!)
- **1990** : Beginning of the worldwide deployment of optical fibre, which will allow the construction of the Internet.



# Fibre optic transmission (3/3)

- **1956** : TAT-1 is the first electric submarine "telephone" cable: 36 circuits (2.3 Mbit/s) over 3700 km
- **1988** : First transatlantic fibre optic submarine cable (TAT-8): 40,000 telephone circuits (2.5 Gbit/s), but the amplification is electrical...
- **1996** : TAT-12 incorporates optical amplification technology for the first time and carries 60 Gbit/s
- **2000** : The world's longest optical cable (Se-Me-We-3) is put into service: 39,000 km long
- **2001** : TAT-14 carries 50 million circuits (3.2 Tbit/s) over 15,000 km
- **2018** : Marea cable between Virginia Beach and Bilbao (6600 km): financed by Microsoft & Facebook, 160 Tbit/s over 8 pairs of fibres (71 million streaming videos in parallel).
- **In total** : more than one billion km of fibre deployed on earth (25,000 times around the earth)



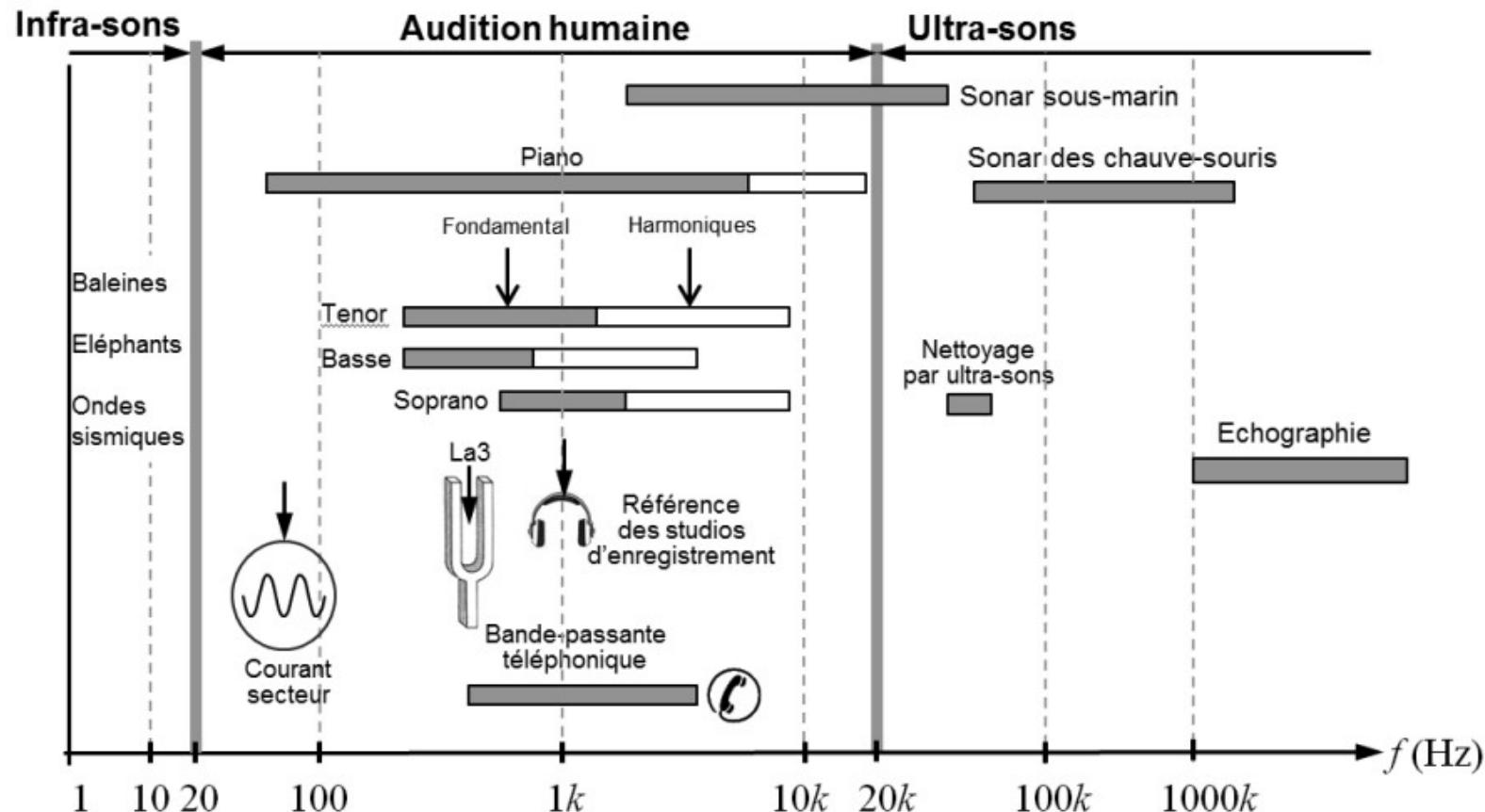
# Main physical transmission media



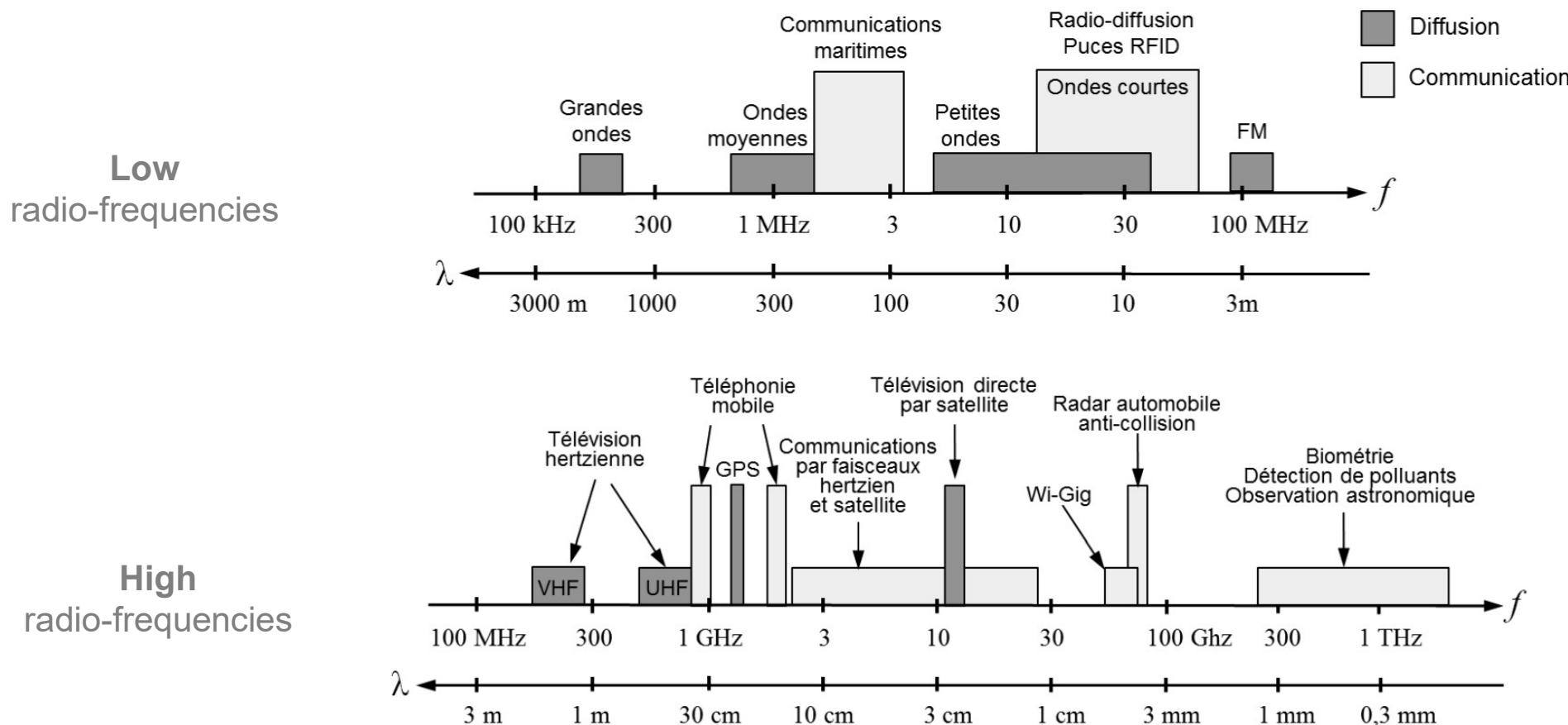
| Support                     | Câble symétrique | Câble coaxial    | Fibre monomode      | Ondes radio  |
|-----------------------------|------------------|------------------|---------------------|--|
| <b>Propagation</b>          | guidée           | guidée           | guidée              | libre  |
| <b>Matériaux</b>            | métal (Cu)       | métal (Cu)       | silice              | Air  |
| <b>Bande-passante (Hz)</b>  | $10^5 - 10^6$    | $10^8$           | $10^{12}$           | $10^9$   |
| <b>Atténuation</b>          | 20 dB/km (1 MHz) | 20 dB/km (1 GHz) | 0,2 dB/km (193 THz) | $AEL = 20 \log_{10} \left( \frac{4\pi d}{\lambda} \right)$ |
| <b>Sensibilité au bruit</b> | forte            | faible           | nulle               | forte  |
| <b>Confidentialité</b>      | limitée          | correcte         | élevée              | nulle  |
| <b>Coût support</b>         | faible           | élevé            | modéré              | nul  |
| <b>Coût interfaces</b>      | très faible      | faible           | élevé               | assez faible   |
| <b>Applications</b>         | téléphone        | réseaux locaux   | très haut débit     | mobiles, satellites  |

