Overview on Cellular and IoT Networks

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TRENDS

33.9 Billion

Connected devices by 2024

8.9 Billion

MBB SUBSCRIPTIONS by 2024

17.8 Billion

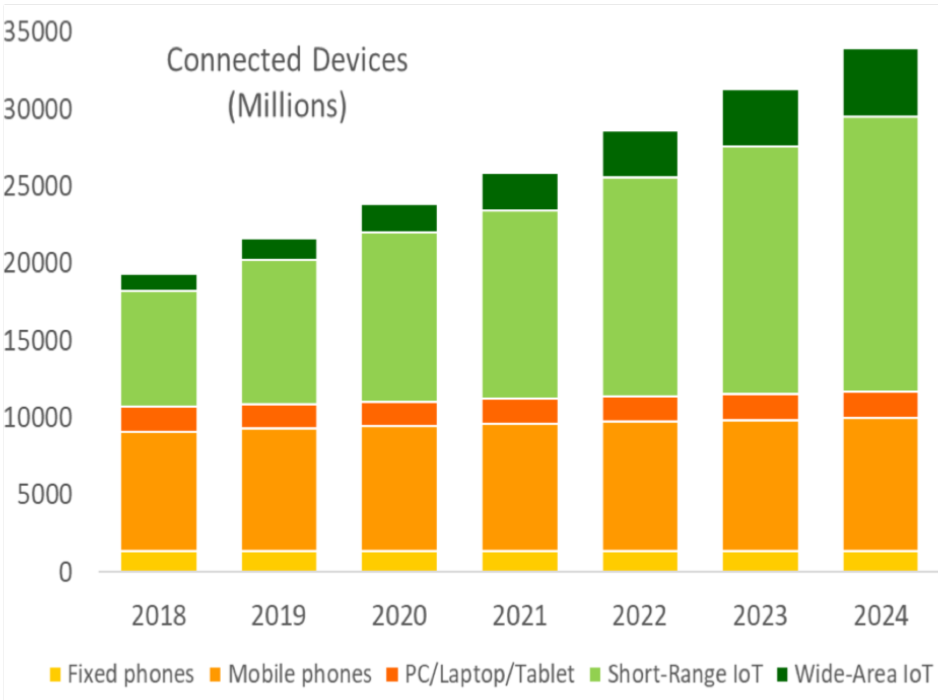
Non Cellular IoT devices by 2024

4.5 Billion

Cellular IoT devices by 2024

Source: Ericsson Mobility Report, June 2017

Market Evolution



	2018	2024	CAGR
Wide-area IoT	1.1	4.5	26.7%
Short-range IoT	7.5	17.8	15.4%
PC/laptop/tablet	1.6	1.7	1.2%
Mobile phones	7.7	8.6	1.8%
Fixed phones	1.4	1.3	-0.4%
	19.3 Billion	33.9 Billion	

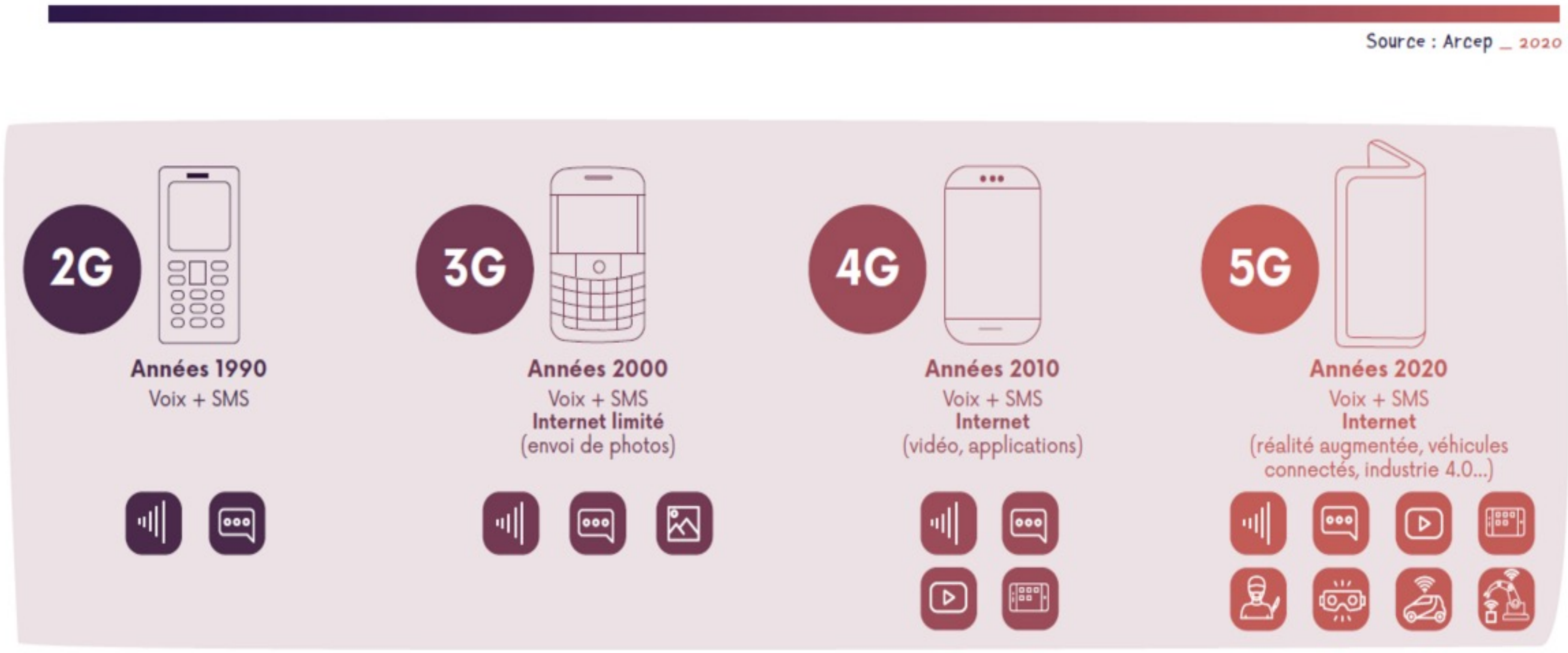
[Ericsson Mobility report, 2019]

Mobile Network History

1973

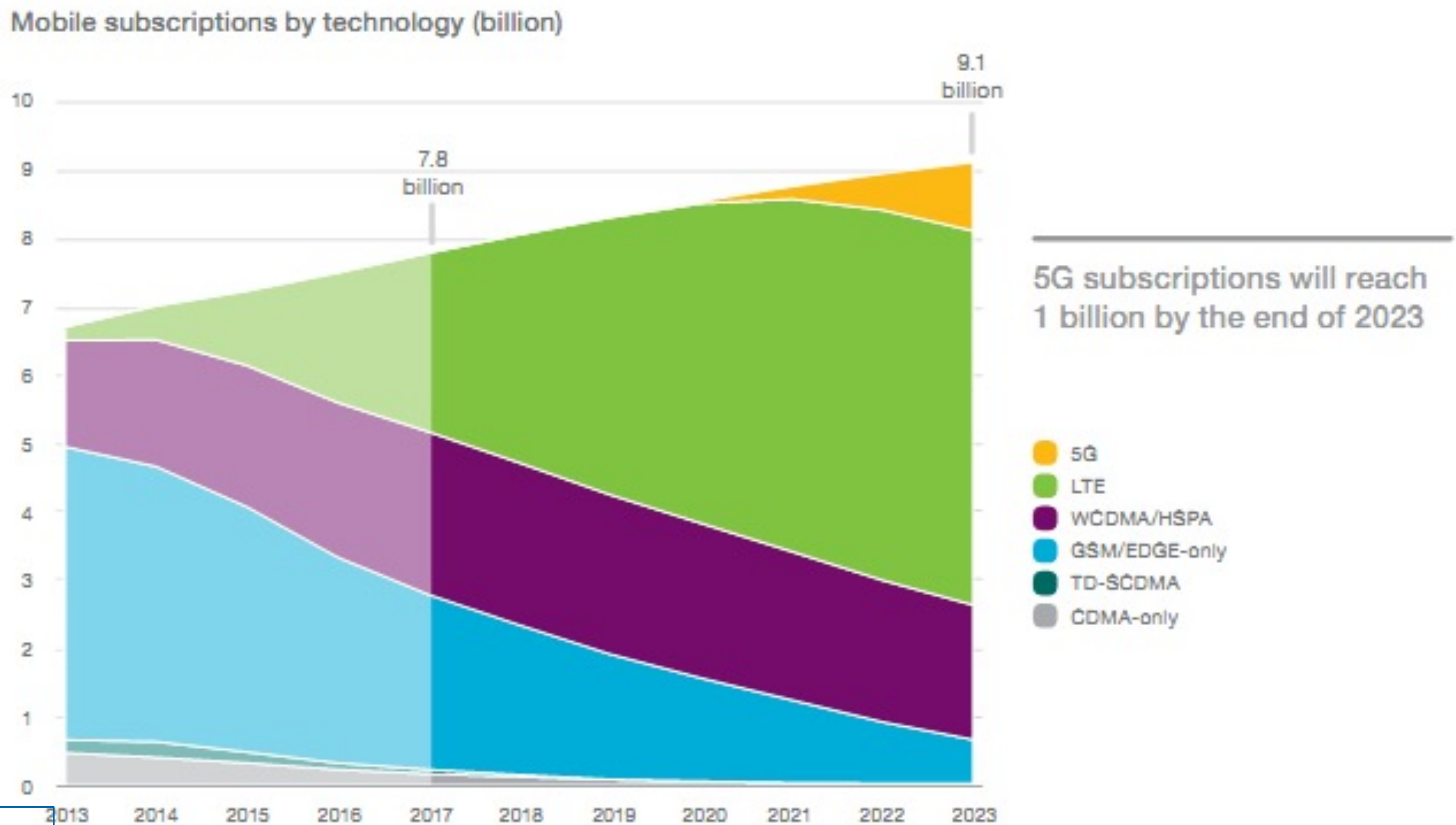
Motorola engineer Martin Cooper makes the first call from a "cell" phone in New York, a prototype DynaTAC 8000.

Five Generations of Mobile Telephony



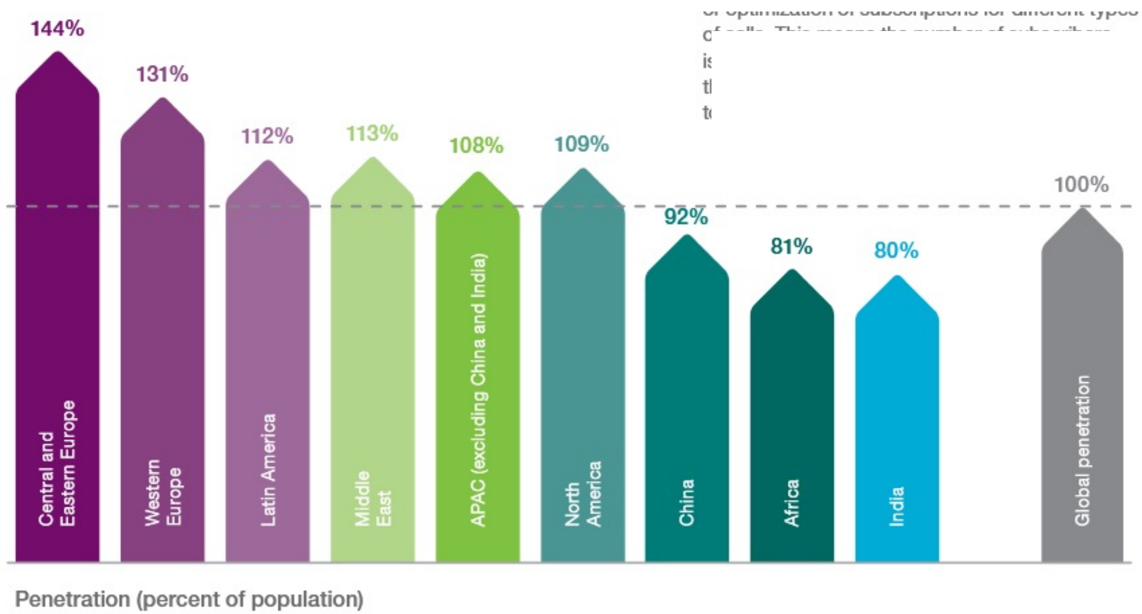
Phone Market

- **Technologies Evolution**

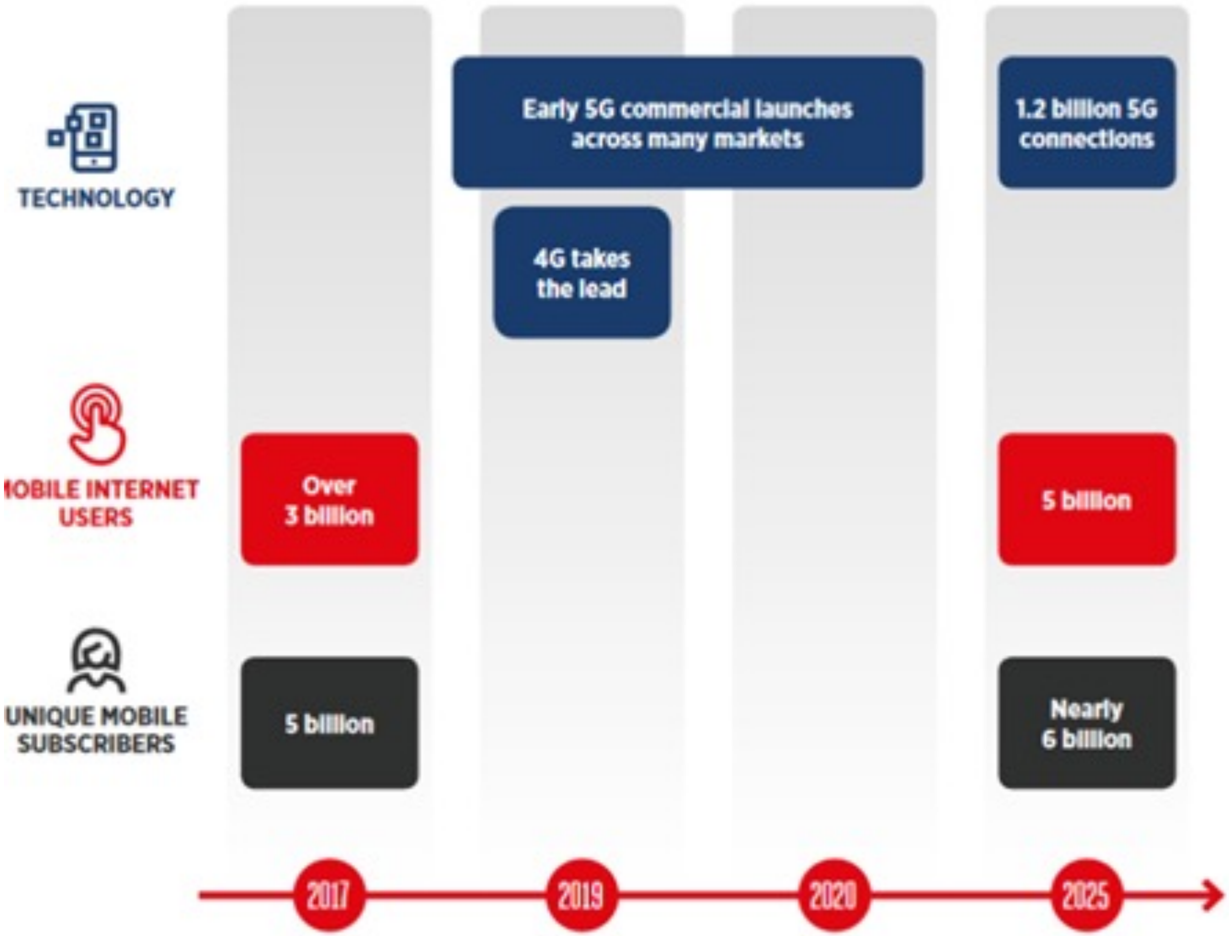


Mobile Market

- Subsribers number
- Average Revenu Per User ARPU
- ARPU/month : Average Revenue Per User (10,25 $)
- Market Penetration rate
- Churn (proportion of lost clients): varies from 3 to 5 % according to the operators



And on the short term …

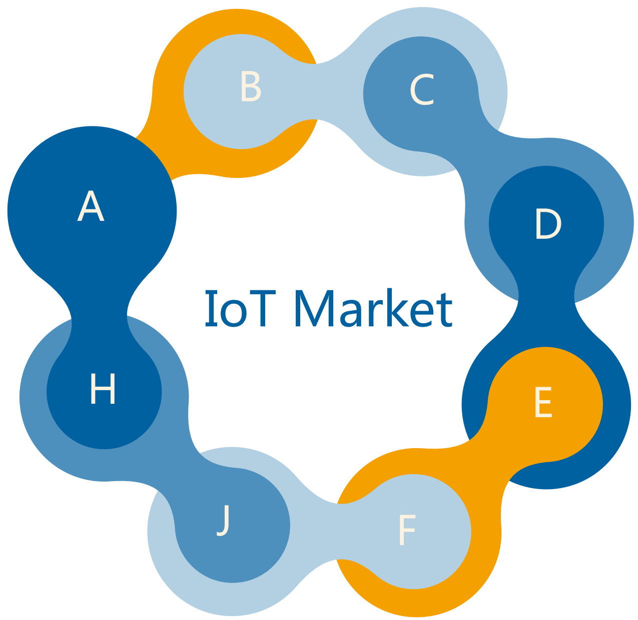


IoT Network: Main Characteristics

IoT Market

Business market

- Electric meters
- Health
- Smart Cities & Smart Buildings
- Car after-market
- Car Embedded



Consumer Market

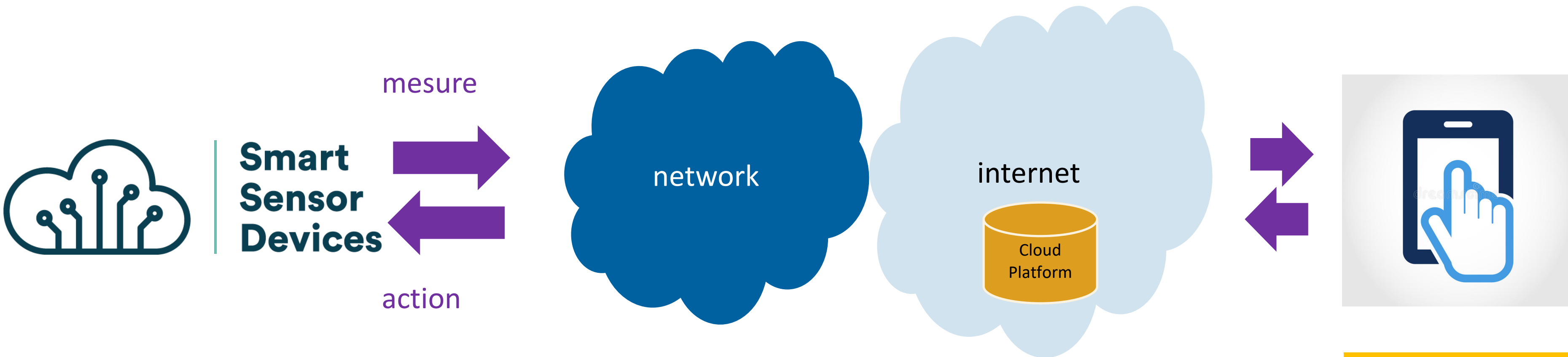
- Fitness band
- Smart watches
- Robots
- Drones
- Motion detectors
- Smoke detector, sprinklers
- Camera
- Smart home

Horizontal and Vertical Market

SaaS = Software as Service
IaaS = Infrastructure as Service
PaaS = Platform as Service

[IEEE Communications and Survey, 2015]

IoT Architecture



Application

IoT devices

Network and Services

Big data and Data analysis

Direct or indirect connectivity

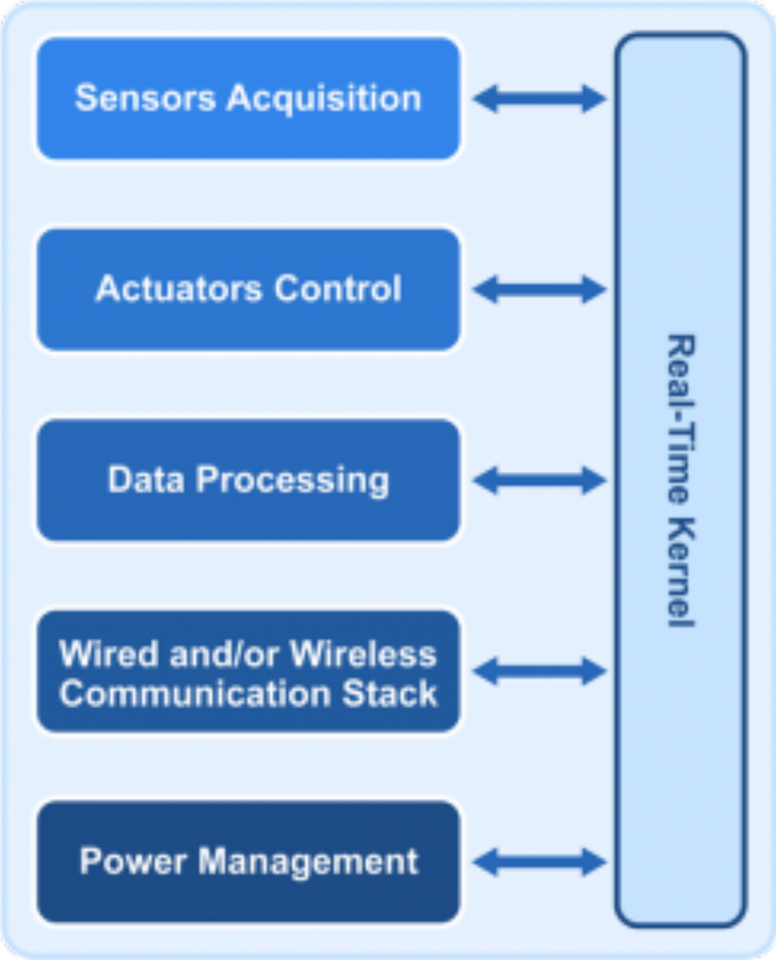
5G NB-IOT sigfox
LTE-M LoRa

Bluetooth ZigBee Alliance
WiFi ZWAVE
THREAD ULE

Connected Objects (1/)

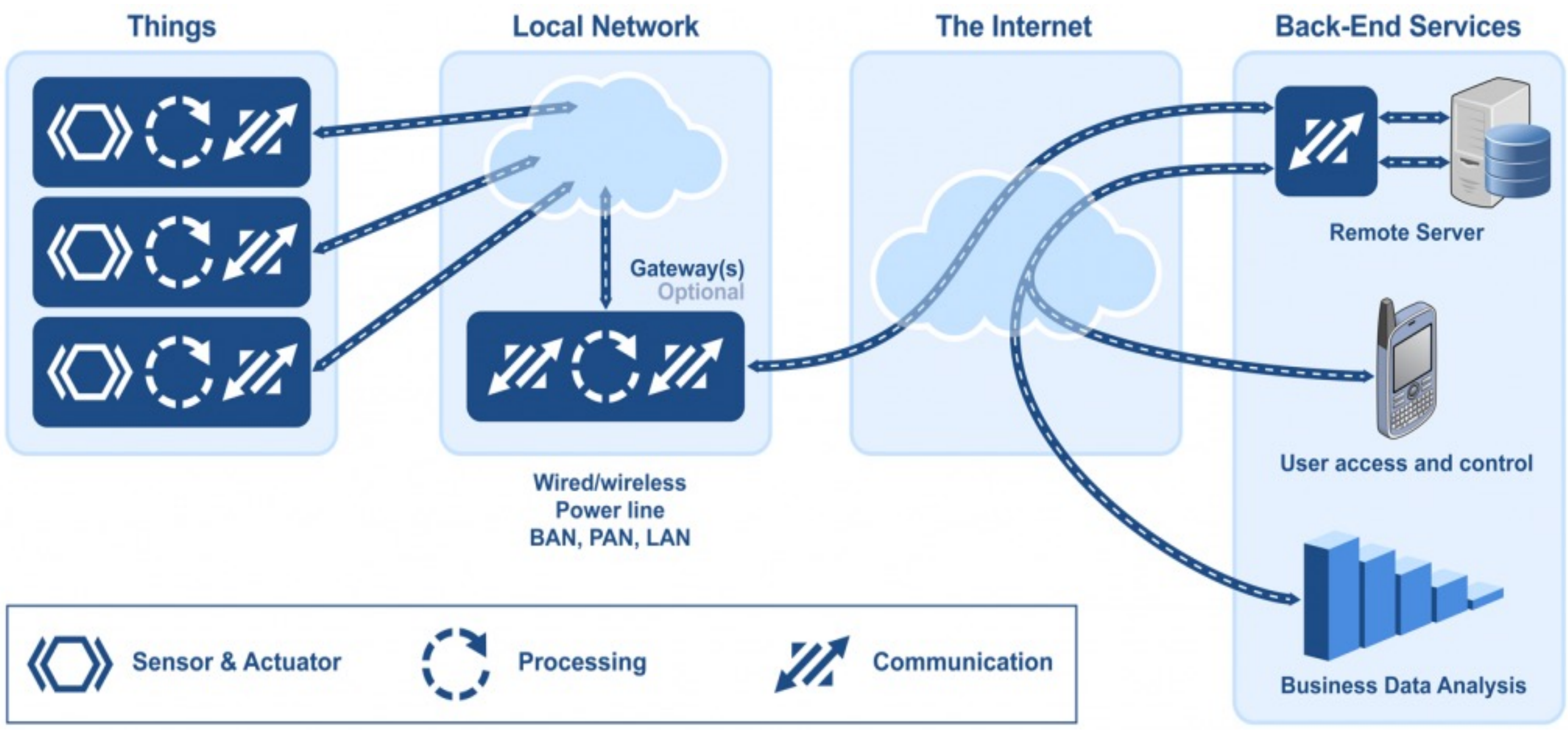
- A device, whose core features partially reside in the cloud (through a direct or indirect internet connectivity).
- The intelligence is distributed between object and cloud
- Internet of Things (IoT) includes connected objects with or without IP addresses
- A connected object is able to communicate both ways, emission and reception

IoT Device Software Architecture



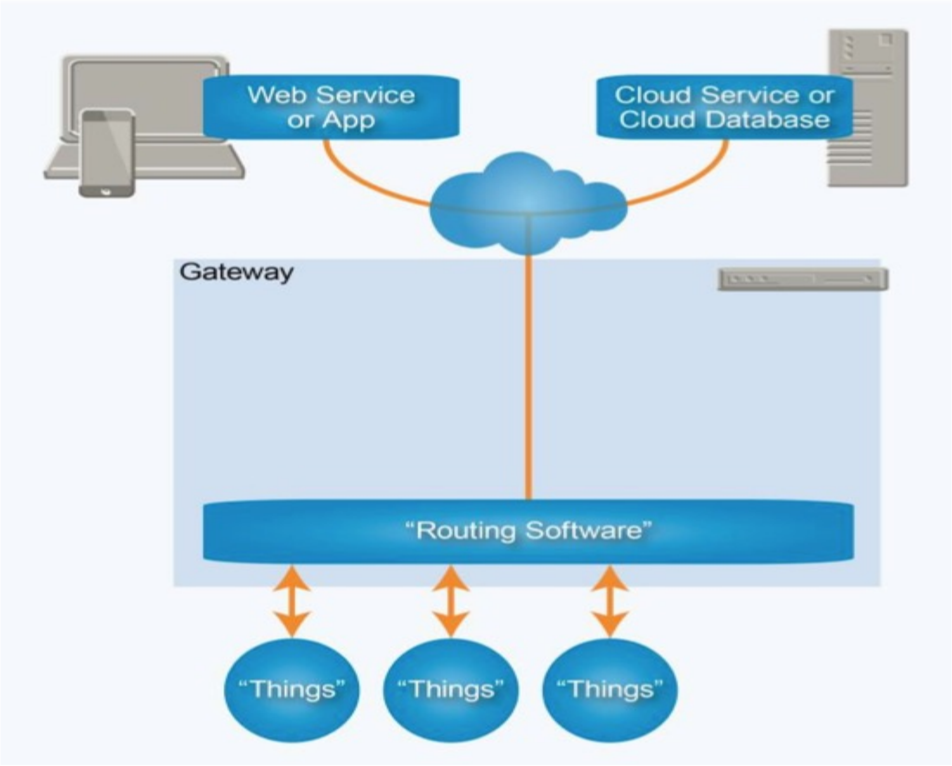
Indirect Network Topology (1/)

- Non direct communication through a Gateway



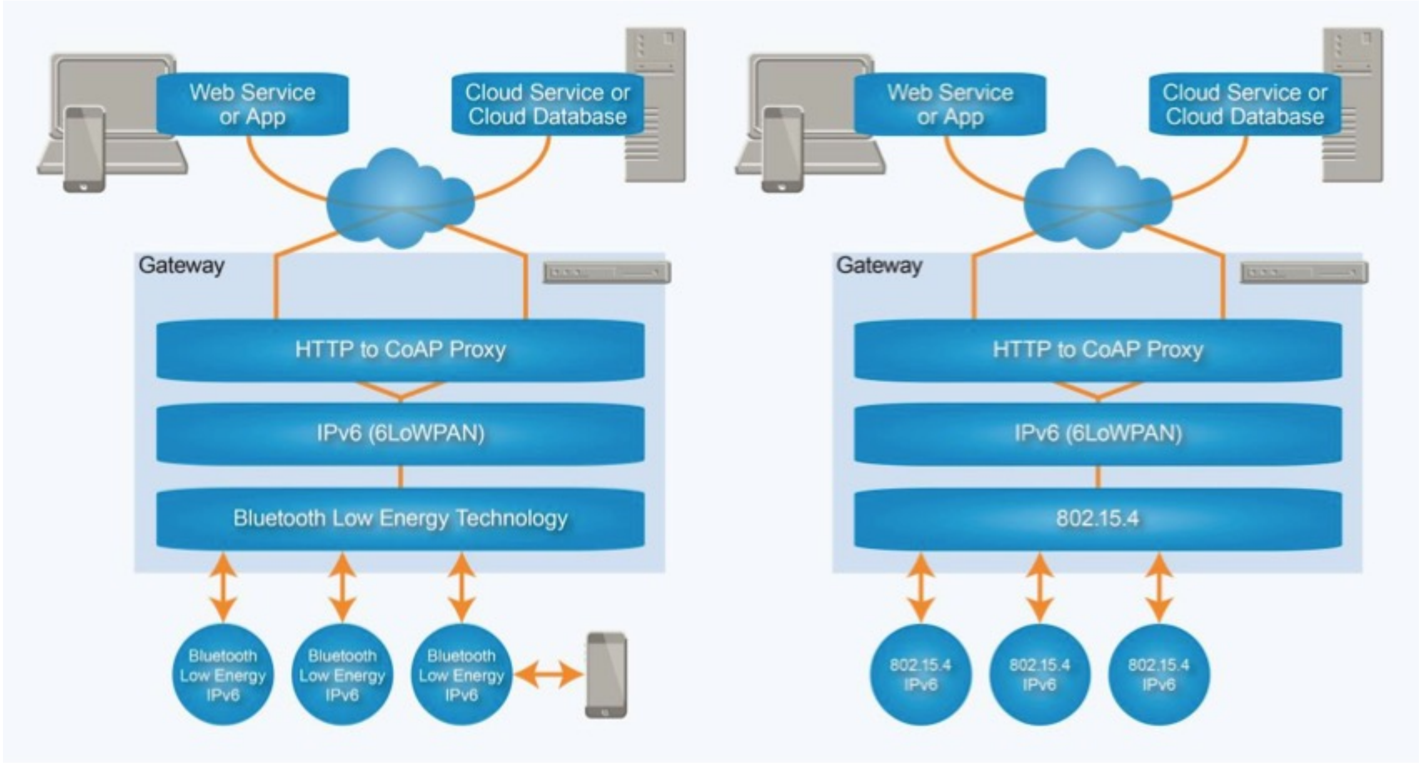
Indirect Network Topology (2/)

- **No-IP Use case:** The gateway will play the interface between the non-IP and the IP world when non-IP based application is used at the devices.



Indirect Network Topology (3/)

- With Bluetooth Low Energy and Zigbee (802.15.4) network, an-IP based application in the sensor can be transparently connected to an Internet service.
- The gateway uses compression techniques such as 6LoWPAN and CoAP protocols to enable an efficient use of the limited resources.



6LOWPAN protocols

- **IPv6 over Low power Wireless Personal Area Networks** (6LoWPAN) is the specification of mapping service required by the IPv6 over Low power WPANs to maintain an IPv6 network.

- 6LoWPAN removes a lot of IPv6 overheads in such a way that a small IPv6 datagram can be sent.

- 6LowPAN provides:
  - header compression to reduce the transmission overhead,
  - fragmentation to meet the IPv6 Maximum Transmission Unit (MTU) requirement,
  - forwarding to link-layer to support multi-hop delivery.

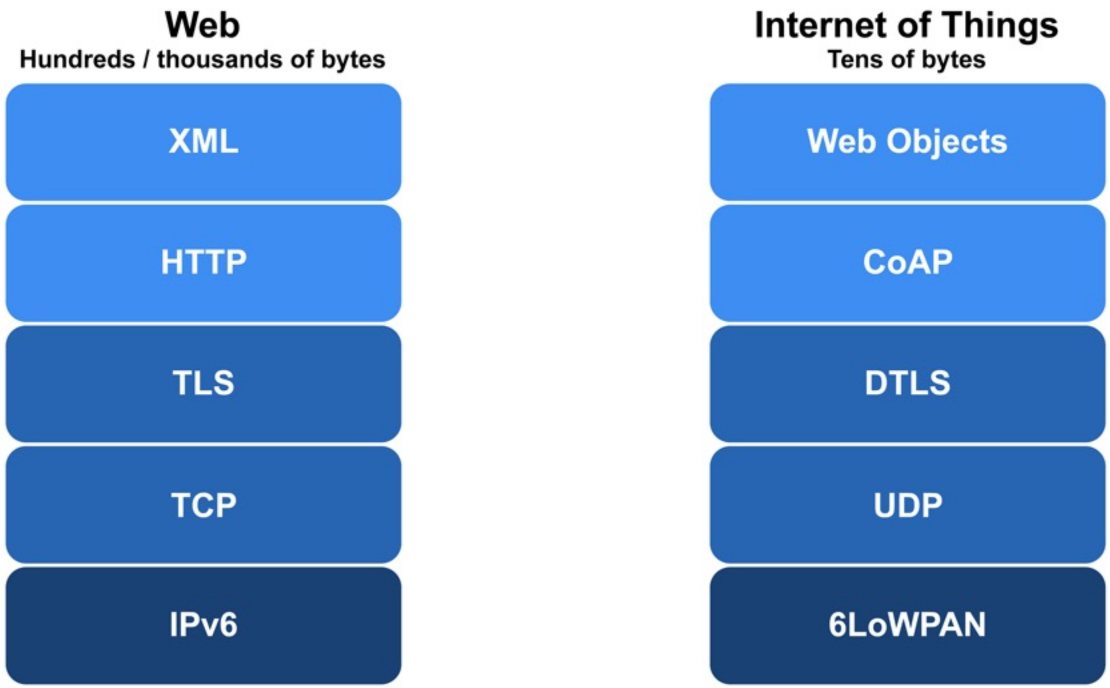
CoAP Protocol

- CoAP = Constrained Application Protocol (CoAP)

- It is semantically aligned with HTTP and has a one-to-one mapping to and from HTTP.

- CoAP aims to enable tiny devices with low power, computation and communication capabilities to utilize REpresentational State Transfer (REST) architecture interactions

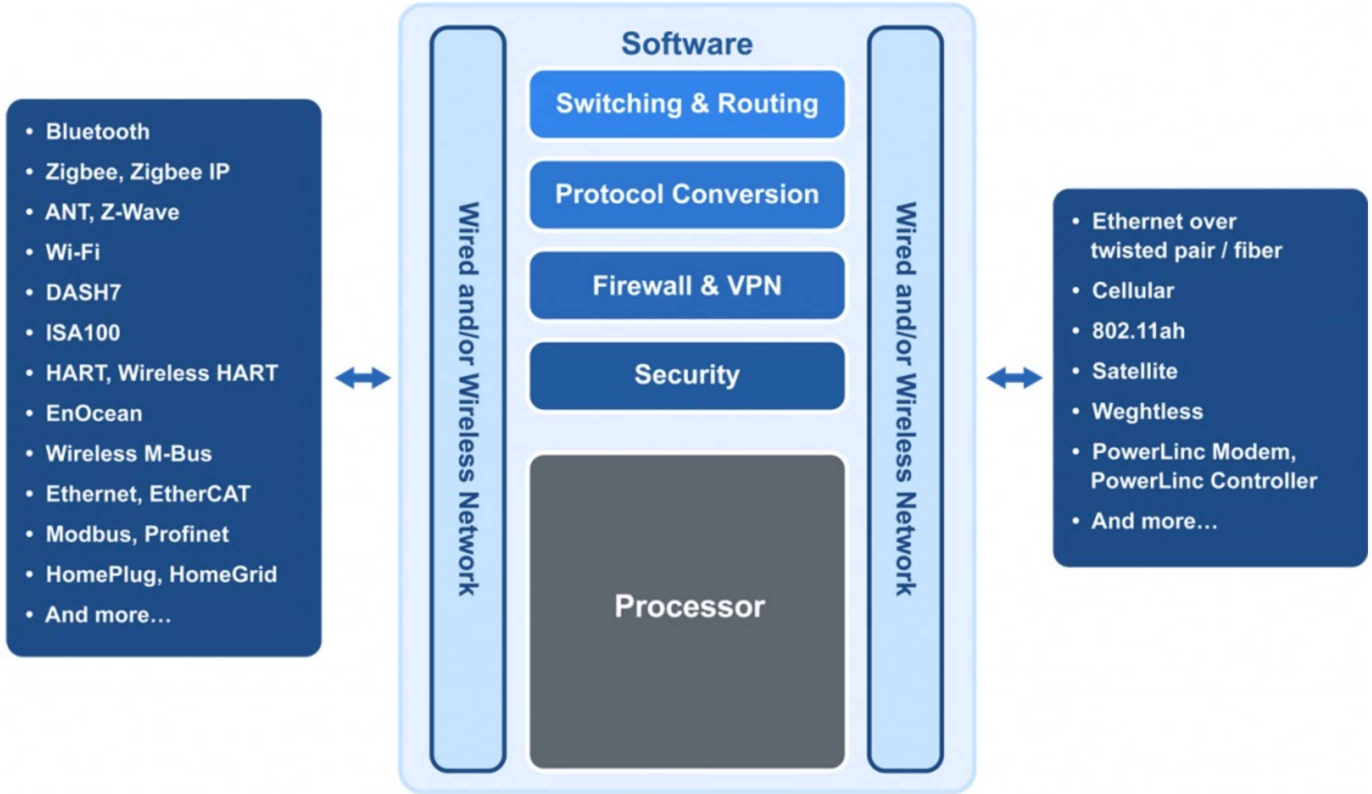
Web versus IoT Protocols



- Inefficient content encoding
- Huge overhead, difficult parsing
- Requires full Internet devices

- Efficient objects
- Efficient Web
- Optimized IP access

Gateway Architecture



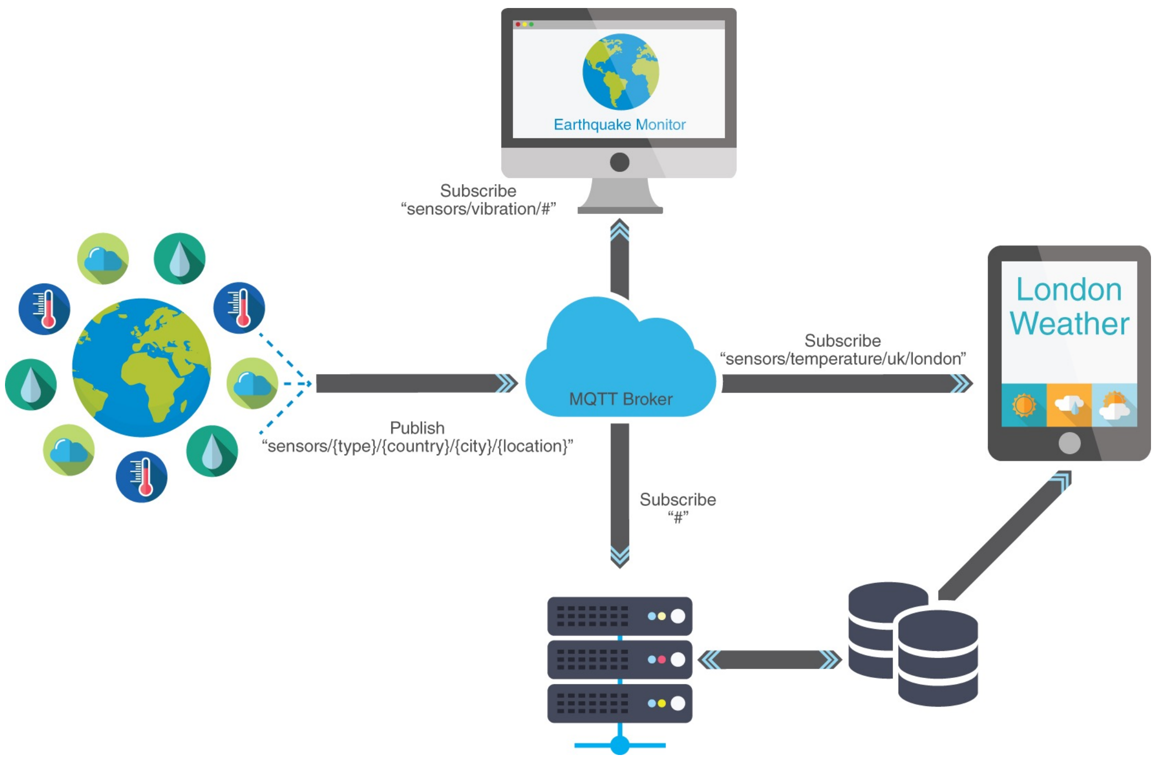
Short Range Communications

- **Wireless Local Area Networks (WLAN)**
  - WiFi = IEEE 802.11
- **Wireless Personal Area Network (WPAN)**
  - Bluetooth IEEE 802.15.1, Bluetooth Low Energy (BLE)
  - Zigbee IEEE 802.15.4
- **Wireless Body Area Network (WBAN)**
- **Radio Frequency Identification**

Short range communication networks operate in unlicensed bands

Indirect Network Topology with MQTT (4/)

- The MQTT (Message Queuing Telemetry Transport) protocol uses a **publish / subscribe** communications model which allows for data to be sent and received asynchronously.
- A web service called a **broker** manages where the data comes from and goes to.