+ Acoustic channels ...

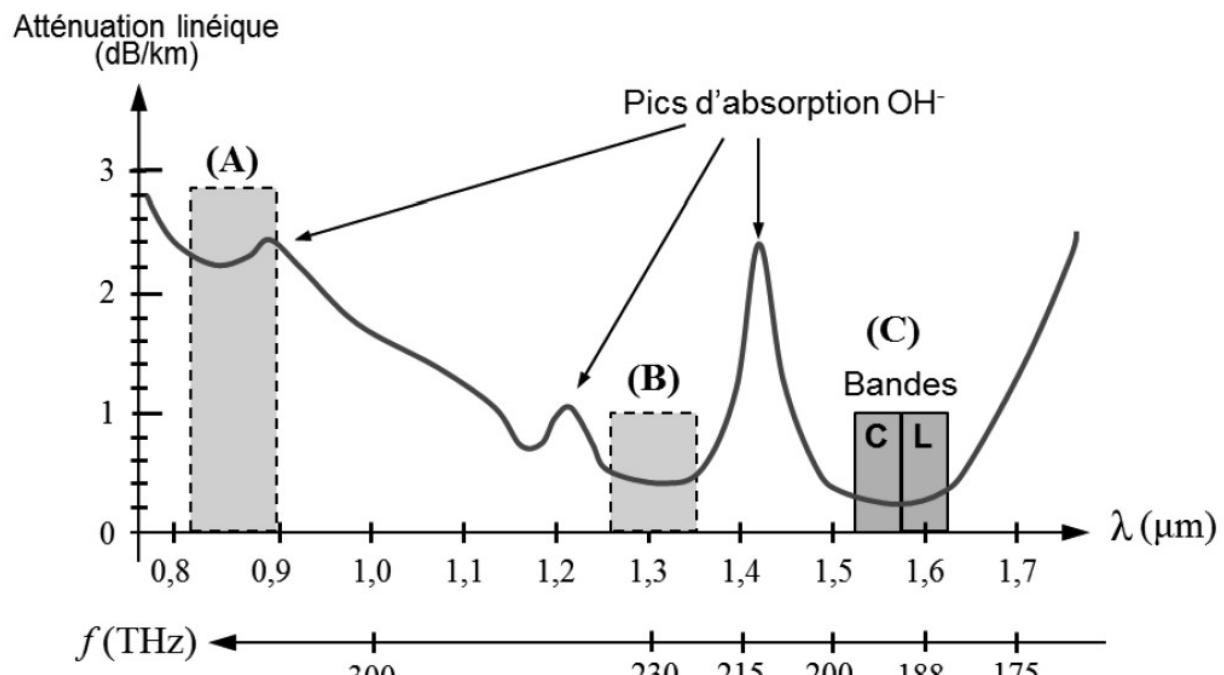
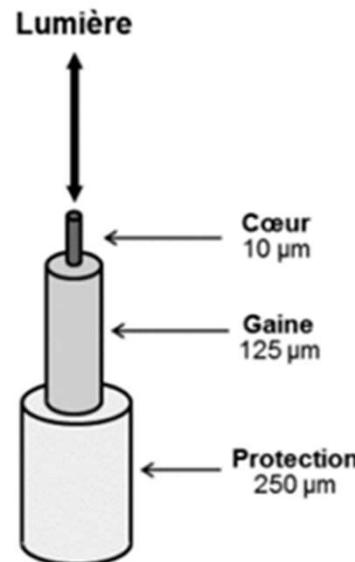
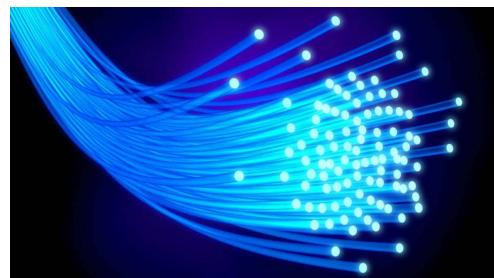
# Acoustic channel: carrier frequencies



# Electromagnetic channel: carrier frequencies



# Optical (fibre) channel: carrier frequencies



$$\Delta f = -c \frac{\Delta \lambda}{\lambda^2}$$

$$|\Delta f| = 3 \cdot 10^8 \cdot \frac{(1.6 - 1.5)10^{-6}}{(1.5 \cdot 10^{-6})^2} = 12500 \text{ GHz}$$

# Different information sources (non-exhaustive list ...)

- **Geophysical sources:** temperature, pressure, velocity, meteorology, seismic
- **Space sources:** cosmic images, space probes
- **Tracking sources:** radar, sonar, lidar
- **Biological sources:** X-ray imaging, MRI, ultrasound, electrocardiogram, electroencephalogram, electromyogram, electro-oculogram
- **Structural sources:** vibration diagnosis of a bridge, a vehicle, a building, a moving structure
- **Telecommunications sources:** data, speech, music, image and video signals transmitted in a communications channel
- **Sources of inter-personal exchanges:** speech, writing, gestures, physiognomy, interpreted by the brain (very complex signals)

# Physical quantities and units

## ■ Definition

- ▶ **Physical quantity** (Wikipedia): any property of nature that can be quantified by measurement or calculation, and whose various possible values are expressed using a real or complex number generally accompanied by a unit of measurement
- ▶ **With unit** (length, mass) or **without unit** (angle, refractive index)
- ▶ Relationships between physical quantities :

$$F = m\gamma \quad q(t) = C \frac{dv(t)}{dt}$$

$$v_s(t) = \int_{-\infty}^{+\infty} v_e(u) h(t-u) du$$

## ■ Main quantities

| Grandeur            | Unité           | Symb. dimens. |
|---------------------|-----------------|---------------|
| Longueur            | mètre (m)       | $L$           |
| Masse               | kilogramme (kg) | $M$           |
| Quantité de matière | mole (mol)      | $N$           |
| Temps               | seconde (s)     | $T$           |
| Intensité lumineuse | candela (cd)    | $J$           |
| Température         | kelvin (K)      | $\Theta$      |
| Courant électrique  | ampère (A)      | $I$           |