Direct Connection

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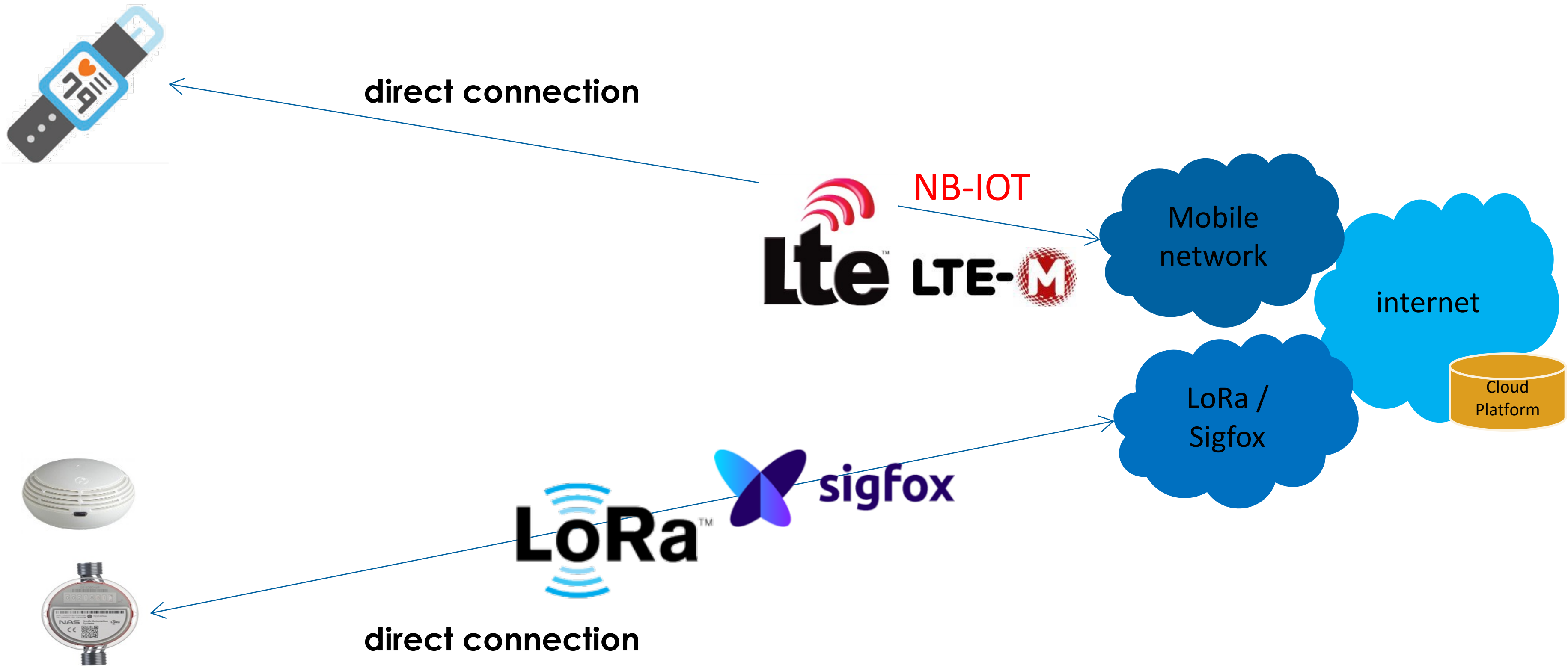
- LPWAN = Low Power Wide Area Network

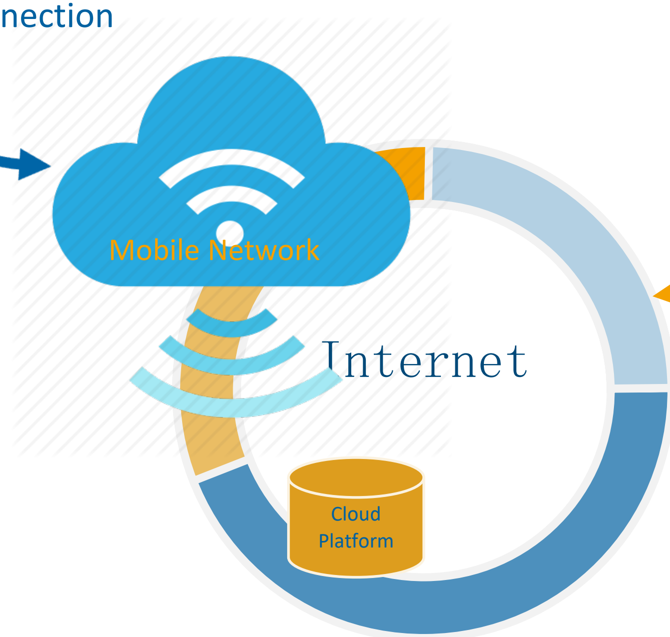


Different types of Connectivities

NB-IoT

LTE-M

Direct connection



Direct Connection

sigfox

LoRa™

Critical IoT
Licensed Band

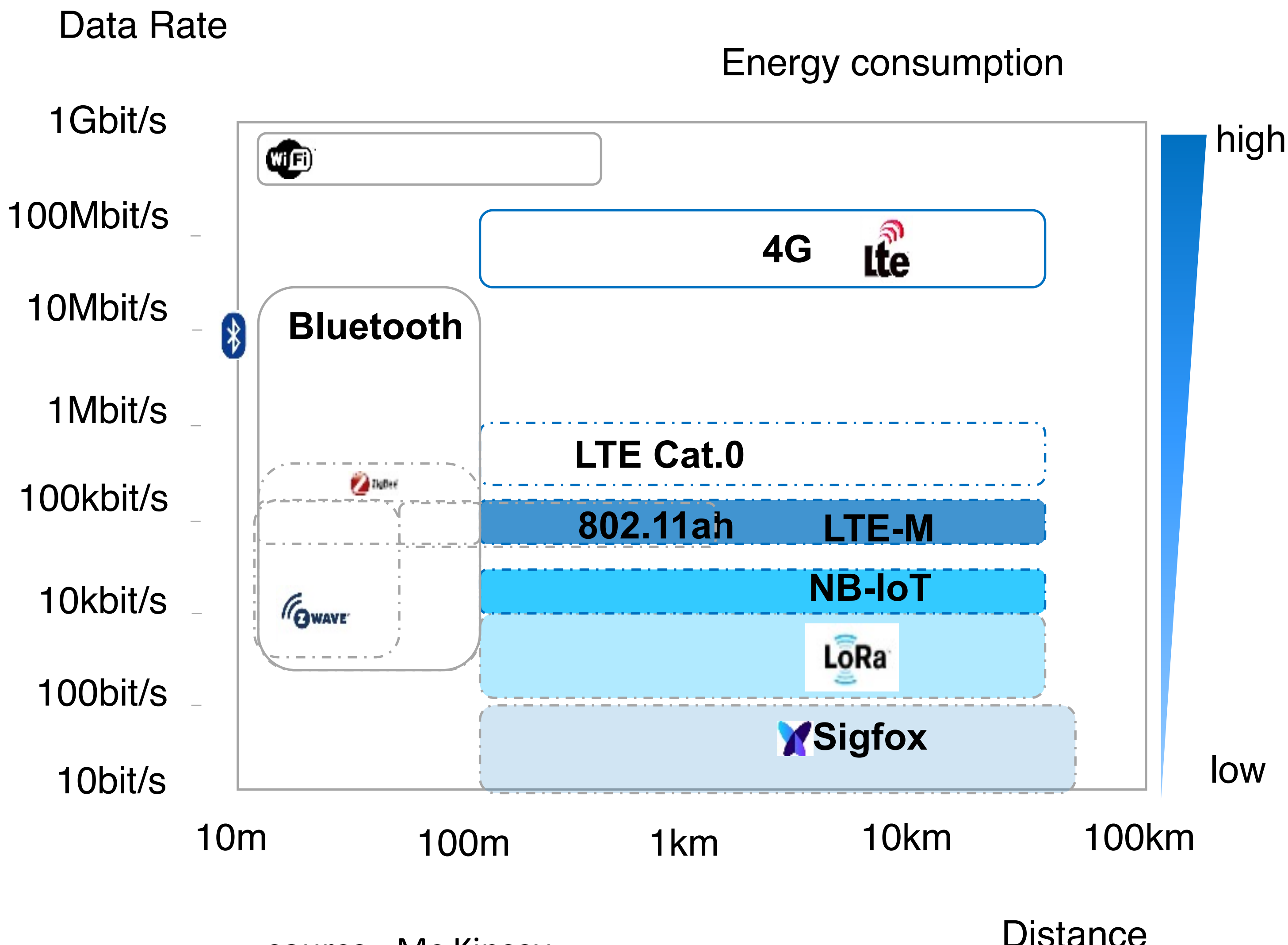
Real time
Critical application
Low data rate
High reliability
Low latency
Mobility & Roaming

Massive IoT
Unlicensed Band

Non real time
Non critical
Very Low data rate
Low cost
Low power consumption

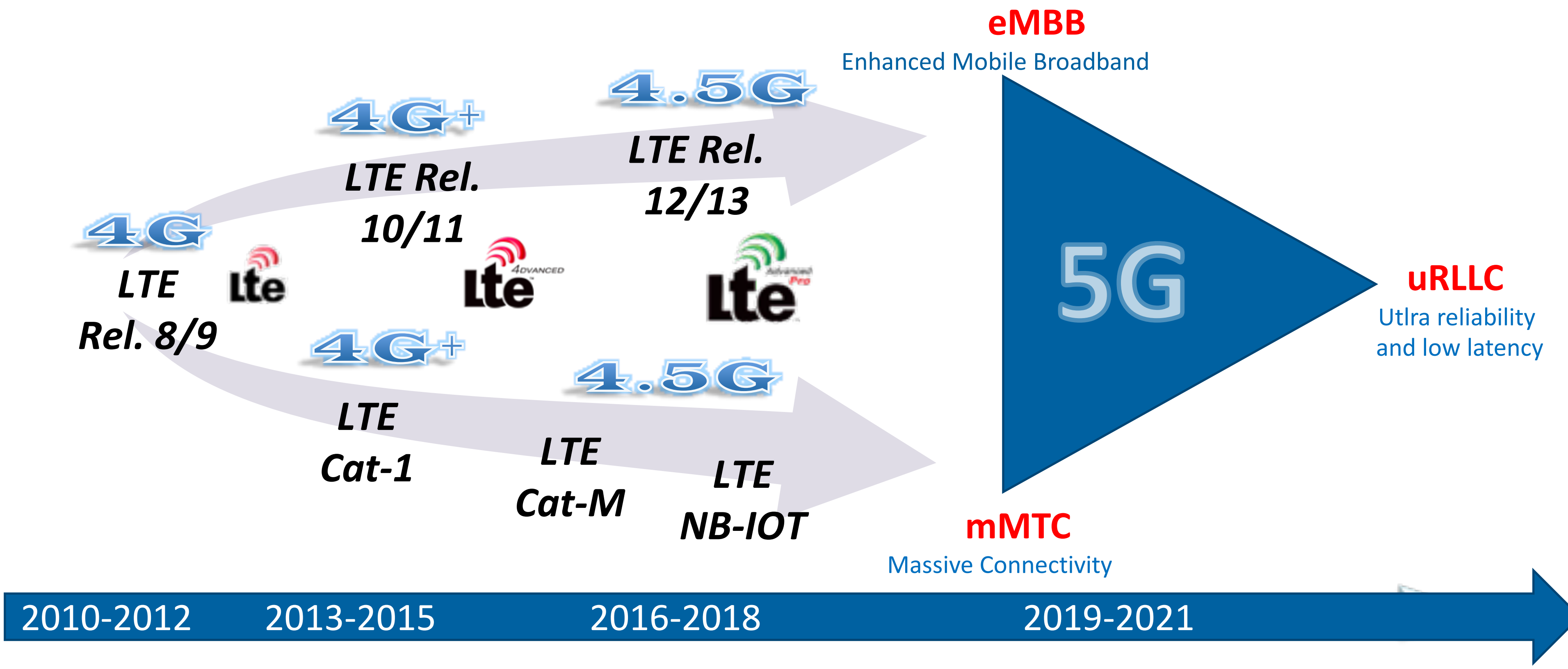
Connectivity Overview (1/)

Connectivity overview



source : Mc Kinsey

Connectivity Overview (2/)



Mobile Networks: Main Characteristics

Architecture : summary

- **Wireless mobile networks architecture is standardised**
  - ⇒ possible interconnexion with equipements from different suppliers

- **The architecture is is divided into two sub-systems:**
  - Radio, or Access, sub-system:
    - users access to the networks
    - Base Station Subsystem = BSS (GSM), Universal Terrestrial Access Network = UTRAN (UMTS), enhanced UTRAN = e-UTRAN (LTE), NR = New Radio (5G)
  - Core Network sub-system:
    - commutation, routing
    - Network Switching Subsystem = NSS (GSM), Core Network = CN (UMTS), System Architecture Evolution = SAE (LTE), NGCN = Next Generation Core Network (NCGN)

  And in parallel:

  - Operating & maintenance sub-system:
    - Operation Support Systems = OSS

- **Each operator rolls out all the architecture and create a Public Land Mobile Network**

Architecture : 1/ Devices

- **Device**
  (terminal, mobile, User Equipment, Mobile Station, etc)

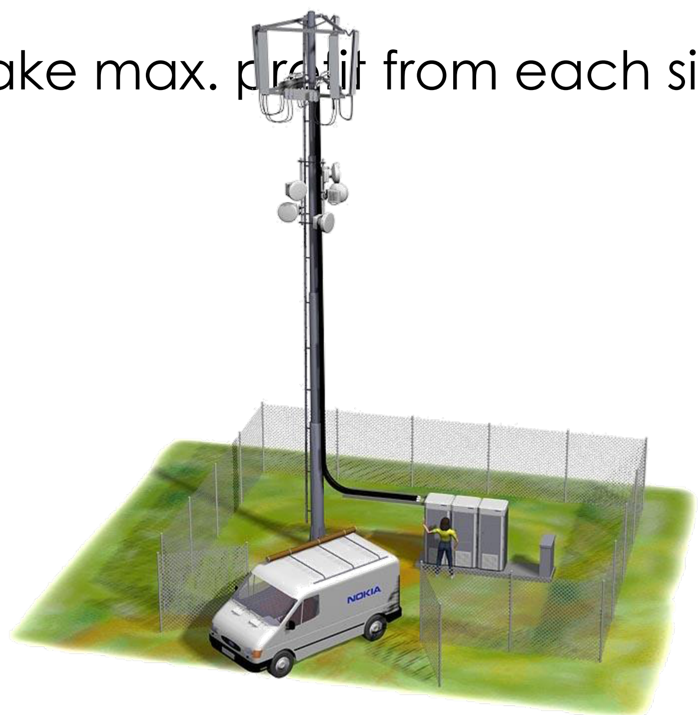
Architecture : 2/ Access Points

- **Acces Points to the network:**
  « Antennes relais », Base Station, NodeB, eNodeB, gNode , etc

- Maximum transmission power: 30-40 W

Architecture : 2/ Access Points

- **Objectives for each network operator:**
  - « cover » all the territory, without « coverage hole », with:
    - Indoor sites
    - Outdoor sites
  - take max. profit from each site

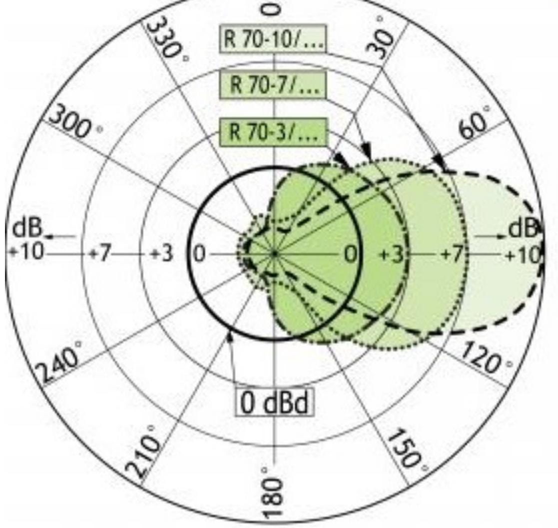


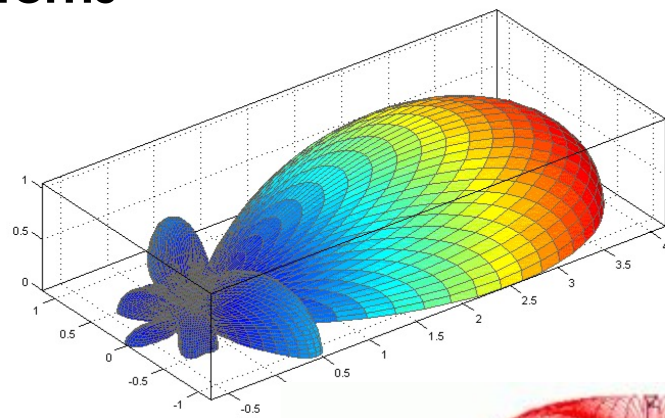
Architecture : 2/ Access Points: Antennas

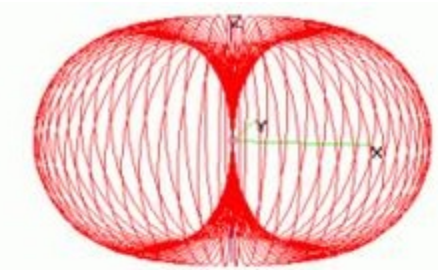
- **The choice of antennas is done by taking into account their characteristics:**
  - usage band:
    800-900 MHz, 1800-2100 MHz, 2600 MHz, Bi-band, Triple-band
  - technology:
    - panels
    - polarisation diversity,
    - etc
  - gain
  - radiation pattern
    - vertical et horizontal aperture
    - sidelobes attenuation
  - electric tilt, fixed or variable (few degrees depending on the range)

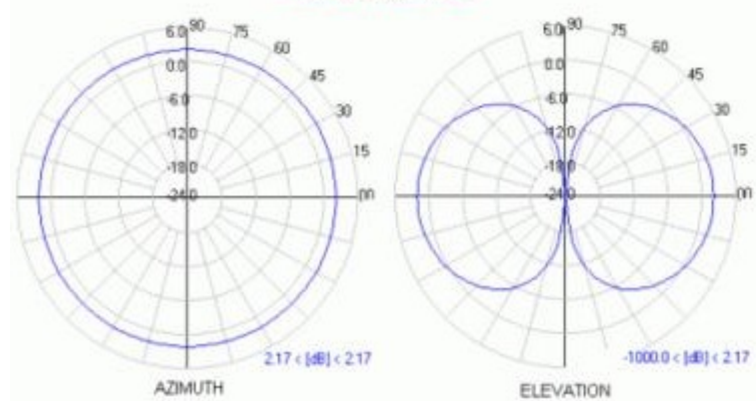
Architecture : 2/ Access Points: Antennas

Exemples of radiation patterns









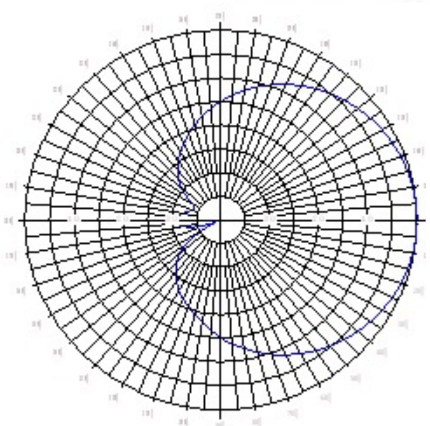


Diagramme Horizontal

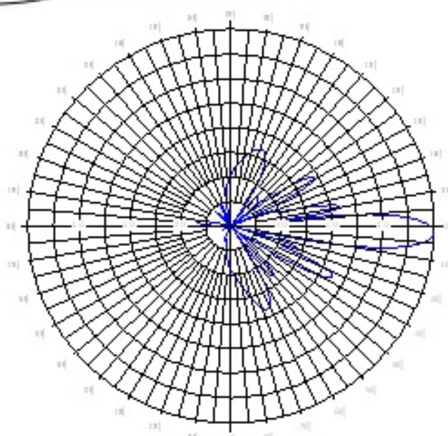
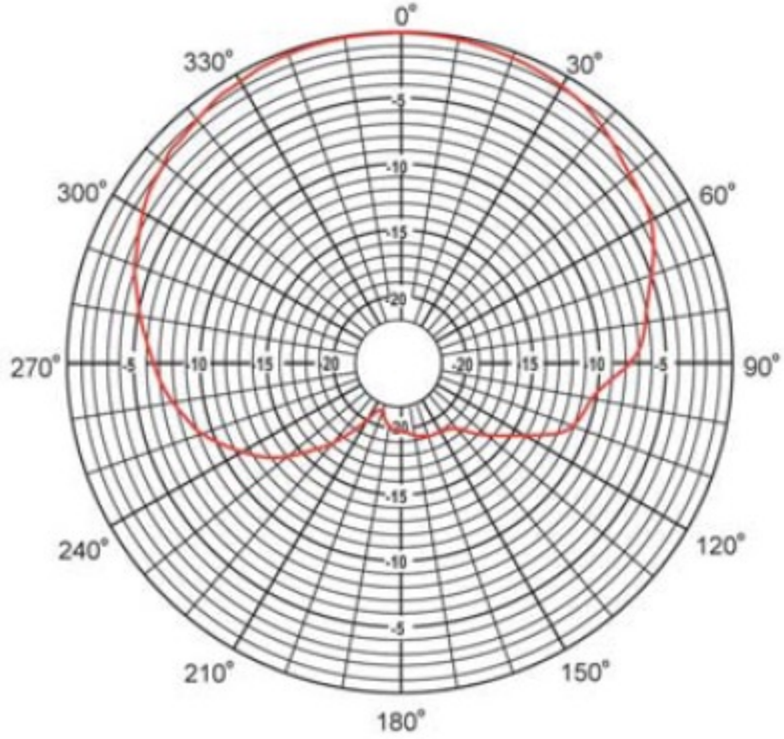


Diagramme Vertical

Architecture : 2/ Access Points: Antennas

- **Determine the Beamwidth of this antenna:**



Architecture : 2/ Access Points

- **Reuse of existing sites for new technology deployment**

Architecture : 2/ Access Points

- **New sites, in 4 steps:**
  (duration: sometimes 3 year for an outdoor site!)
  - Negociation
    - environment constraints
    - radiowave effects
  - Constructability
    - depends on the towns
    - administrative authorizations
  - Construction
  - Connection
    - electric

difficult for the operator

fixed costs, whatever the site capacity

Architecture : 2/ Access Points

- **Role**
  - interface between fixed network and mobile devices:
    - through a « radio interface » towards the mobile devices
    - through a fixed link, radio (microwave) or not (copper or optical fiber), towards the fixed network

  - radio transmission: modulation, demodulation, equalization, channel coding, ciphering

  - carrier frequency, users multiplexing
  - mandatory measures to check that the information is correctly transmitted/received
    $\Rightarrow$ anticipation of the HO

Architecture : 3/ Controllers

- **Access Points Controllers:**
  Base Station Controller (BSC), Radio Network Controller (RNC)

- **smart Equipment of the operator's access network:**
  - radio resources management
    (which circuit/packet? to whom? for which duration?)