The 7 quantities of the International system  
(S.I.)



| Grandeurs                   | Nom de l'unité | Symboles | Equivalent S.I.                |
|-----------------------------|----------------|----------|--------------------------------|
| Force                       | newton         | N        | $m \ kg \ s^{-2}$              |
| Pression                    | pascal         | Pa       | $m^{-1} \ kg \ s^{-2}$         |
| Energie                     | joule          | J        | $m^2 \ kg \ s^{-2}$            |
| Puissance                   | watt           | W        | $m^2 \ kg \ s^{-3}$            |
| Fréquence                   | hertz          | Hz       | $s^{-1}$                       |
| Charge électrique           | coulomb        | C        | As                             |
| Résistance électrique       | ohm            | $\Omega$ | $kg \ s^{-3} \ A^{-3}$         |
| Potentiel électrique        | volt           | V        | $m^2 \ kg \ s^{-3} \ A^{-1}$   |
| Capacité électrique         | farad          | F        | $m^{-2} \ kg^{-1} \ s^4 \ A^2$ |
| Densité de champ magnétique | tesla          | T        | $kg \ s^{-2} \ A^{-1}$         |
| Radioactivité               | becquerel      | Bq       | $s^{-1}$                       |

Some derived quantities

# Fundamental constants

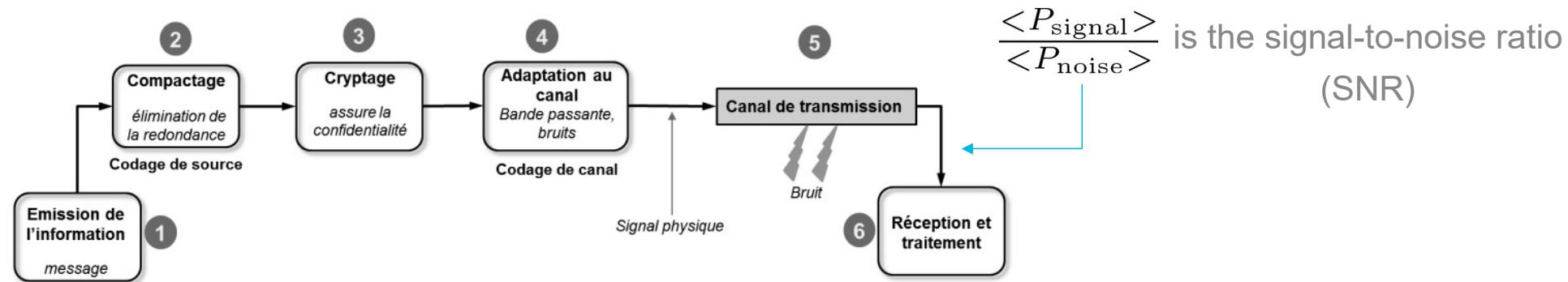
Widely used  
in this teaching unit

| Nom                               | Variable     | Valeur                   | Unité                             |
|-----------------------------------|--------------|--------------------------|-----------------------------------|
| Constante d'Avogadro              | $N$          | $6,022 \cdot 10^{23}$    | $\text{mol}^{-1}$                 |
| Charge élémentaire de l'électron  | $e$          | $1,6 \cdot 10^{-19}$     | C                                 |
| Vitesse de la lumière (vide)      | $c$          | $2,99792458 \cdot 10^8$  | $\text{ms}^{-1}$                  |
| Constante de gravitation          | $G$          | $6,67 \cdot 10^{-11}$    | $\text{N m}^2 \text{kg}^{-2}$     |
| Constante de Boltzmann            | $k$          | $1,38 \cdot 10^{-23}$    | $\text{J K}^{-1}$                 |
| Constante de Planck               | $h$          | $6,63 \cdot 10^{-34}$    | Js                                |
| Permittivité diélectrique du vide | $\epsilon_0$ | $8,85 \cdot 10^{-12}$    | $\text{F m}^{-1}$                 |
| Perméabilité magnétique du vide   | $\mu_0$      | $4\pi \cdot 10^{-7}$     | $\text{H m}^{-1}$                 |
| Masse de l'électron               | $m_e$        | $9,10938 \cdot 10^{-31}$ | kg                                |
| Masse du proton                   | $m_p$        | $1,67262 \cdot 10^{-27}$ | kg                                |
| Masse du neutron                  | $m_n$        | $1,67493 \cdot 10^{-27}$ | kg                                |
| Constante des gaz parfaits        | $R_0$        | 8,314462                 | $\text{J K}^{-1} \text{mol}^{-1}$ |

# Information transmission

## ■ Simplified chain (detailed in UE Coeur “digital communications”)

- ▶ Messages are transmitted from a source to a destination



- ▶ Messages containing  $k$  symbols in an alphabet with  $n$  éléments ( $n^k$  symbols in total)
- ▶ Equiprobable messages : amount of information  $I = k \log_2(n)$  (Hartley, 1928)
- ▶ If  $P_i$  is the probability of message  $M_i$ , then  $I(M_i) = -\log_2(P_i)$  (Shannon, 1948)
- ▶ Entropy of a repetitive and stationary source :  $H_S = -\sum_{i=1}^N P_i \cdot \log_2(P_i)$

# Capacity of a communication channel

- **Information rate:** number of elementary messages flowing in the communications channel per unit of time
- **Capacity of a communications channel:** maximum information rate that a communications channel can carry
- **Intuitive (but false) approach:** capacity is proportional to the bandwidth  $B$  (in Hz) of the transmission channel  
→ "the bigger the pipe, the more information it can transmit in a given time" :

$$C = \alpha B \quad \text{with} \quad \alpha = \text{cst}$$

- The capacity of a channel, as defined by Shannon (1948), for a source delivering a message in the form of a sequence of binary symbols (bits):

$$C = B \log_2 \left( 1 + \frac{\langle P_{\text{signal}} \rangle}{\langle P_{\text{noise}} \rangle} \right) \quad \rightarrow \text{in bit/s} \quad \frac{\langle P_{\text{signal}} \rangle}{\langle P_{\text{noise}} \rangle} \quad \text{is the signal-to-noise ratio (SNR)}$$

- **Example :** « old » wired telephone - SNR = 50 dB,  $B = [300, 3400$  Hz]

►  $C = (3400 - 300) \log_2(10^5) = 51490 \text{ bit/s}$

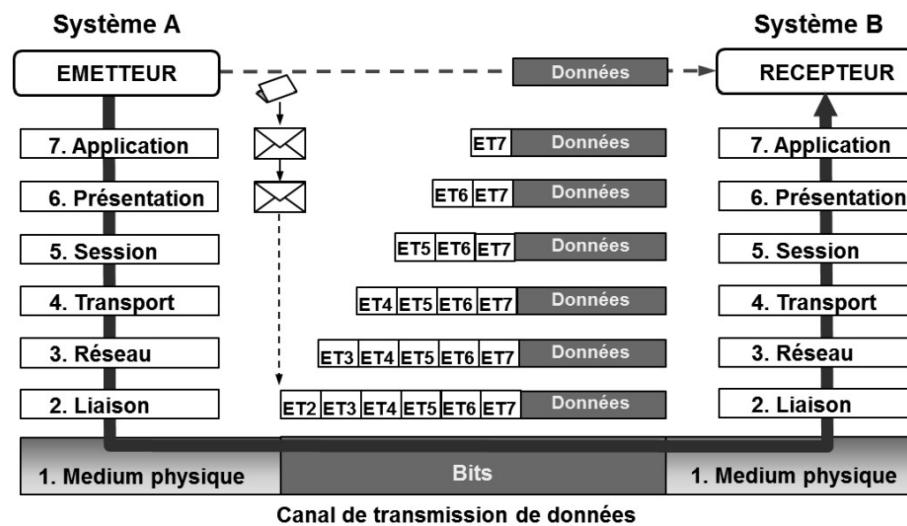
► **WARNING** : the more  $B$  increases, the more  $P_{\text{bruit}}^m$  increases, et the more  $C$  decreases !