- **usually connected to access points by microwave links**

Architecture : 4/ Switches

- **Switches / Gateways**
  Mobile Switching Center (MSC), Gateways, Servers, etc
- **Components of the operator's core network**
- **Decide the route to take to reach the recipient(s):**
  - circuits to establish
  - packets to send
- **Manage the subscribers mobility**
- **In relation with databases, help to:**
  - subscribers authentication
  - subscribers devices authentication
  - subscribers localisation
  - subscribers billing

Architecture : 5/ Databases

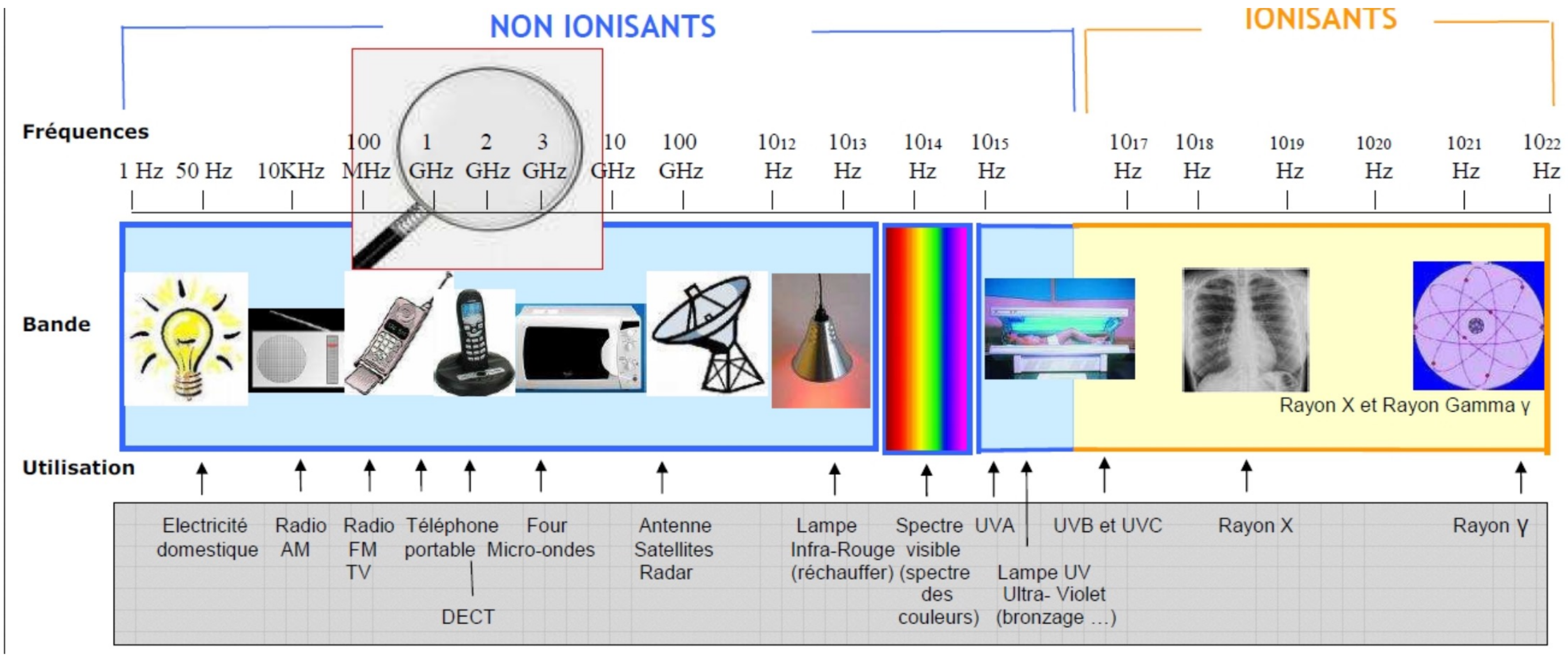
- **Home Location Register, Home Subscriber Server**
- **Database content, for each operator's subscriber:**
  - identity, references (bank, postal mail, etc)
  - tools for authentication :
    - of the subscriber
    - of the subscriber's device
  - subscription characteristics
  - « localisation »

Fundamentals in Wireless Communications

Technology's parameters

- Carrier frequency
- **Data rate** = bits/second
- **Spectral occupancy** = bandwidth
- **Transmitter power, battery life**
- **Receiver sensibility** = minimal reception power
- **Communication range** = **Maximal distance** between the transmitter and the receiver

Electromagnetic Spectrum



Electromagnetic Spectrum

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International

ITU International Telecommunications Union

ONU

Europe

CEPT
Conférence Européenne des Postes de Telecom

UE

France

ANFR
Agence Nationale des Radios Fréquences

France

Operators

Gouvernement Administration

Conseil Supérieur d'audio-visuel

Licensed and Non-Licensed Frequency

Licensed	Non Licensed
Fees to exploit frequency bands	Free
3G (2100 MHz) 4G (800 MHz et 2.6 GHz)	Industrial, Scientific and Medical (ISM) Band 2.4 GHz: WiFi, Bluetooth, Zigbee, Domestic Band 440 MHz (Baby phone) 868 MHz: LoRa, Sigfox

Telecom Standardization Institute

- **The telecommunication standard requires a collaboration between manufacturers, constructors, operators, service providers, research centers and administration.**

  - European Telecommunications Standards Institute
    - GSM
  - IEEE, Institute of Electrical and Electronics Engineer
    - WiFi, IEEE 802.11
    - Bluetooth, IEEE 802.15.1
    - Zigbee, IEEE 802.15.4
  - 3GPP, 3rd Generation Partnership Project:
    - conceive and publish the specifications of the 3rd , 4th and 5th generation of mobile network

Information and Representation

- **What type of information is transmitted?**
  - Sound signal: voice, music;
  - Data (a text, an image, a video, a measure);

- **How to represent the information?**
  - The information is mapped into a **binary stream**
  - The **compression** techniques are used to represent the information with the lowest possible number of bits.
  - The **redundancy** techniques are used to be able to find back the information at the reception when a part of the information is lost.

Representation of a binary stream

- **What is the data rate?**
  - The data rate is the **number of bits transmitted per second**.

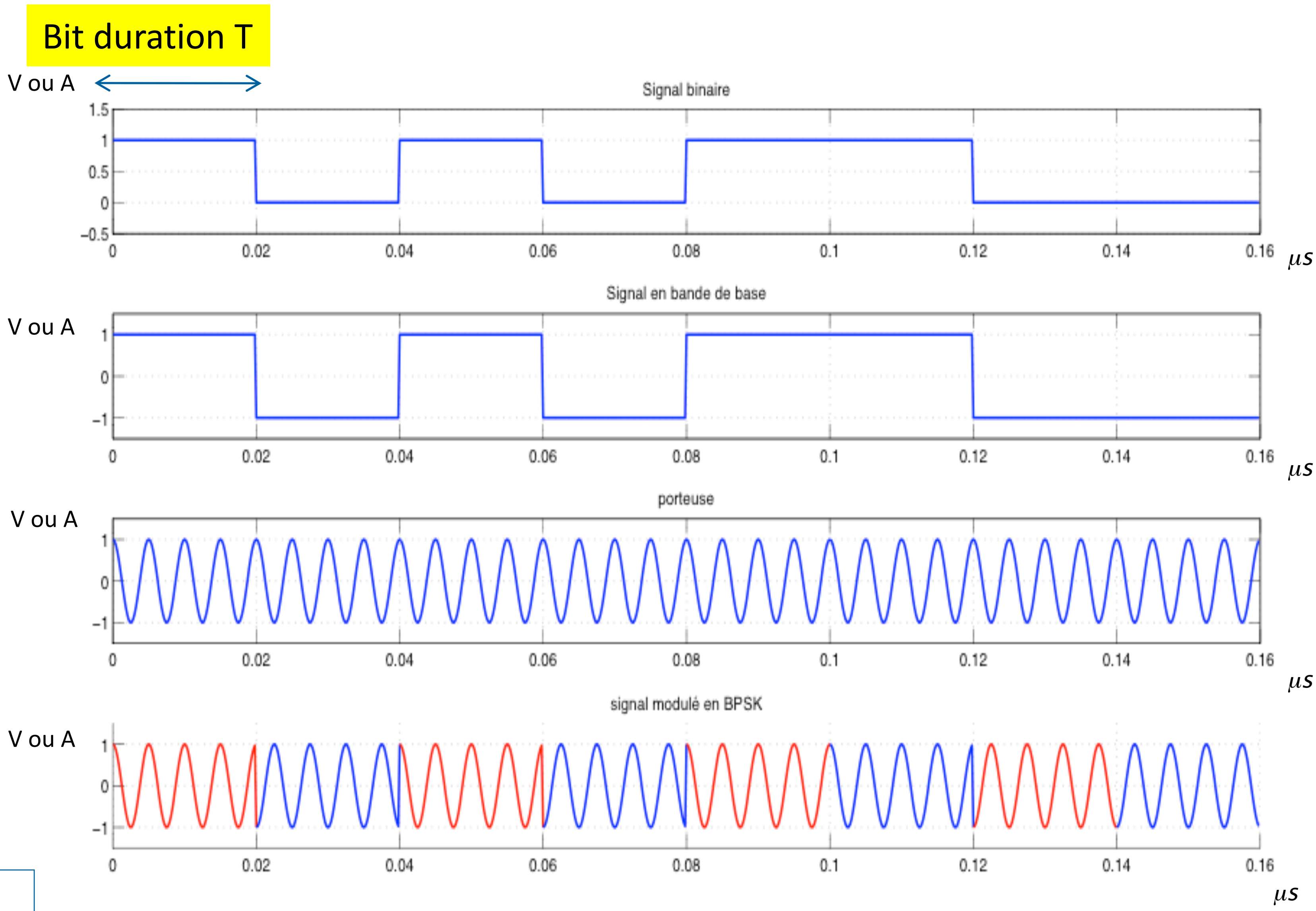
- **What is a modulation?**
  - The modulation associates a **physical representation to a binary stream.**

- **What type of representation is used?**
  - We use the **sinusoidal signal** with pulsation $2\pi f_0$
  - To distinguish bits, we modify the **phase**, the **amplitude** and the **frequency** of the sinusoid.

Example of modulation: BPSK

- Modulation BPSK = **Binary Phase Shift Keying**, means that the key (the information) is in the phase.
- Binary stream: 10101100 to transmit with data rate of 50 Mb/s;
- Each bit is then transmitted during $1/(50 \times 10^{6}) = 0.02 \times 10^{-6}$ s;
- The bits are represented as follow:
  - 1 par $\cos(2\pi f_0 t)$;
  - 0 par $\cos(2\pi f_0 t + \pi) = -\cos(2\pi f_0 t)$;
- The frequency carrier is $f_0 = 200$ MHz;

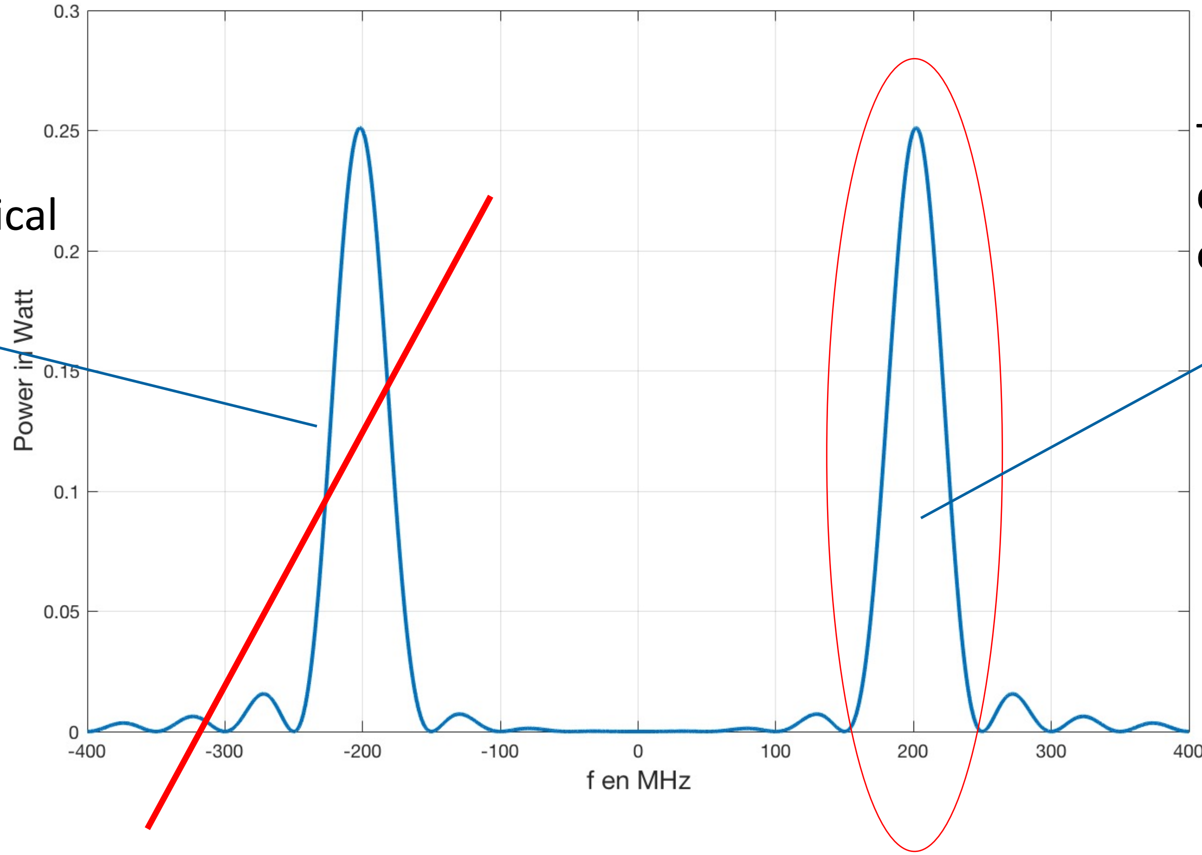
Example of modulation: BPSK



Spectral Power Density (SPD)

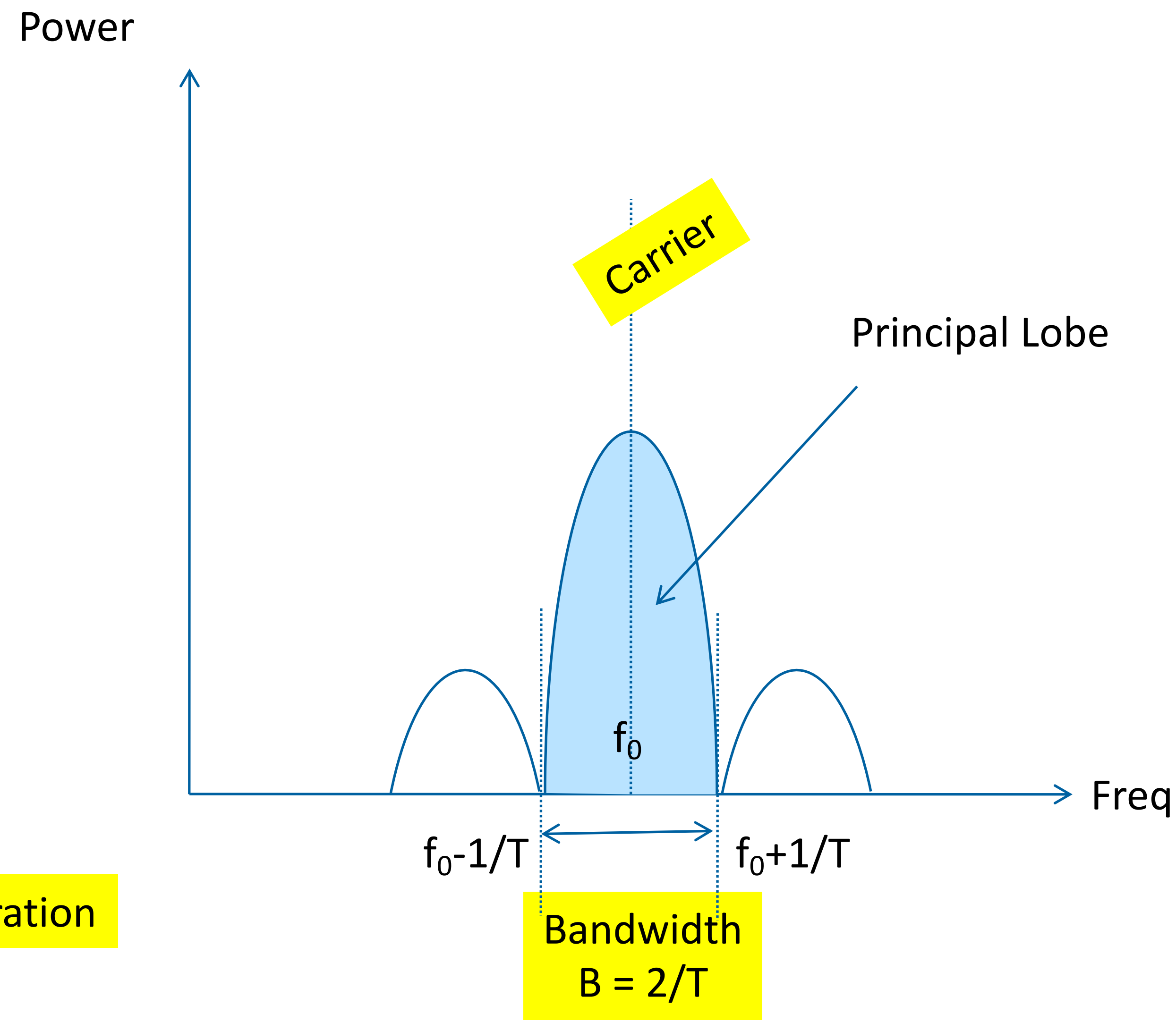
- The spectral power density represents the statistical distribution of the power over the different frequencies.
- For a signal modulated with BSPK, the SPD is:

Mathematical



The principal lobe that contains the majority of the energy

Carrier and Bandwidth



T = Bit duration

Properties of the Radio Frequencies

- The attenuation increases with the frequency and the distance.

- The data rate is proportional to the bandwidth

- The antenna size is proportional to the wavelength and inversely proportional to the carrier frequency.

- The directivity of the wave increases with the frequency.

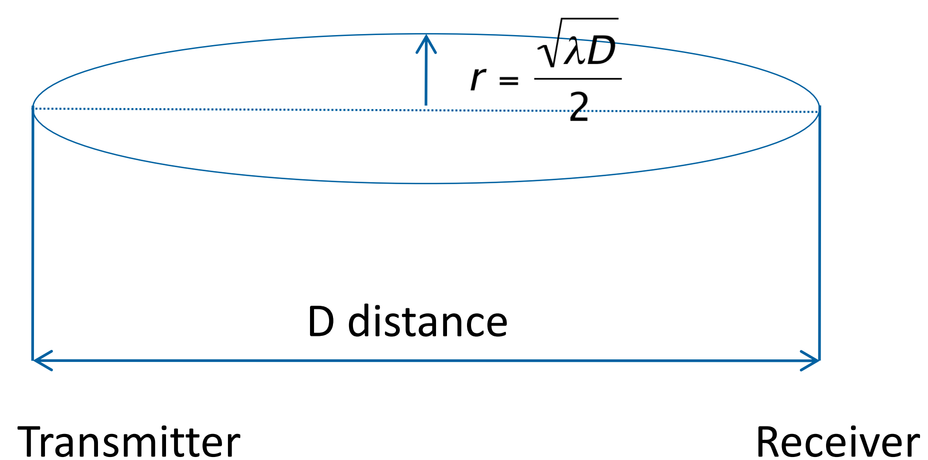
Line of Sight and Non Line of Sight

- The radio link is in **Line of Sight** if the first **ellipsoid of Fresnel** is clear (does not contain any obstacle).

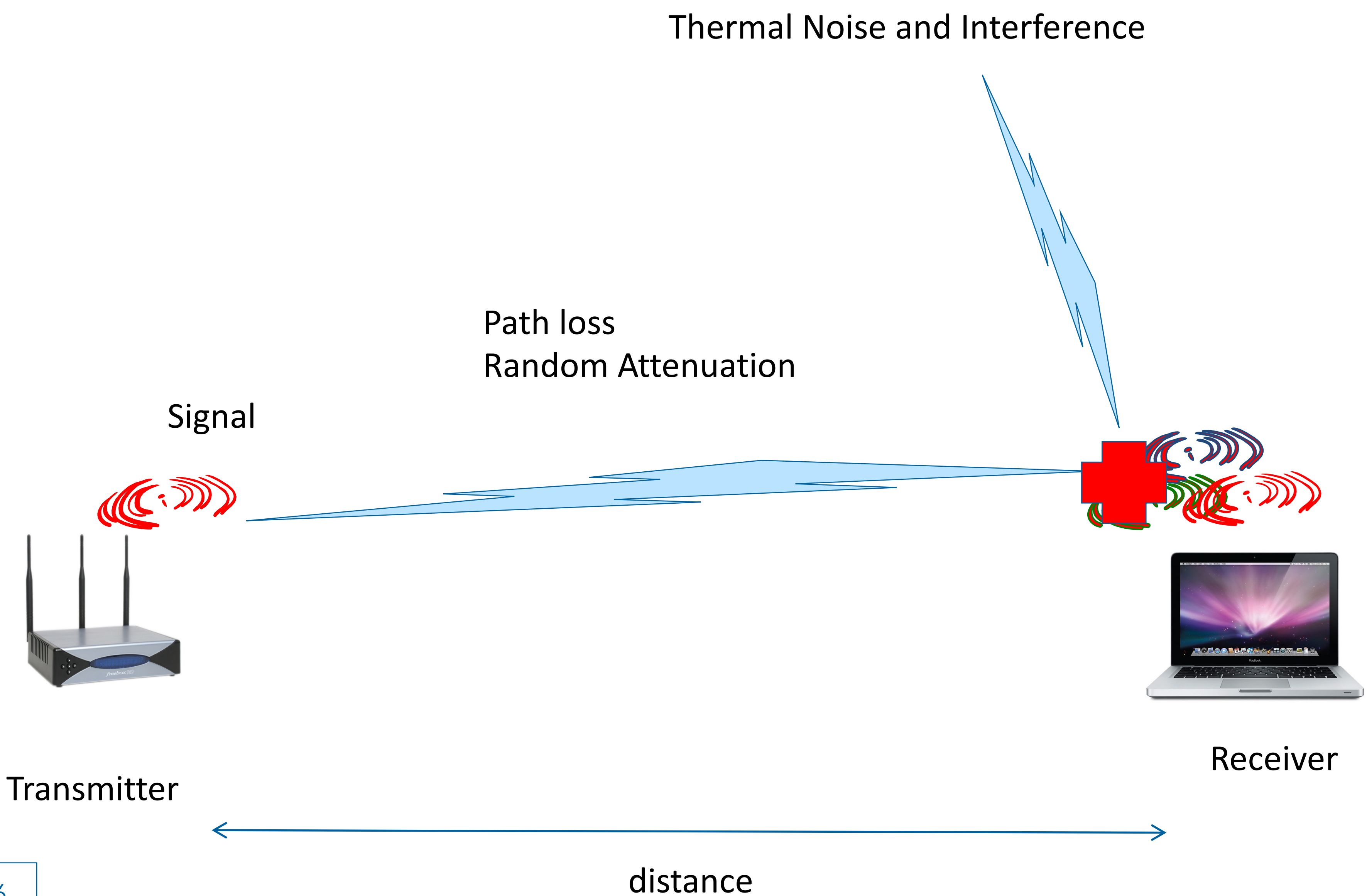
- In radio-frequency, the ellipsoid of Fresnel contains the majority of the energy.

  The radius of this ellipsoid is $r = \frac{\sqrt{\lambda D}}{2}$ with λ being the wavelength.

- The ellipsoid is very thin for high frequencies and the wave is then directive.