# From point-to-point transmission ... to network

## ■ Different communication system types

- ▶ Point-to-point: cable, microwave link
- ▶ Broadcasting: satellite TV, fibre to the home
- ▶ Collection: oceanographic monitoring, micro-sensors
- ▶ Local area network: connected terminals communicating via nodes (Ethernet)

## ■ Layered network model (OSI, 1979)



# Compétences et résultats d'apprentissage visés

## ■ Compétences (CSDI/CST)

- ▶ **MATH2** : modélisation mathématique des transferts
- ▶ **PHY1** : intégration et dimensionnement des systèmes multi-physiques
- ▶ **PHY2** : modéliser un système physico-chimique multiéchelle
- ▶ **CST 1** : poser, analyser, reformuler, structurer
- ▶ **CST14** : concevoir, modéliser, simuler

## ■ Résultats d'apprentissage visés (RAV)

- ▶ Décrire par leurs **paramètres physiques** les principaux **milieux support des canaux de propagation**, et de manipuler les principaux modèles en exprimant la variabilité ;
- ▶ Manipuler les **modèles physiques des ondes porteuses** utilisées dans les canaux de propagation
- ▶ Décrire, modéliser et évaluer les **distorsions** impactant la **propagation** d'une **onde** dans les principaux canaux physiques (libre/guidé radio, libre/guidé optique, acoustique sous-marin)
- ▶ Choisir le canal de propagation le plus **adapté** (compromis performance/complexité) à un besoin donné en matière de lien de communication.
- ▶ Choisir, décrire et modéliser les **interfaces physiques** et briques de remises en forme (e.g. amplificateurs, filtres) les plus adaptées à la propagation dans un canal de transmission donné.
- ▶ Évaluer la qualité d'un **signal physique** transitant sur un canal de propagation donné et en déduire une estimation des performances du système de transmission supporté.

# Modes pédagogiques

## ■ Situations d'apprentissage

- ▶ Exposé magistral
- ▶ Travaux dirigés (en îlots)                      **îlot** = résolution de problèmes en groupe (de 4)
- ▶ Étude de cas (bureaux d'études en binômes, BE)
- ▶ Analyse de documents scientifiques (au cours des BE)

## ■ Evaluation

- ▶ QCM sur le cours en début de TD (10 mn)
- ▶ Bureau d'études
- ▶ Examen écrit individuel (QCM et exercices d'application du cours)