Perturbation of the Propagation



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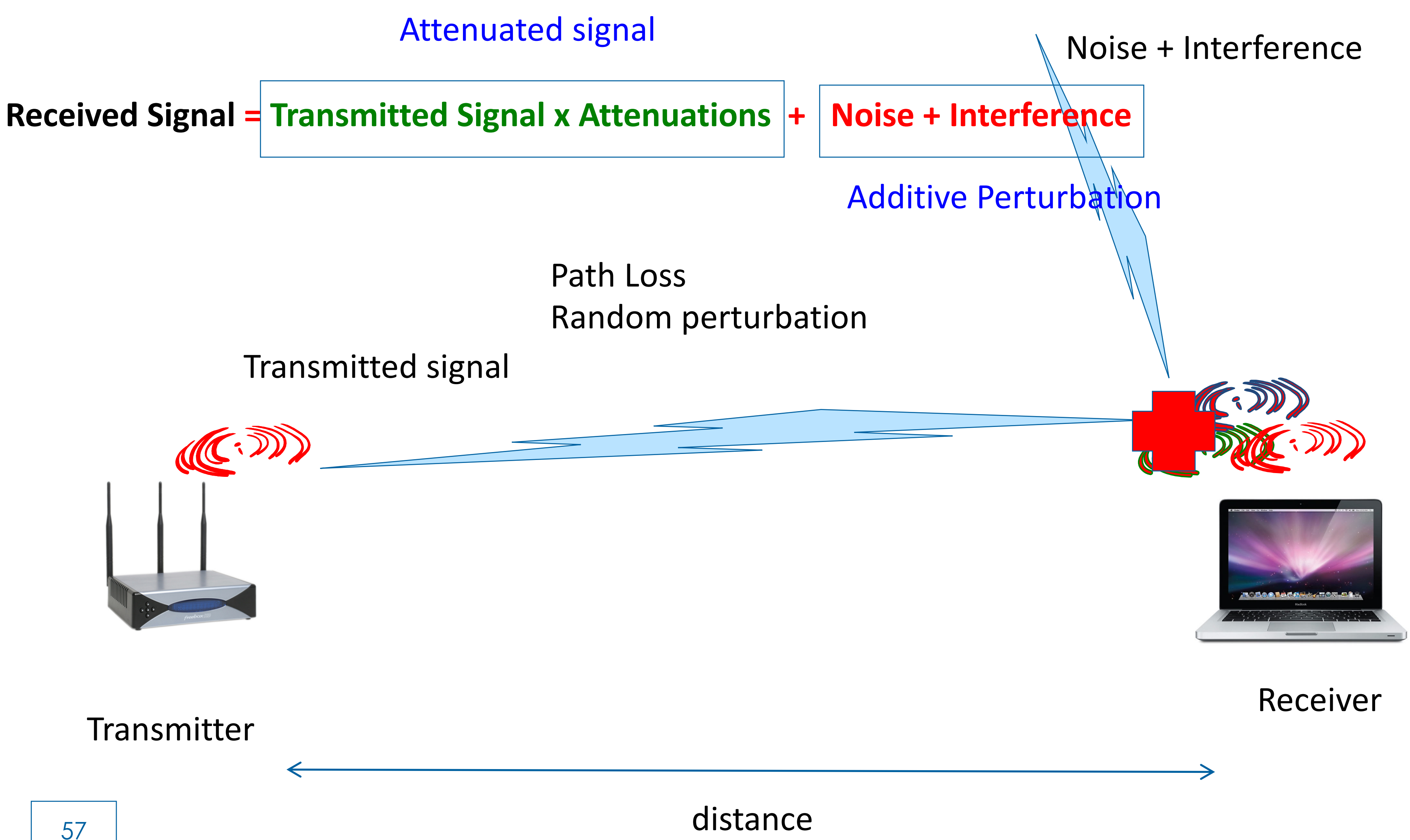

Units of telecommunications

- The power of the signal is defined in Watt or in mW
- The received power are generally very low. That's why a **logarithmic scale** dBm ou dBW is defined.
- PdBm = 10 $\log_{10}$ (P_{mw}) ou PdBW = 10 $\log_{10}$ (P_W)

- The attenuated power in W or mW is $P_{received} = 1/L \times g \times P_{transmitted}$

with g the antenna gain and 1/L is the attenuation factor

- En dBm, $P_{received}$(dBm) = $P_{transmitted}$ (dBm) + Gain (dBi) – Attenuation (dB) with Gain(dBi) = 10 $\log_{10}$ (g) and Attenuation(dB) = 10 $\log_{10}$ (L)

Path loss

- The path-loss depends on the environment, the frequency, the distance between the transmitter and the receiver and the antenna heights.

- The path-loss is computed using:
  - A deterministic model **for the free space**;
    - $A(dB) = 32.4 + 20 \log_{10} (f_{MHZ}) + 20 \log_{10} (d_{km})$
    - d = distance between the transmitter and the receiver
    - f = carrier frequency
  - An empiric model: Okumura Hata in outdoor and an IEEE 802.11model in indoor.
    - Example: for f = 2.6GHz, $A(dB) = 139 + 39\log_{10} (d_{km})$

Random Attenuation

- The fading is due to multi-path propagation of the same signal. On each significant path, a different phase shift occurs. At the receiver, all the paths are added.

- **Example:** Assume that the transmitted signal is $\cos(2\pi f_0 t)$ and that there is two significant paths.
  - **Worst case:** no phase shift on path 1 and phase shift of pi on path 2. Received signal = $\cos(2\pi f_0 t) + \cos(2\pi f_0 t + \pi) = 0$
  - **Best case:** np phase shift on both paths. Received signal = $\cos(2\pi f_0 t) + \cos(2\pi f_0 t) = 2\cos(2\pi f_0 t)$

- It is not known in advance how the signal will behave on the different paths(a **constructive or destructive way**). These attenuations are random and are known as **Fading**.

Random Attention (2/)

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- The **shadowing** is related to attenuation of the signal due to obstacle.
- The obstacle absorbs partially or totally the energy of the wave.
- The size of the obstacle is compared to the wavelength.
- The **penetration-loss** increases with the frequency. The wavelength is very small compared to the width's of the wall.
- The use of femtocell operating with high frequency guarantees that the wave remains inside the building

Signal to Noise Plus Interference

- Signal to Noise Plus Interference Ratio

$$\text{SINR} = \frac{\text{Attenuated signal (mW)}}{\text{Power of noise (mW)} + \text{Interference (mW)}}$$

- This ratio is without unit. It can be expressed also in dB.

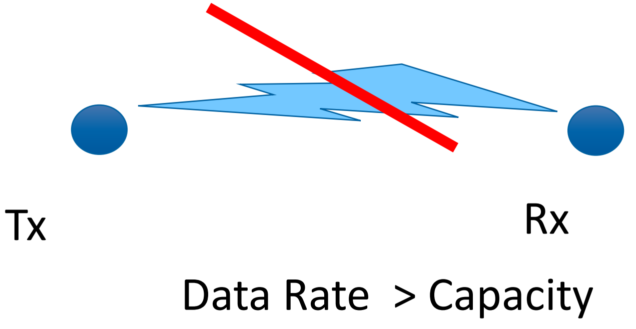
$$\text{SINR (dB)} = \text{Received Power (dBm)} - 10\log_{10}(\text{Noise (mW)} + \text{Int(mW)})$$

Theoretical Data Rate

- The maximal theoretical data rate is computed using the Shannon capacity:

$$\boxed{\text{Capacity (b/s)} = \text{Bandwidth} \times \log_2(1 + \text{SINR}_{\text{without unit}})}$$

- If the transmitted data rate exceeds the Shannon capacity, the communication is said to be in outage (and the packet is not delivered correctly to the receiver).



Network Engineering: Planification and Dimensioning

Radio propagation: useful formulas

École d'ingénieurs du numérique

- **Wavelength of a signal, that is transmitted on the carrier frequency f :**

$$\lambda = \frac{c}{f} \qquad c = 3.10^8 \text{ m/s}$$

- **Indoor penetration is impossible when the thickness of the obstacle is greater than the wavelength**

Fréquency $\uparrow \Rightarrow$ Indoor penetration $\downarrow$

- **Attenuation in <u>free space</u> by a signal transmitted on the carrier frequency f over a distance d :**

$$A = \left(4\pi \frac{d}{\lambda}\right)^2$$

Frequency $\uparrow \Rightarrow$ Attenuation $\uparrow$
Space density $\uparrow \Rightarrow$ Attenuation $\uparrow$

Why propagation modelling is crucial?

- **During access points deployment process, it is necessary for the operator to know the received signal strength at all points in the study area, to know if it is possible or not to transmit/receive information wherever in the area.**

- **Measures can be done by dedicated teams, but it is impossible to go everywhere.**

- **Propagation studies main objectives:**
  - using computers, from the geographic location of the access points and using software propagation models:
    - determine the locations covered by the network
    - deduce the "coverage holes" & the interferences
  - time & money gain

Radio propagation: transmission channel

- **Air, on the access point – mobile device link**
- **caracteristics :**
  - very large fluctuations in time and space
- **degradations :**
  - propagation losses
  - « shadowing »: effect due to obstacles
  - « fading »: effect due to multipath
  - co-channel and adjacent channel interferences

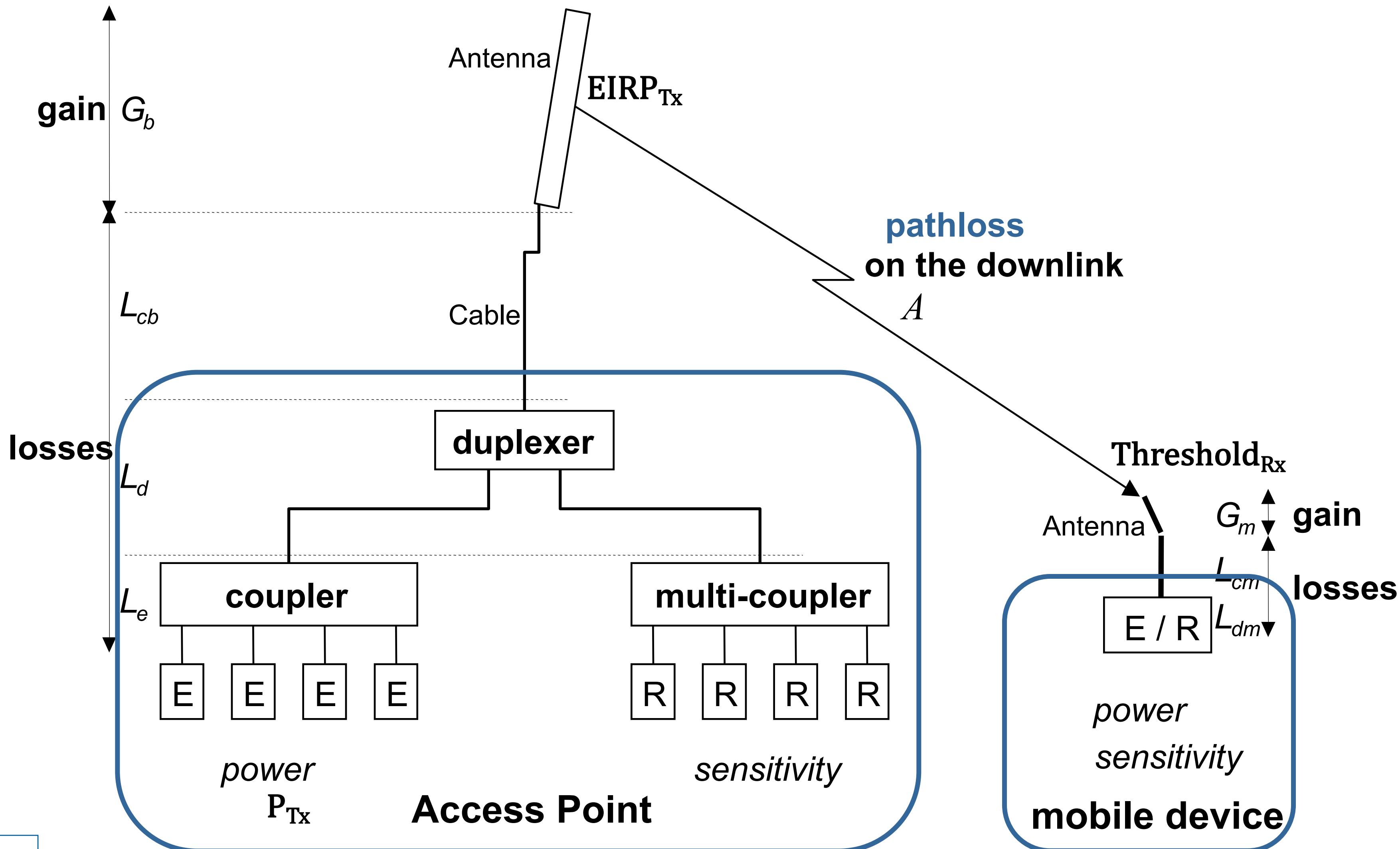
« pathloss »

⇨ link budget between the transmitter and the receiver

Radio propagation: Link budget (1/)

- **material characteristics are supposed to be known:**
  - antennas gains
  - losses in couplers/cables/duplexers
- **assumption: transmission of a signal on a given carrier frequency f_1**
- **power budget :**
  - on the downlink:
    - transmitter: Access Point
    - receiver: mobile device
  - on the uplink:
    - transmitter: mobile device
    - receiver: Access Point

Radio propagation: Link budget (2/)



Radio propagation: Link budget (3/)

- Equivalent Isotropic Radiated Power (Puissance Isotrope Rayonnante Equivalente PIRE, in French):

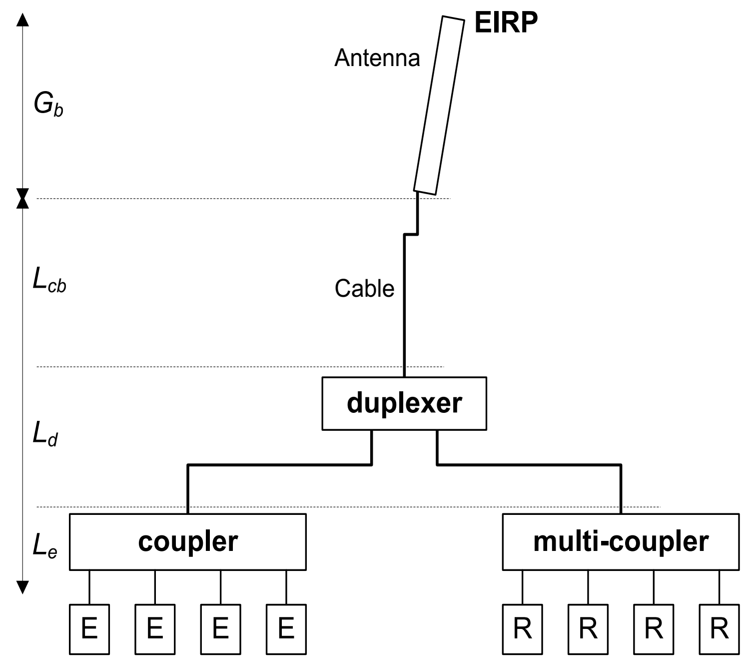
$$\mathrm{EIRP}_{\mathrm{Tx}}=\mathrm{PIRE}_{\mathrm{Tx}}=\left(\frac{\mathrm{GA}}{\mathrm{LO}}\right)_{\mathrm{Tx}}\mathrm{P}_{\mathrm{Tx}}$$

- Reception threshold of the receiver :

$$\mathrm{threshold}_{\mathrm{Rx}}=\mathrm{seuil}_{\mathrm{Rx}}=\left(\frac{\mathrm{LO}}{\mathrm{GA}}\right)_{\mathrm{Rx}}\mathrm{sensitivity}_{\mathrm{Rx}}$$

Radio propagation: Link budget (4/)

- **Access Point side:**
  - G_b: 15 dBi
  - L_{cb} : 3 dB
  - L_d : 1,5 dB
  - L_e : 6 dB
  - sensitivity : -108 dBm
  - P_{Tx} : 35 - 42 dBm

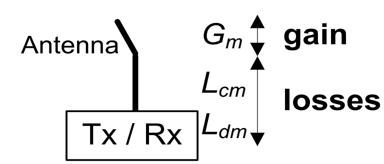


Tx power *Rx sensitivity*

Access Point

- **Mobile device side:**
  - G_m: dBi
  - L_{cm} : dB
  - L_{dm} : dB
  - sensibilité : -102 dBm
  - P_{Tx} : 1 ou 2 Watts

0 dB



Tx power
Rx sensitivity

mobile device

Radio propagation: Link budget (5/)

- **Results on the downlink:**
  - Device_sensitivity - (G_m - L_{cm} - L_{dm}) = - 102 dBm
  - P_{TX} + G_b - L_{cb} - L_d - L_e = P_{TX} + 4,5 dB
  - pathloss_downlink = P_BTS +106,5 dB

- **same on the uplink:**
  - AccessPoint_sensitivity - (G_b - L_{cb} - L_d - L_e) = - 112,5 dBm
  - P_{TX} + G_m - L_{cm} - L_{dm} = 33 dBm
  - pathloss_uplink = 145,5 dB

- **Link balancing: we must reach pathloss_downlink = pathloss_uplink**

⇒ Access Point Transmission power tuning: P_{TX} = 39 dBm

Radio propagation: Pathloss (1/)

- **Determination of the pathloss A:**
  - with the help of a propagation model, chosen as a function of:
    - its complexity
    - the environment
  - must be lower than the maximum authorized pathloss computed by the link budget (145.5 dB in the previous example)

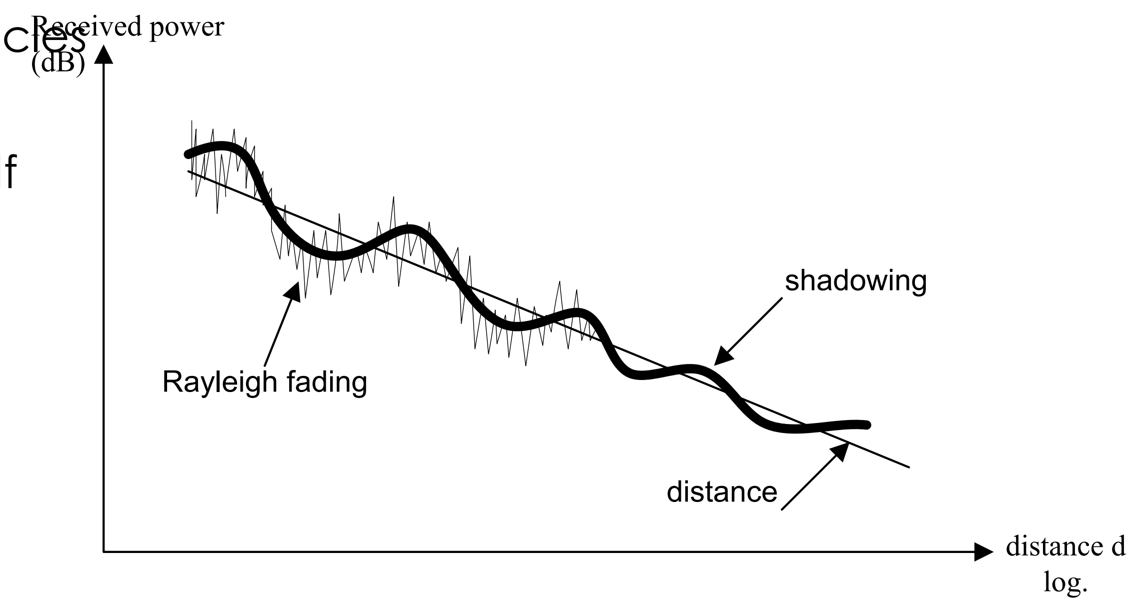
- **Operator confidential know-how**

- **Models**
  - **outdoor** :
    - Okumura-Hata,
    - Deygout,
    - Walfish Ikegami...
  - **indoor** :
    - Erceg,
    - Wiart..

All the propagation models have constraints and limitations. Most of the time, they can not all be respected.

Radio propagation: Pathloss (2/)

- **Three propagation parameters must be considered:**
  - pathloss, subject to the Tx/Rx distance:
    - free space ↓: Fresnel ellipsoid is masked
    - caracterization : $1 / d^{\gamma}$ **« coefficient de propagation »**
  - mask effect,
    or "slow fading"
    - presence of obstacles
    - caracterization :
      log-normal law pdf
  - Rayleigh fading,
    or "fast fading"
    - multipath effect
    - caracterization :
      Rayleigh law pdf



Radio propagation: Pathloss (3/)

- **Necessity of environment knowledge:**
  - necessity of obstacles knowledge
  - estimation of the degradations impacting the transmitted signal

  - Establishement of geographical databases:
    - satellites views, topological mesurements, etc

  ⇔ ‘raster’ : terrain composition: waters, trees, cemente, etc
    - dense urban, urban, suburban, rural, hilly, etc
    - price :
      function of the precision (250 m → 5 m, Paris : 200 k€$_{\text{JGR 01/2008}}$)

Radio propagation: Models (O. H.)

- **empirical**
  - Okumura measurements
- **pro :**
  - simple
- **validity :**
  - Access Point antenna height between 30 and 200 meters
  - Mobile device antenna height between 1 and 10 meters
  - Access Point – Mobile device distance between 1 and 20 km
  - Carrier frequency f between 150 MHz and 1500 MHz ;
- **Formula (Hata) :**

$$A_{dB} = 69{,}55 + 26{,}16 \log_{10} f_p - 13{,}82 \log_{10} h_{BS} - A(h_{MS}) + (44{,}9 - 6{,}55 \log_{10} h_{BS}) \log_{10} d$$

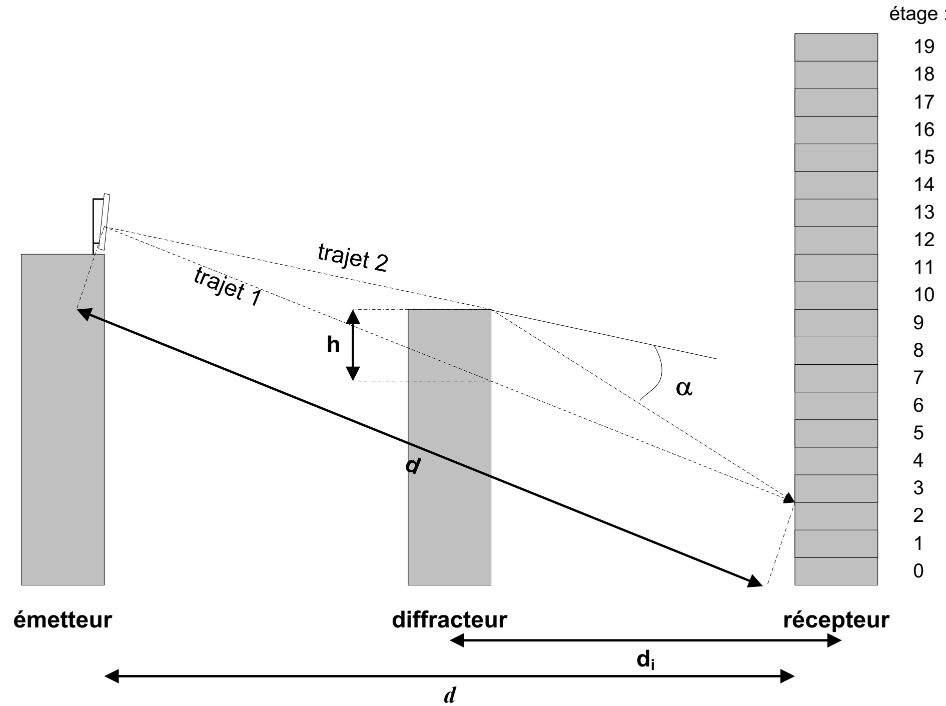
$A(h_{MS})$ **function of the considered environment**

Radio propagation: Models (Deygout)

- **pros:**
  - variable mobile device height
  - diffraction on several obstacles
- **validity :**
  - α must be lower than 12°
- **formula :**
  - free space loss
    - on *trajet 1*
    - $A_{libre\ dB} = 32{,}44 + 20 \log_{10} f_1 + 20 \text{ Log } d$

+

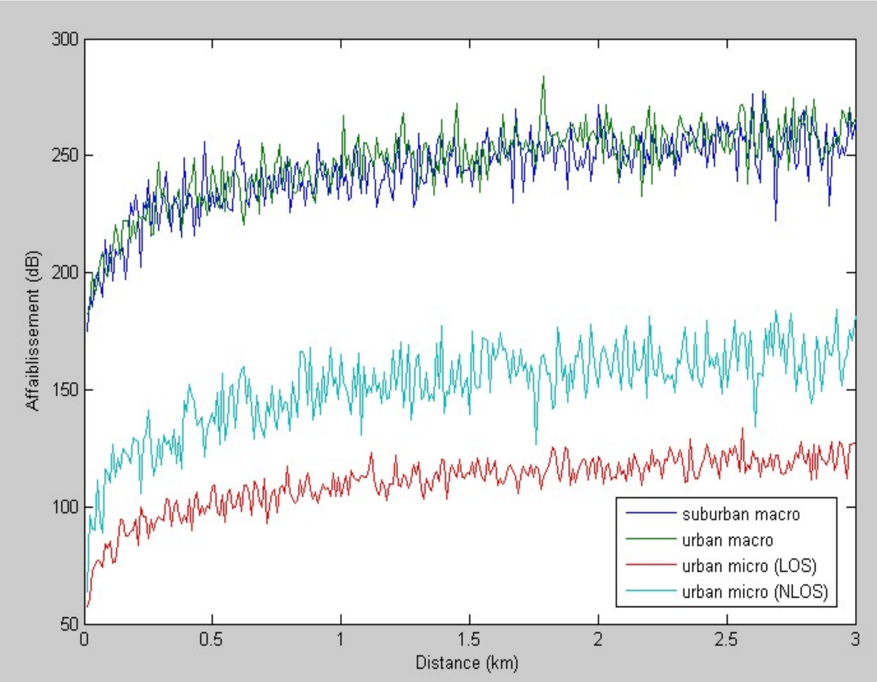
  - diffraction losses (r: 1st Fresnel ellipsoid radius)
    - sur le *trajet 2* :
      - si h/r < -0,5
        $A_{diff\ dB} = 0$
      - si h/r > -0,5, w = 1,41 h/r – 1
        $A_{diff\ dB} = 6{,}9 - 20 \log_{10}((w^2 + 1)^{1/2} - w)$



$$\frac{h}{r} = \frac{h}{\sqrt{\dfrac{\lambda \times (d - d_i) \times d_i}{d}}}$$

Radio propagation: Models (802.16m)

- **Pathloss as a function of the environment:**
  - Suburban macro :
    $A_{\mathrm{dB}} = 25.74 + 35 \log_{10}(d) + 33.81 \log_{10}(f_p)$
    shadowing : 8 dB
  - Urban macro :
    $A_{\mathrm{dB}} = 28.74 + 35 \log_{10}(d) + 33.81 \log_{10}(f_p)$
    shadowing : 8 dB
  - Urban LOS :
    $A_{\mathrm{dB}} = -35.4 + 26 \log_{10}(d) + 20 \log_{10}(f_p)$
    shadowing : 4 dB
  - Urban NLOS :
    $A_{\mathrm{dB}} = -55.9 + 38 \log_{10}(d) + (24.5 + 1.5\, f_p/925) \log10(f_p)$
    shadowing : 10 dB



900 MHz/1800 MHz in propagation

- **Outdoor :**
  - Free space attenuation is proportional to the carrier frequency

    900 : ☺ **1800 : ☹**

  - For a given gain, the antenna size is proportional to the wavelength

    900 : ☹ **1800 : ☺**

- **Indoor :**
  - Penetration in a building is impossible when the wall's thickness is very higher than the wavelength

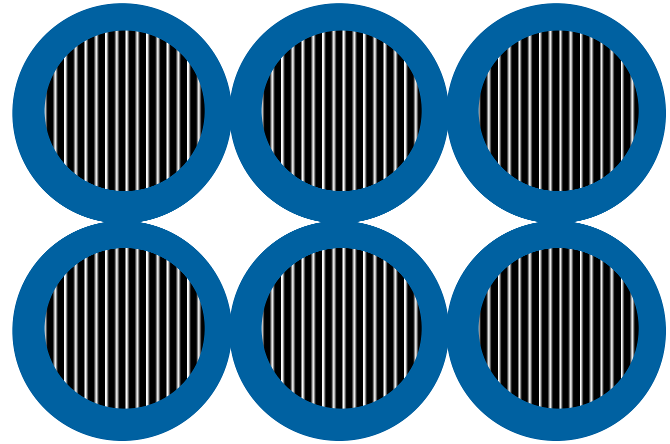
    900 : ☺ **1800 : ☹**

  - Inside the building, walls act as a waveguide

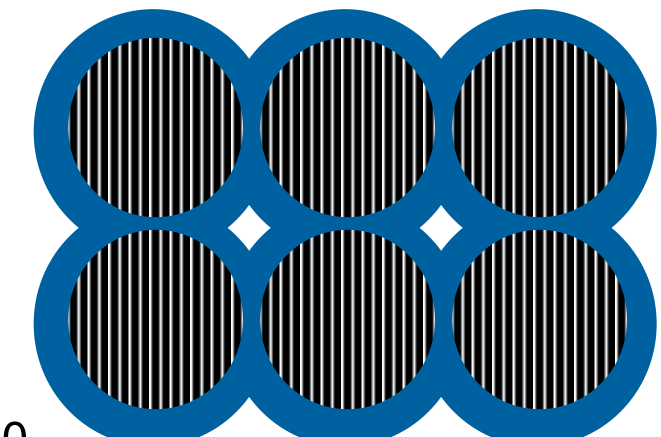
    900 : ☹ **1800 : ☺**

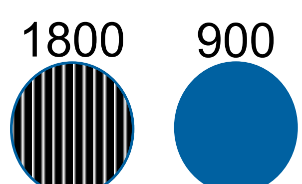
Radio propagation: Reuse of existing sites

- **« historic » operator 900:**
  - Bi(tri)-band : add of carrier frequencies 1800, 2000, etc
  - capacity at the cells centers ↑↑
  - coverage holes →



- **historic » operator 1800 :**
  - Bi(tri)-band : add of carrier frequencies 900
  - capacity ↑↑
  - coverage holes ↓↓

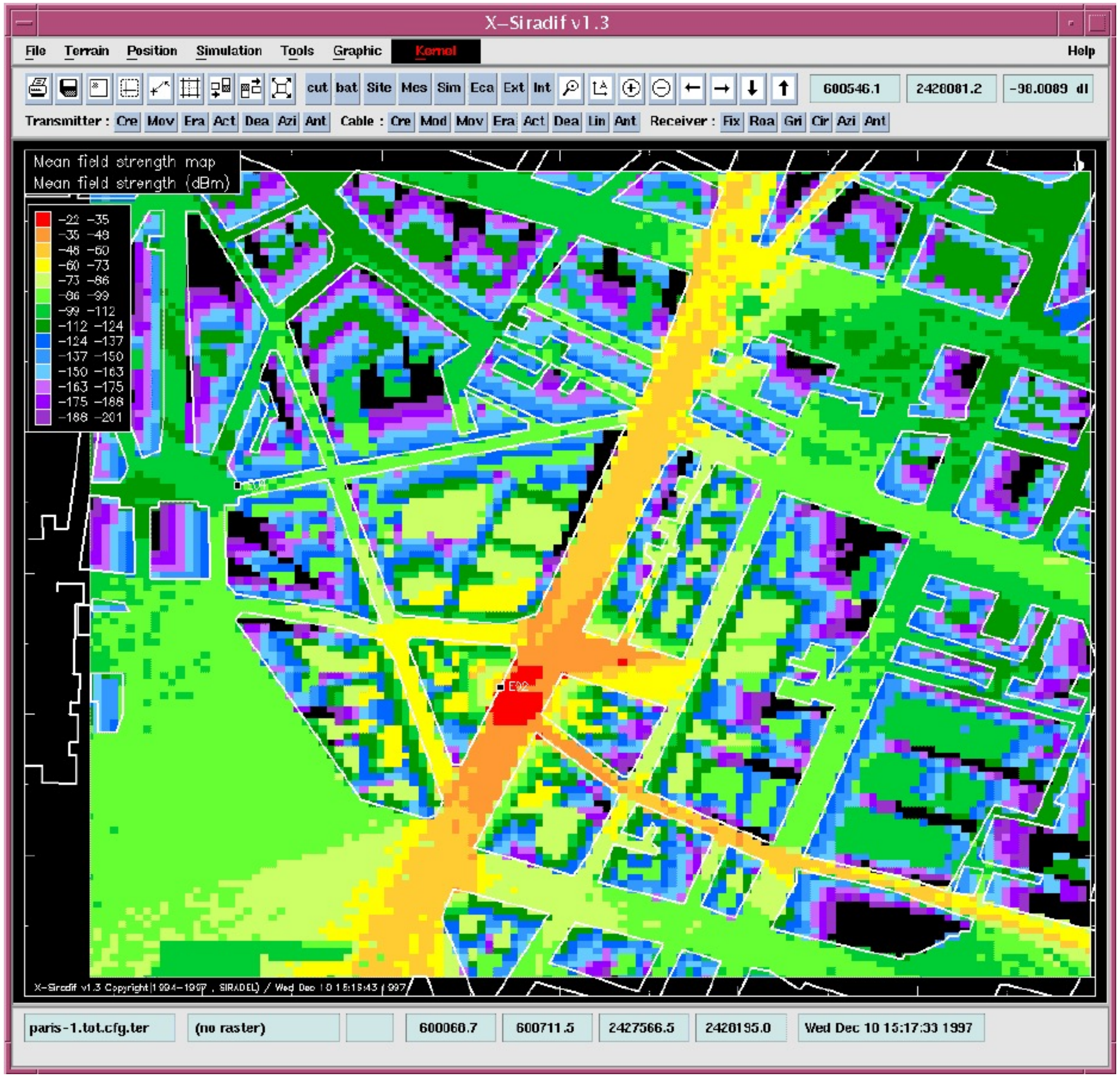




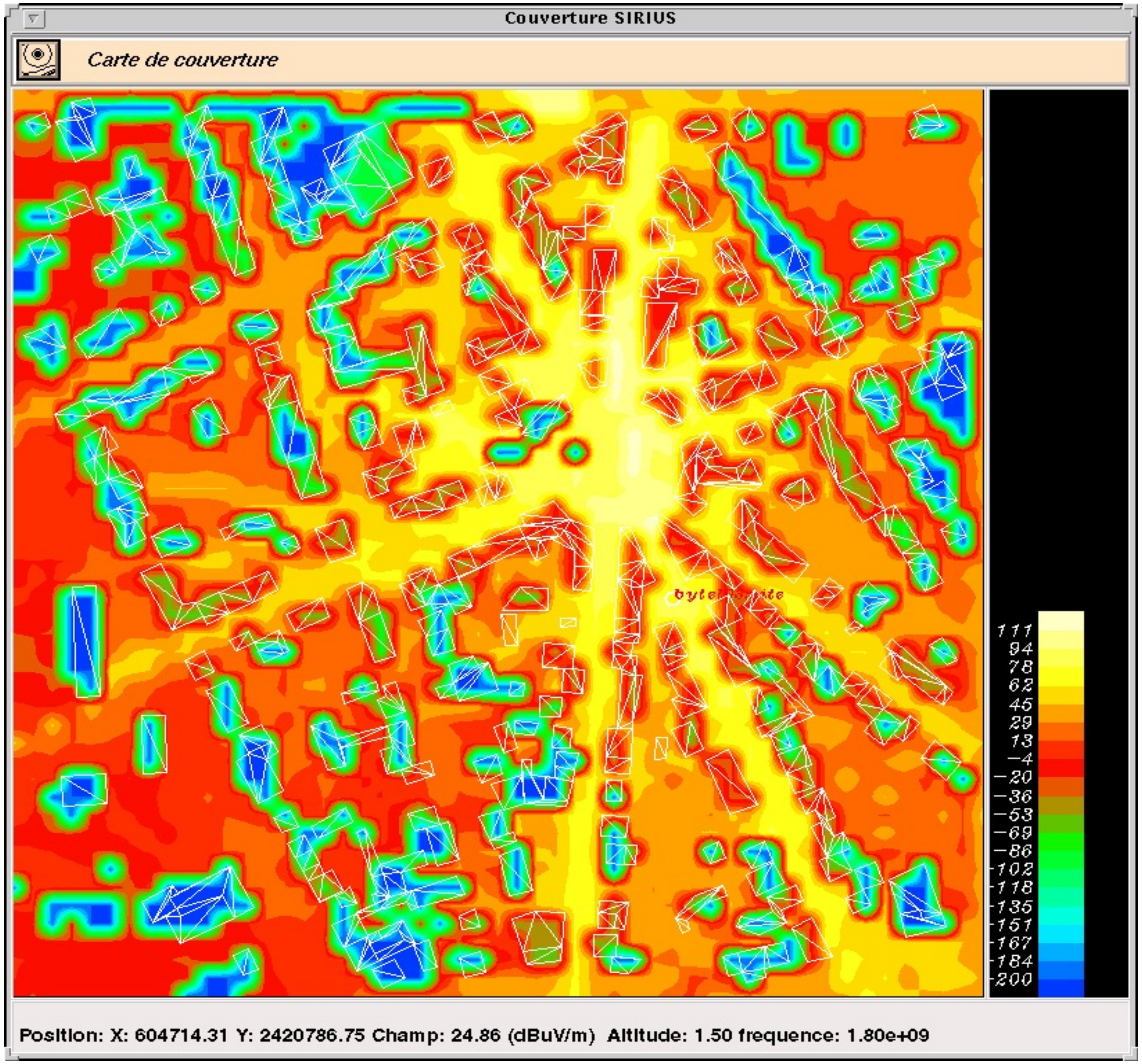
Radio propagation: Types of cells

- **macro-cells: fast moving mobile devices**
  - range: 0,4 km to 30 km
  - Access Point antenna height: above the roofs
- **micro-cells: pedestrian**
  - range: 100 to 300 m; « canyon » coverage (couloir)
  - Access Point antenna height: *below* the roofs
- **pico-cells: inside the buildings**
  - rayon: 10 to 50 m
- ***femto-cells : home radio coverage***
  - *Direct connection to the operator's Core Network*

Radio propagation: Simulation (1/)



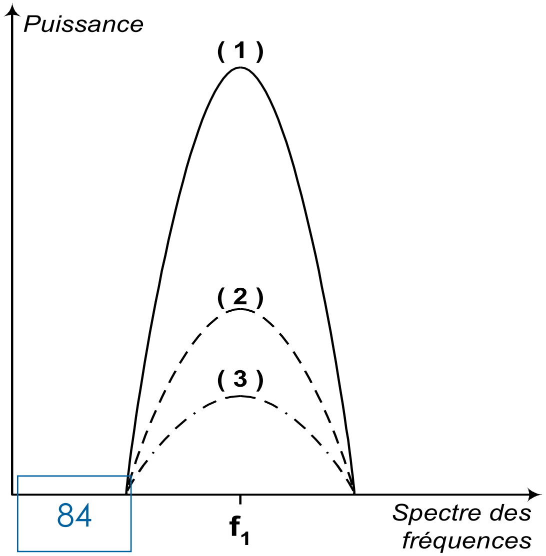
Radio propagation: Simulation (2/)

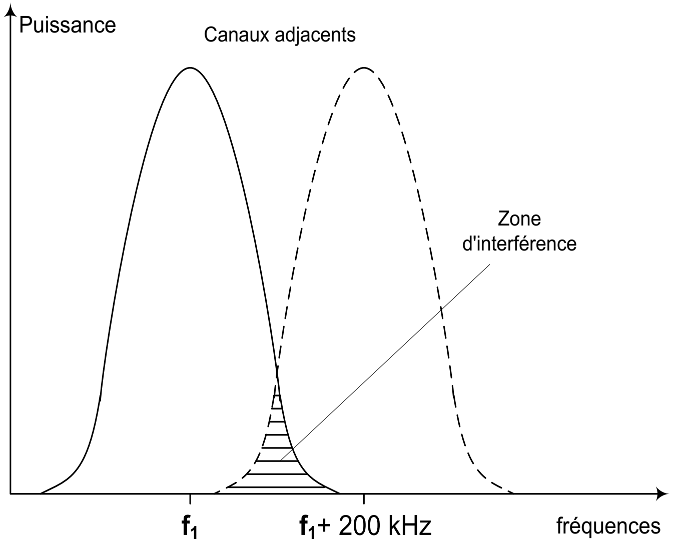


Radio propagation: Interferences

- **A « high » received power (RXlevel,Reference Signal Received Power) is not enough.**

- **Interferences management is essential:**
  - noise
  - interferences (RXqual,CQI, RS Srength Indicator)





Radio propagation: Link Quality (1/)

- **Radio Link high quality ⇔ :**
  - Received signal power: high
  - Interferences power : low

$$\left.\begin{array}{l}\text{Received signal power: high}\\ \text{Interferences power : low}\end{array}\right\} \quad \frac{C}{I} >> 1$$

- **Compromise (max received power/ min interferences) in order to adjust the Tx power : « power control »**
  - ⇒ ensure the required QoS requise for each user in all the network
  - ⇒ ensure a minimum power consumption for the transmitters:
    - « green communications »
    - mobile devices battery life ↑
    - the amount of operators electricity bills ↓

Radio propagation: Link quality (2/)

- **Shannon theorem :**

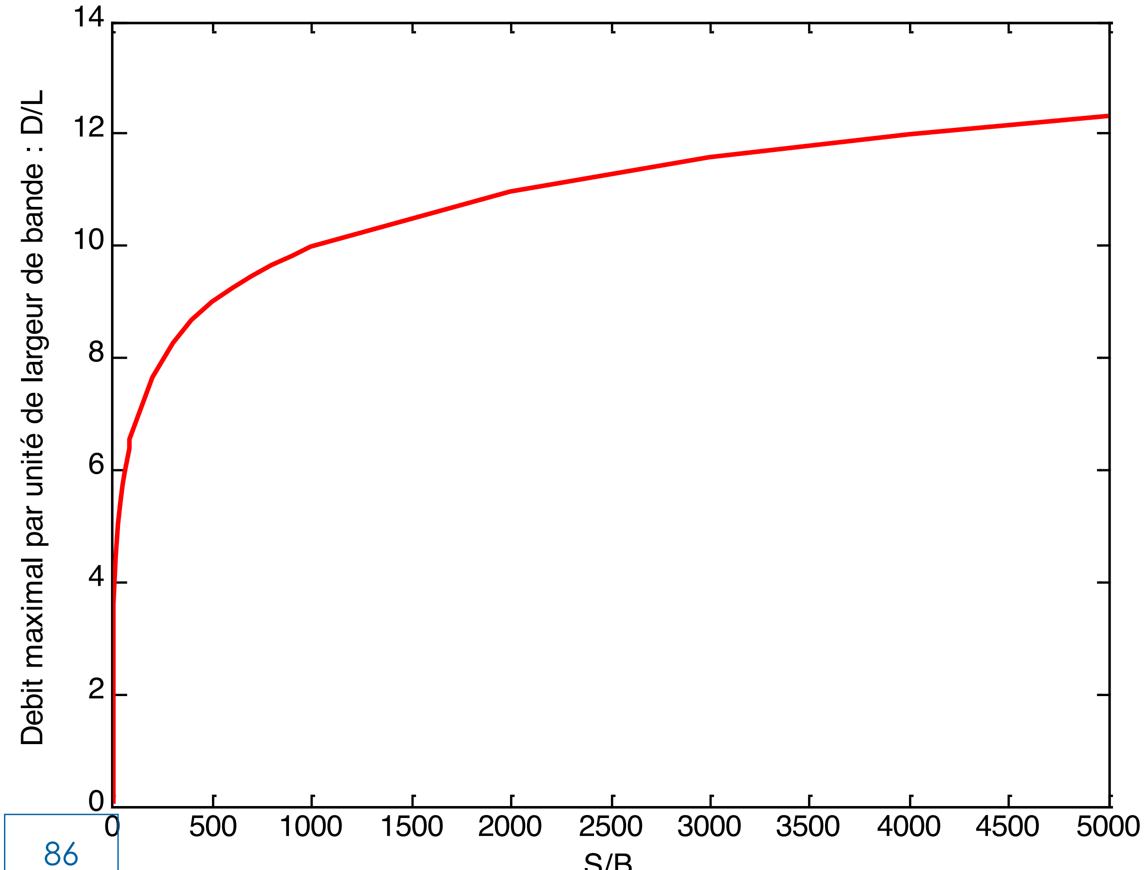
$$D = L \times \log_2\left(1 + \frac{C}{I}\right) \quad \text{bits/s}$$

Max offered throughput

Power of received signal

bandwidth

Power of received interferences & noise



Radio propagation: Link quality (3/)

- **C / I increase ⇔ :**
  - listening quality (voice communication),
  - data throughput (multimedia transfer)

  ⇒ Subcribers satisfaction

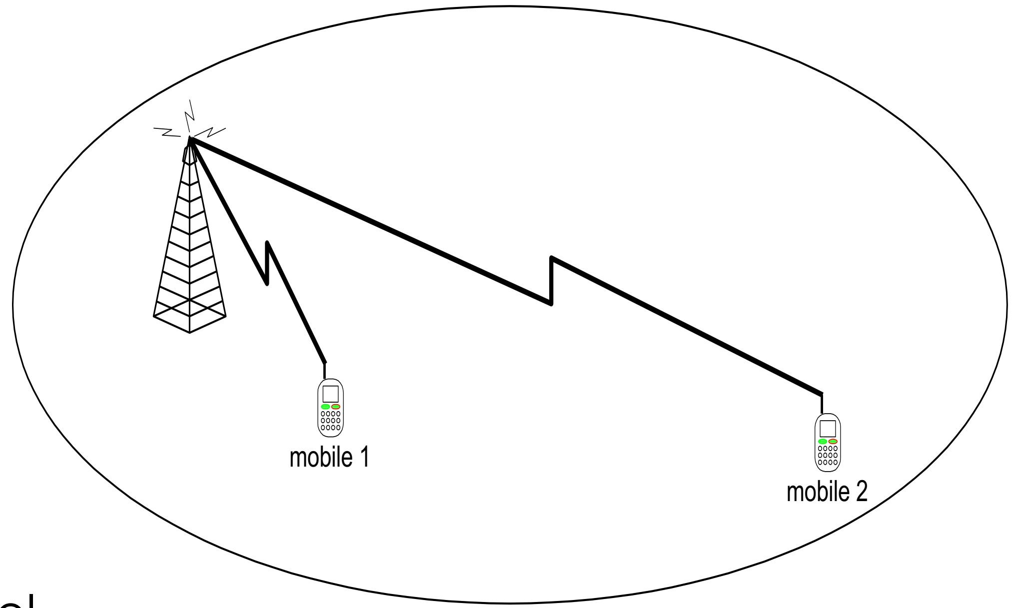
- **Enhancement factors :**

  Only on the Air interface

  - Power control
  - Discontinuous transmission
  - Frequency hopping

Radio propagation: Link quality (4/)