# Sequencing : lectures, tutorials, practical classes

| Code   | Date  | Horaire | Nature de l'activité  | Formateur                     | TAF     |
|--------|-------|---------|---|-------------------------------|---------|
| C1     | 01/10 | 09:30   | Introduction de l'UEC1 (Canaux physiques de propagation)              | B. Fracasso                   | ISC     |
| C2     | 01/10 | 11:00   | Rappels - pré requis - ondes porteuses                                | F. Le Pennec                  | ISC/OPE |
| C3     | 01/10 | 13:30   | Propriétés physiques des milieux                                      | K. Heggarty                   | ISC/OPE |
| C4     | 02/10 | 08:00   | Bruits physiques et rapport signal-sur-bruit                          | B. Fracasso                   | ISC+OPE |
| TD1    | 02/10 | 09:30   | <i>Bruit de grenade électronique</i>                                  | B. Fracasso – L. Dupont       | ISC+OPE |
| C5     | 02/10 | 11:00   | Interaction onde-milieu : filtrage des signaux physiques              | B. Fracasso                   | ISC+OPE |
| C6     | 08/10 | 09:30   | Supports de propagation guidée  | F. Gallée                     | ISC+OPE |
| C7     | 08/10 | 11:00   | Antennes : notions de base et mise en réseau                          | F. Gallée                     | ISC+OPE |
| TD2    | 08/10 | 13:30   | <i>Bilan de puissance sur les ondes communicantes (RF vs Optique)</i> | B. Fracasso                   | ISC     |
| TD3    | 09/10 | 11:00   | <i>Rayonnement, antennes résonantes, antennes à balayage</i>          | F. Gallée                     | ISC     |
| C8     | 15/10 | 09:30   | Propagation Radio-Fréquence (1/2)                                     | P. Pajusco                    | ISC     |
| C9     | 15/10 | 11:00   | Propagation Radio-Fréquence (2/2)                                     | P. Pajusco                    | ISC     |
| C10    | 16/10 | 13:30   | Canal optique guidé (fibre optique)                                   | K. Heggarty                   | ISC+OPE |
| C11    | 16/10 | 15:00   | Interfaces physiques en optique pour l'émission et la réception       | K. Heggarty                   | ISC+OPE |
| TD4    | 22/10 | 16:30   | <i>Limites de propagation dans une fibre optique</i>                  | B. Fracasso                   | ISC     |
| TD5    | 23/10 | 08:00   | <i>Interface physique optique - photoréception</i>                    | M. Morvan                     | ISC     |
| BE1    | 23/10 | 09:30   | <i>Propagation RF (multi-trajets)</i>                                 | P. Pajusco – F. Le Pennec     | ISC     |
| BE2    | 04/11 | 08:00   | Dimensionnement d'une liaison optique WDM                             | M.-L. Moulinard – B. Fracasso | ISC     |
| TP1    | 12/11 | 15:00   | Simulation d'un lien optique multicolore (Couplé avec BE)             | M.-L. Moulinard – B. Fracasso | ISC     |
| C12    | 19/11 | 13:30   | Communications optiques en espace libre                               | B. Fracasso                   | ISC     |
| TD6    | 19/11 | 15:00   | <i>Liaisons laser terre-lune/satellite</i>                            | B. Fracasso                   | ISC     |
| C13    | 20/11 | 13:30   | Propagation acoustique (1/2)  | C. Sintes                     | ISC+OPE |
| C14    | 20/11 | 15:00   | Propagation acoustique (2/2)  | C. Sintes                     | ISC+OPE |
| TD7    | 25/11 | 08:00   | <i>Propagation acoustique : approche rayon</i>                        | C. Sintes + F Maussang        | ISC+OPE |
| TD8    | 25/11 | 09:30   | <i>Propagation acoustique : approche modale</i>                       | C. Sintes + F. Maussang       | ISC+OPE |
| TD9    | 26/11 | 13:00   | <i>Liaison optique LiFi</i>   | B. Fracasso                   | ISC     |
| BE3    | 03/12 | 15:00   | <i>Téléphone acoustique sous-marin</i>                                | C. Laot                       | ISC     |
| Examen | 10/12 | 09:30   | Contrôle de l'UE (1h15)   | Equipe pédagogique UE         | ISC     |

# Prochain(s) cours

- Rappels sur les ondes porteuses guidées et libres
- Propriétés physiques des milieux (généralités)
- Une première approche du bruit physique en communications (dans cette UE)
- Les bases théoriques du bruit dans l'UE Cœur 2 « Communications numériques » : les processus aléatoires.