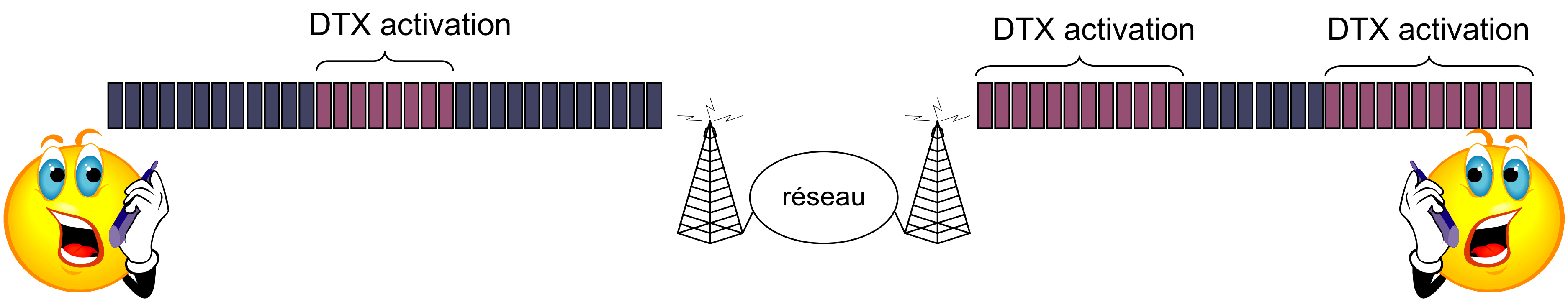
- **Power Control:**
  Tuning of transmission power, as a function of the radio propagation conditions



- **pros:**
  - devices battery life
  - interference mitigation
- **cons:**
  - Not on the beacon channel
- **Parameters :**
  - By step of 2 dB (till around ~100 mW [Paris])

Radio propagation: Link quality (5/)

- **Discontinuous transmission (circuits services): break in transmission during periods of silence**

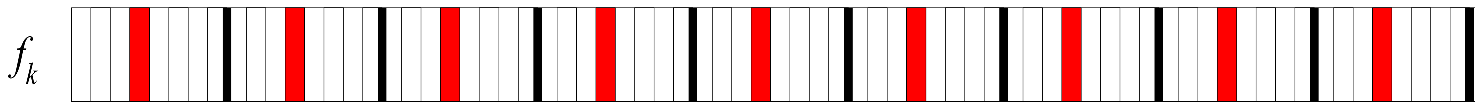


- **pros:**
  - mobile devices battery life
  - interferences mitigation

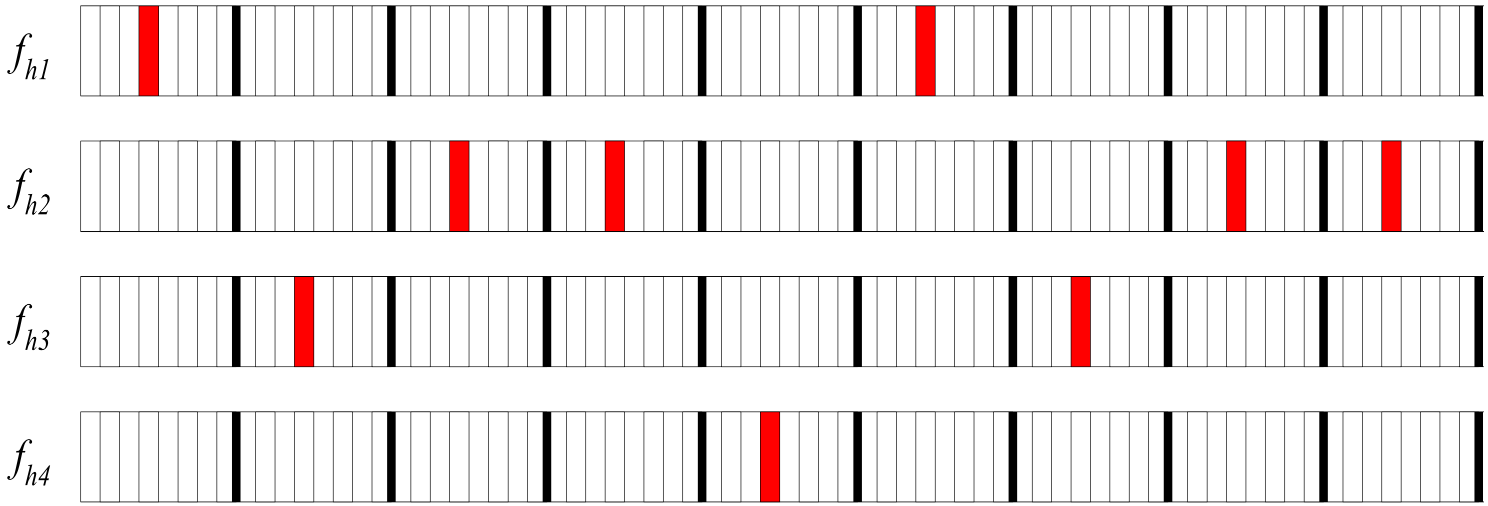
- **Parameters :**
  - Voice activity detector «VAD»
  - transmission of a « background noise» : 260 bits each 120 ms (≠244 bits each 20 ms)

Radio propagation: Link quality (6/)

- **Without frequency hopping:**

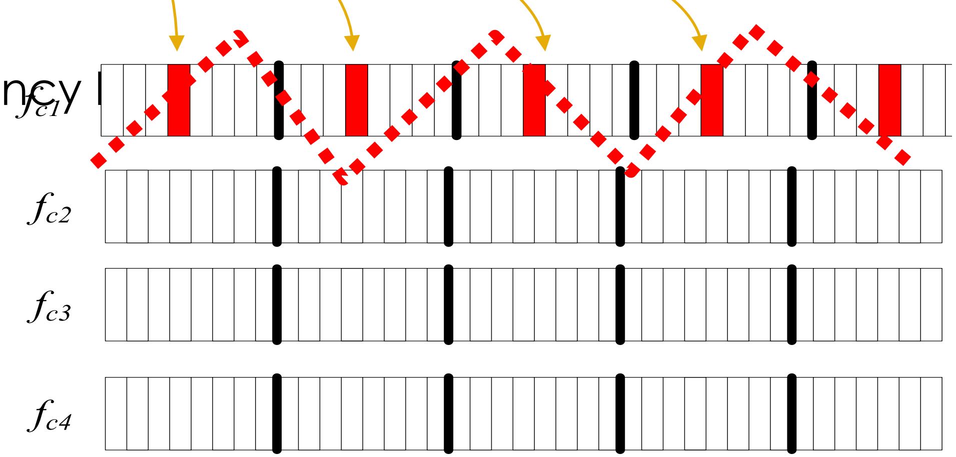


- **With frequency hoping:**
  - Change of carrier frequency at each burst transmission



Radio propagation: Link quality (7/)

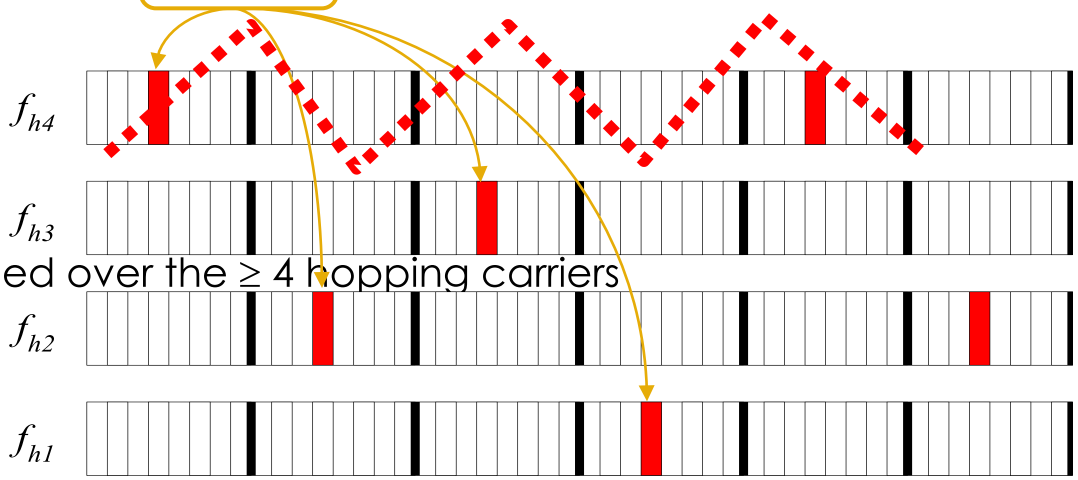
- **Thanks to frequency hopping, averaging of all interferences:**
  - 20 ms voice $\Rightarrow$ N coded bits (N > 244, for protection: channel coding)
  - N bits = 4 $\times$ N/4 bits
  - Without frequency



- f_{c1} users Qos $\neq$ other users QoS

Radio propagation: Link quality (8/)

- With frequency hopping : N/4 bits



- Users QoS averaged over the ≥ 4 hopping carriers

- **pros:**
  - mainly for slow moving devices
  - protection against Rayleigh fading
  - interferences level averaging
- **cons :**
  - not on the beacon channel

Cellular patterns (1/)

- **To each cell is allocated a certain number of « subcarriers » included in the operator's frequency bandwidth**

- **Nb of subcarriers allocated to a cell ↑**
  (elementary bandwidth subcarrier: 2G : 200 kHz, 3G : 5 MHz, 4G : 180 kHz)

  ⇒ cell's capacity ↑ :

  - Number of simultaneous served subscribers ↑ and Throughput offered to each subscriber →

  or

  - Number of simultaneous served subscribers → and Throughput offered to each subscriber ↑

- **BUT the operators are allocated a very limited bandwidth, much lower than the one required to handle the trafic requested by their subscribers ⇒ Each operator reuse the subcarriers, following a frequency reuse pattern**

Cellular patterns(2/)

- **Frequency cellular pattern :**

  smallest group of cells that contains one and only once all the available subcarriers.

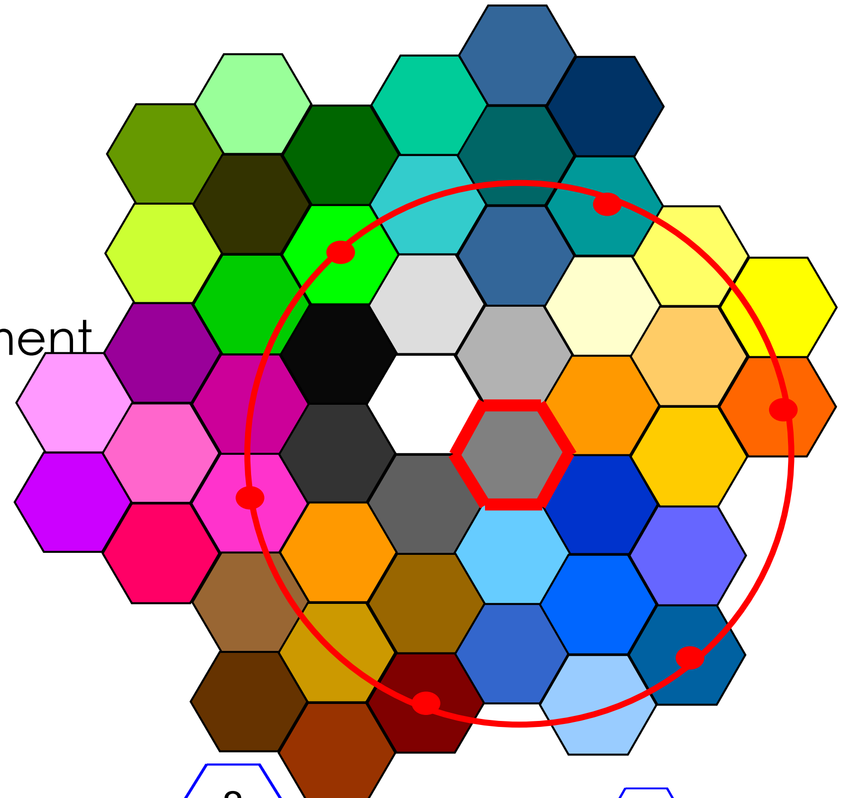
- **The frequency cellular pattern is repeated over all the territory: it is the frequency planning**

- **Each cell's capacity is a function of the pattern size:**
  - pattern size $\uparrow \Rightarrow$ individual cell's capacity $\downarrow$

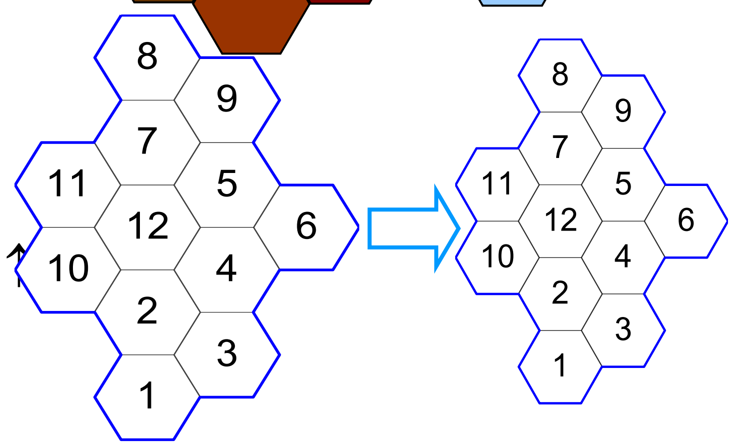
- **reusing distance: D (see below)**

Cellular patterns (3/)

- **Example of pattern: size = 7**
  - Regular size
    ⇒ interfors on a circle
    ⇒ easier interferences management



- **Network densification:**
  - inter-site distance ↓
    ⇒ capacity per km² ↑
  - Pattern size ↓ (3)
    ⇒ bandwidth allocated to each cell ↑
    nb of subcarriers ↑
    ⇒ capacity per cell ↑



Cellular patterns (4/)

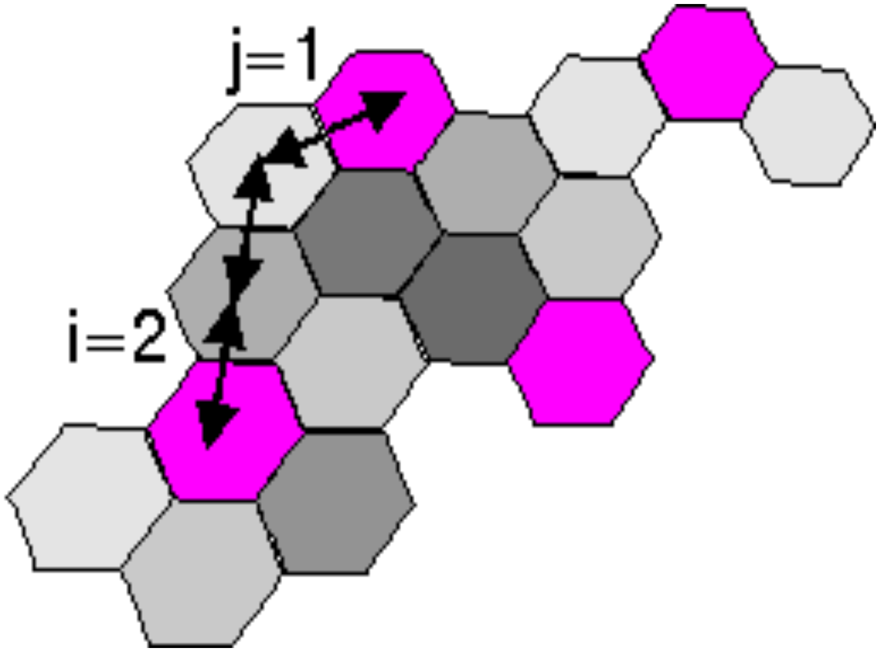
- **Example of a 7 cells pattern**

- **Integers *i* and *j* determine the relative location of co-channel cells (in this case, i = 2 and j = 7)**

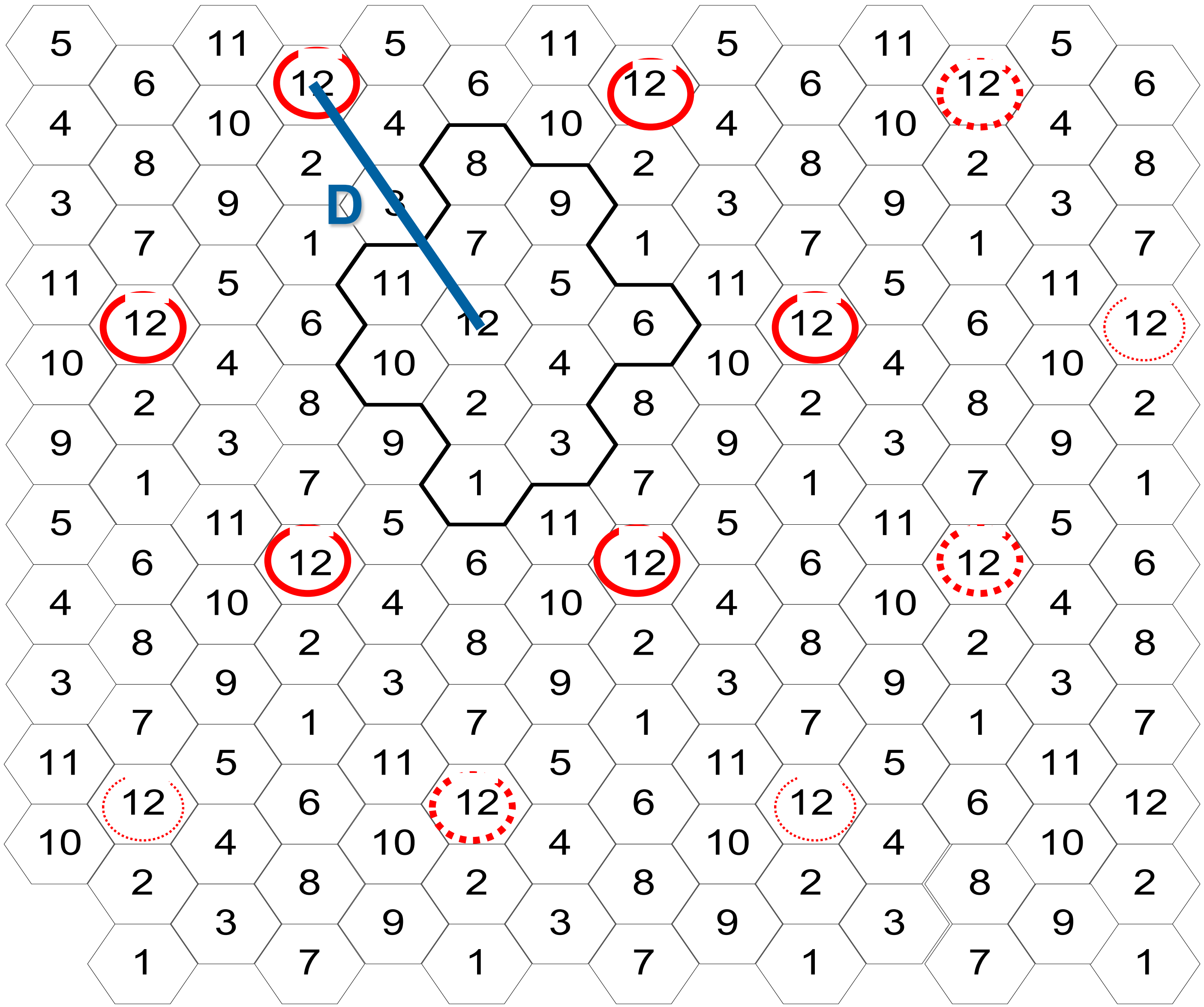
- **Regular pattern of size K :**

  - $K = i^2 + i.j + j^2$

  - i and j values
    are useful to determine
    the interferors location



Cellular patterns : Interference ring



Cellular patterns : « jokers »

Cellular patterns : Signal / Interferences

- **General formula:**
  - C : Power of the received useful signal
  - I : Power of the received interferences
  - D : reuse distance
  - R : max Tx-Rx distance in a cell
  - γ : propagation coefficient

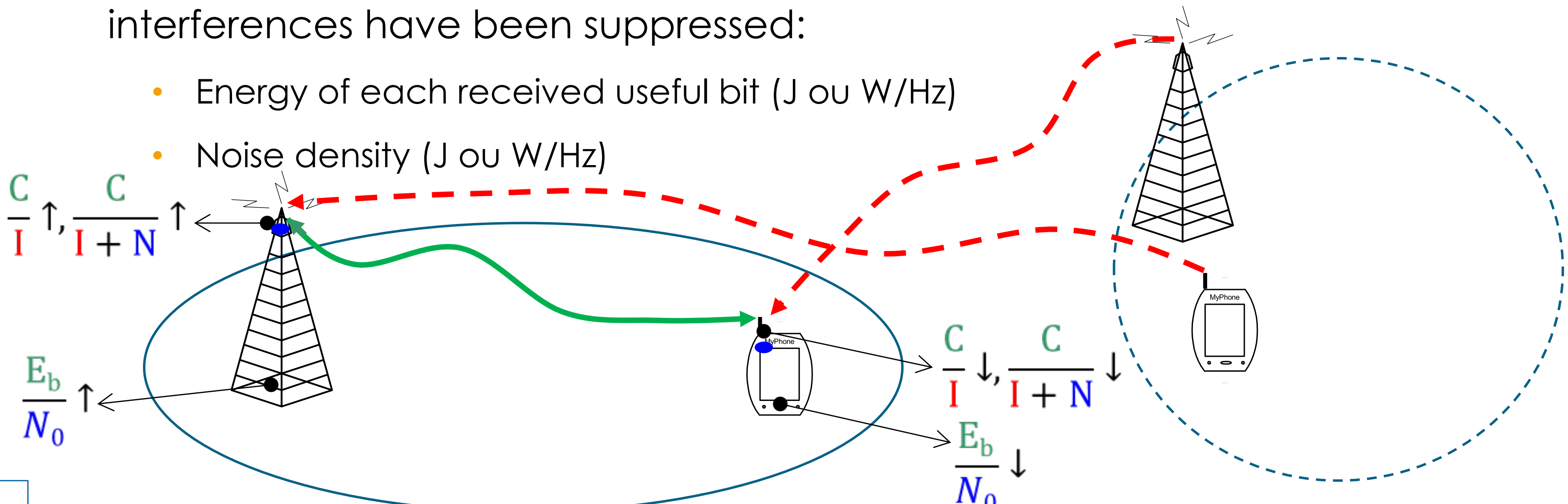
$$\frac{C}{I}=\frac{1}{6}\left(\frac{D}{R}\right)^{\gamma}$$

$$\frac{C}{I}=\frac{1}{6}\left(\sqrt{3K}\right)^{\gamma}$$

- **This formula can be first adopted for GSM and LTE, but more accurate studies are then necessry… Pay attention to the asumptions!!!**

Signal / Interferences (1/)

- **Radio link quality evalution criteria:**
  - C/I (= SIR), C/(I+N) (= SINR) :
    POWER ratio, at the input of the receiver:
    - Power of the received useful signal (W or mW)
    - Power of the received interferences (W or mW)
    - (Power of the received thermal noise (W or mW))
  - E_b / N_0 :
    ENERGY ratio, at the end of the « reception chain », assuming that the interferences have been suppressed:
    - Energy of each received useful bit (J ou W/Hz)
    - Noise density (J ou W/Hz)



Signal / Interferences (2/)

- N_0 : **Thermal noise density:**
  N_0 = k T = 1.38 10^{-23} x 300 = - 204 dBJ = -174 dBmJ = -174 dBmW/Hz

- C : **Power of the received useful signal at the input of the receiver:**

$$C = \frac{EIRP_{Tx}}{LO_{propagation}} = \frac{E_b}{T_b} = E_b \times D_b$$

- **Power of the received useful signal at the end of the reception chain:**

$$C \times \left(\frac{GA}{LO}\right)_{Rx} = \frac{EIRP_{Tx}}{LO_{propagation}} \times \left(\frac{GA}{LO}\right)_{Rx}$$

- E_b / N_0 **is assimilated to: Energy of the received useful signal / Energy of the disturbances (it is hpoed that only the thermal noise remains):**

$$\frac{E_b}{N_0} \approx \frac{E_b}{N_0 + I_0} = \frac{C \times T_b}{N \times T_b + I \times T_b} = \frac{C}{I+N}$$

Network engineering (1/)

- **engineering = network deployment/roll-out**

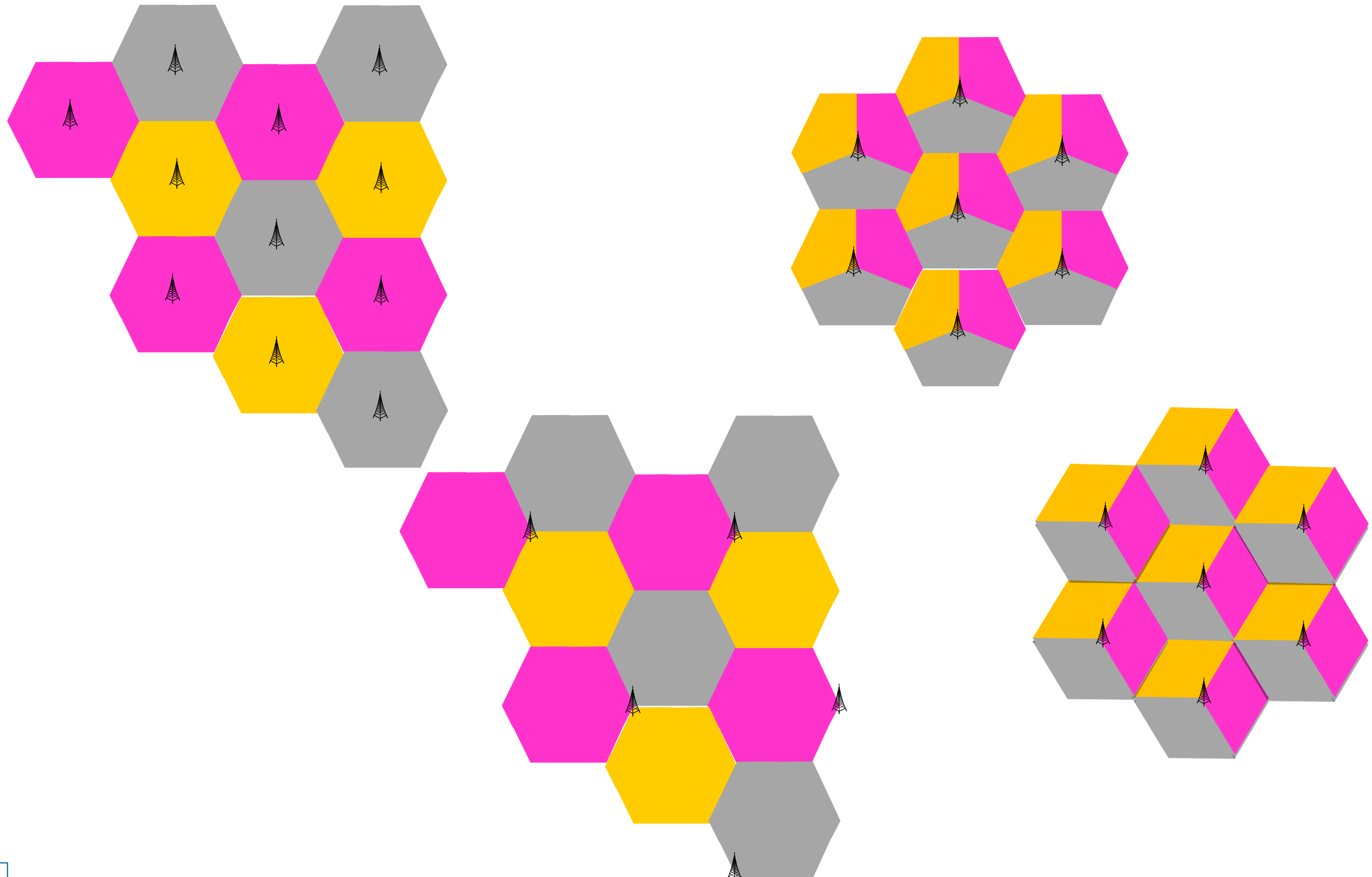
- **To each site of the network are associated from 1 to 3 cells or sectors.**

- **The network is a juxtaposition of cells**

- **Each cell:**
  - is allocated a given number of subcarriers among those belonging to the operator
  - has consequently a given traffic capacity.

Network engineering (2/)

École d'ingénieurs du numérique



Network engineering (3/)

- **Example of network specifications:**
  - **Voice communication of 2 mn perturbated less than 10s**
  - Small rate of failure during the network access and during the communication
  - Quality of voice communication excellent/ good/ average/ low
  - Quality of data communication:
    acces time, data rate, time of access, size of blocks temps

- **Definition of coverage product:**
  - List of geographical zones to cover with RF level for different services (car, perdestrain, train, outdoor, indoorr)

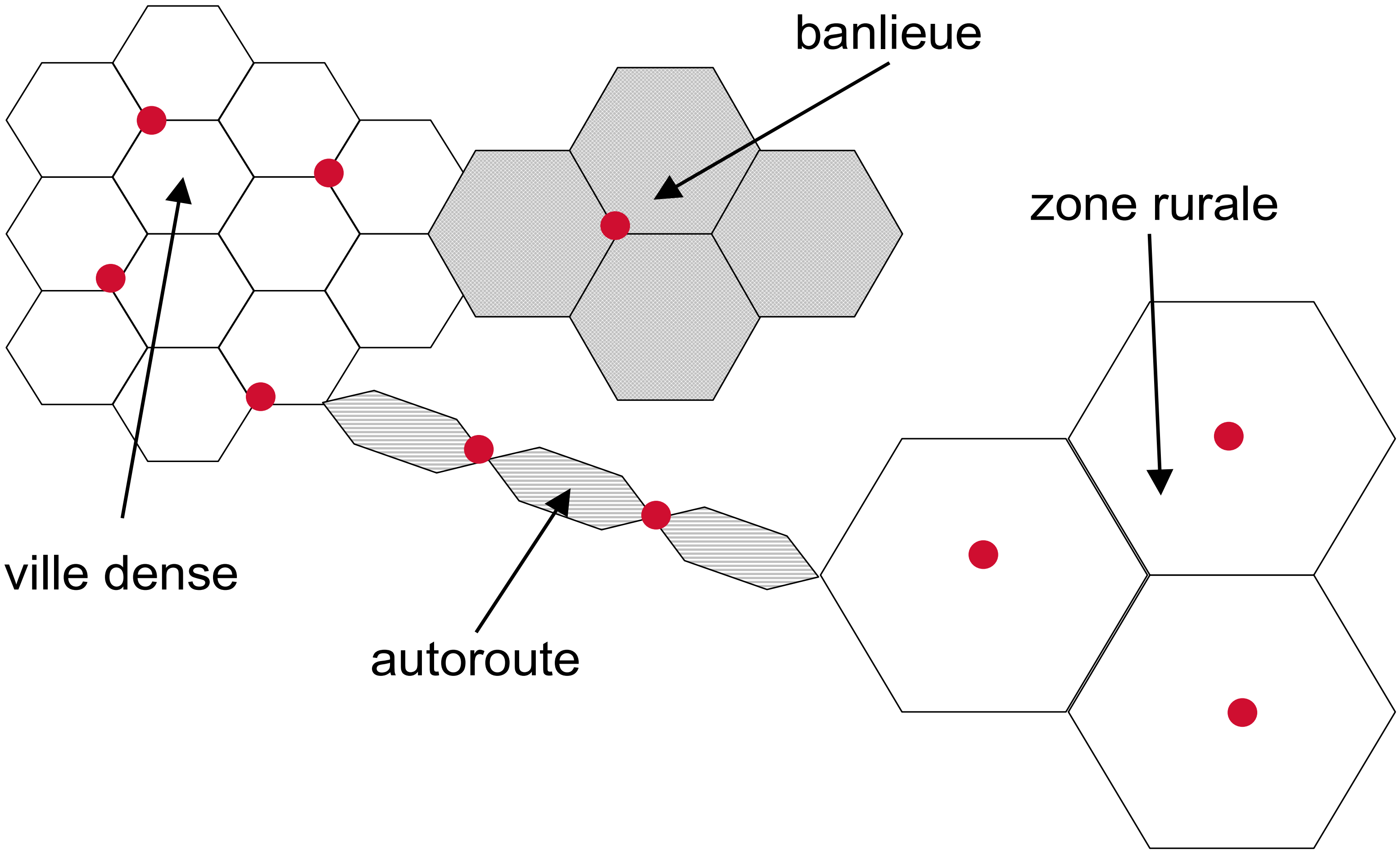
- **Traffic specification**

Network engineering (3/)

- **engineering $\Rightarrow$ roll-out strategy:**
  - points of presence vs. coverage
  - density
  - axes vs traffic nodes
- **needs analysis:**
  - coverage vs. capacity
- **terrain database**
  - 25 m for rural et suburban
  - 5 m pour urban (when > 400 000 inhabitants)
- **Topology choice**
  - Macro cells: coverage & capacity
    - inter sites distance : from 500-800m to 10-15km
  - Macro cells: capacity
    - inter sites distance : 100-200m
- **As appropriate prediction tool**

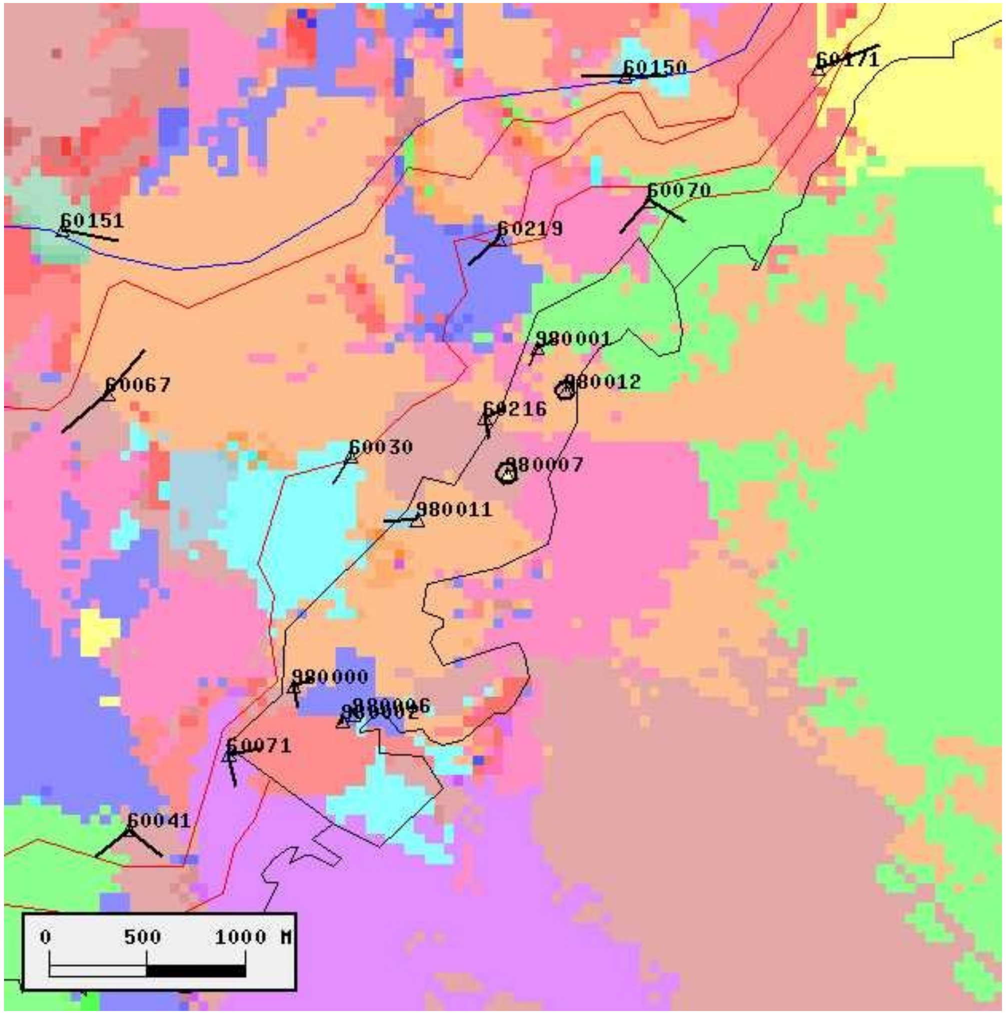
Network engineering (4/)

- **Cells shape and size are adapted to the environment :**



Network engineering (5/)

- **Cells shape in the real world…**
  example - Monaco



Network engineering: Densification

- **Max capacity of a site is reached**
  ⇔ new sites must be added: densification sites

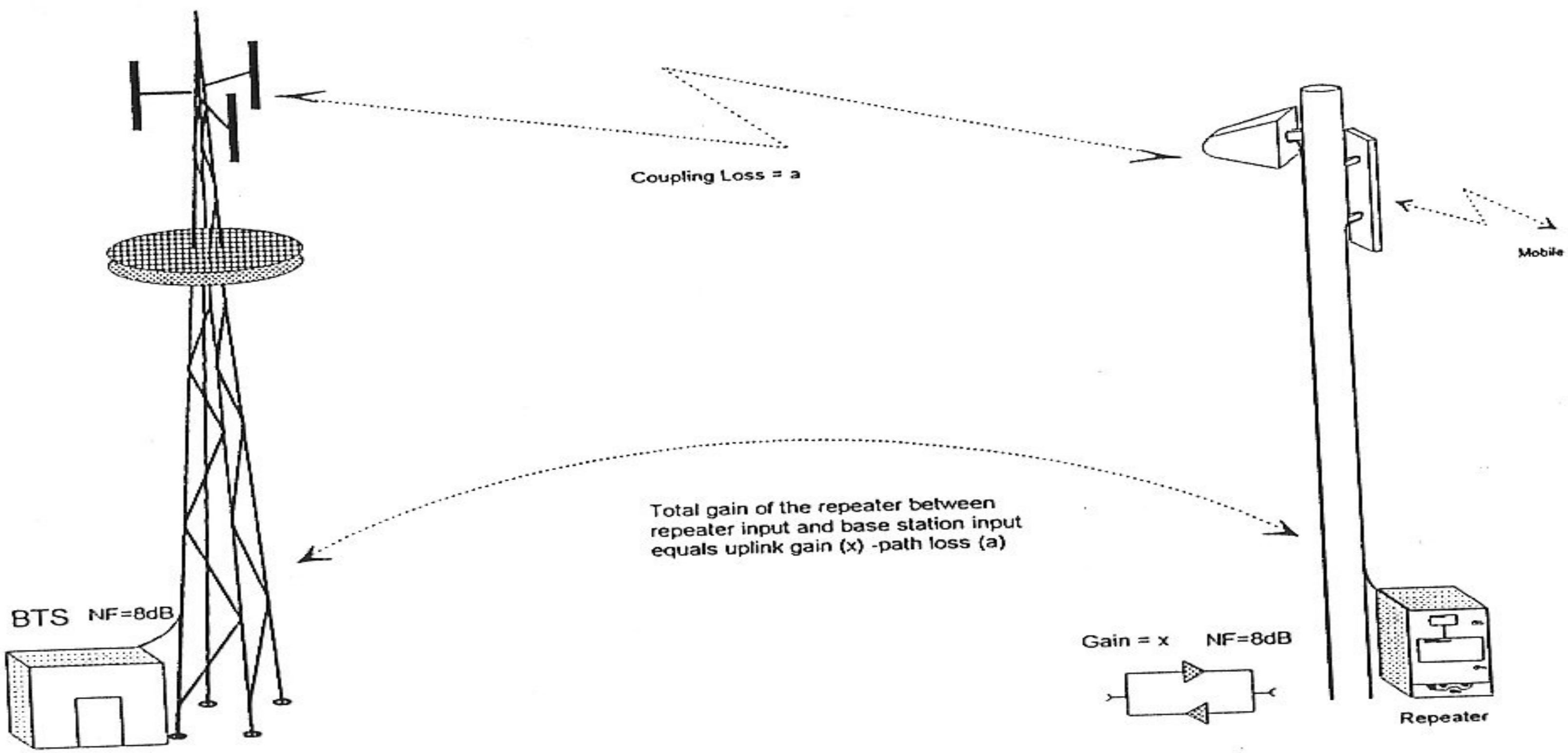
- **Site dimensionning:**
  - number of subcarriers in function of the voice trafic (Erlang laws), the multimedia services offered by the operator (min throughput, QoS), and the operator economic strategies,
  - ensuring an economic efficiency: utilization rate of the site capacity

- **Confine the radiation / Tx power control**
  - coverage of a crossroads / an road
  - frequency plan compliancy
  - taking advantages of the obstacles
  - low horizontal beamwidth (~65°) vs directivity
  - antenna tilt: fixed or variable

- **Homogeneity of the engineerin over a large territory:**
  - Easier paramaters tuning & densification

Network engineering: Repeaters

Coverage extension



Network engineering: circuit traffic 1/

- **Circuit traffic unit: the Erlang**
  - one channel occupation rate over 1 hour
  - 1 Erlang = 1 hour of communication on one subcarrier
  - 1 Erlang = 2 communications of 30 min. each on two subcarriers
  - 1 Erlang = …
  - Typical example: 1 subscriber = 50 mE
- **Blocking probability**
- **Trafic capacity function of the number of subcarriers allocated to each cell**
- **«Busy hour » dimensionning:**
  - of the day
  - of the week
  - etc

Network engineering: circuit traffic 2/

École d'ingénieurs du numérique

- **Erlang B table: estimated traffic in function of a blocking probability (in %) and the number of circuits expected for this traffic transmission:**

$$99\% \times 8.1\ Erl$$

Actually, the network will offer:

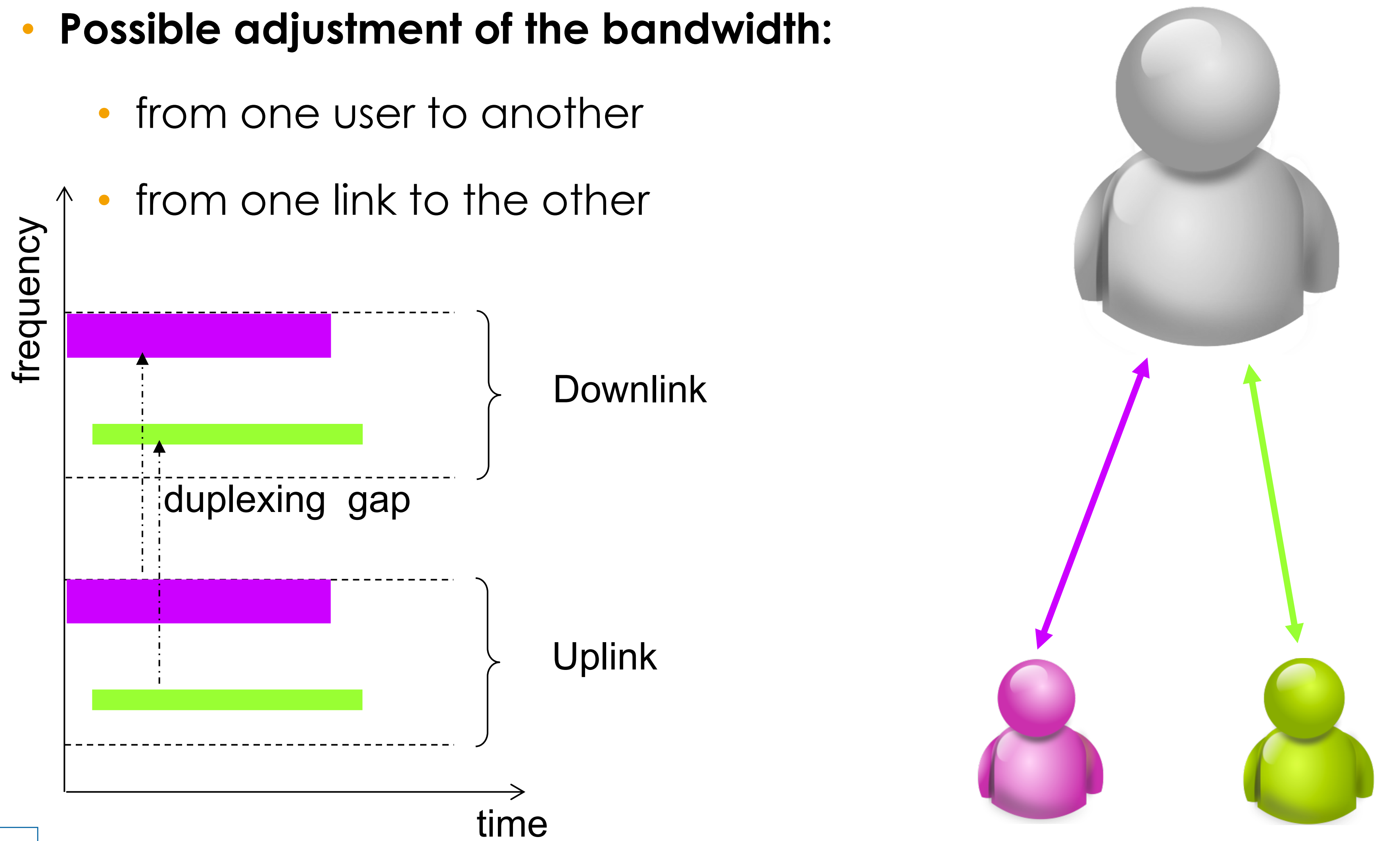
N/E	.01	.05	.1	.5	1.0	2	5	10	15	20	30	40
1	.0001	.0005	.0010	.0050	.0101	.0204	.0526	.1111	.1765	.2500	.4286	.6667
2	.0142	.0321	.0458	.1054	.1526	.2235	.3813	.5954	.7962	1.000	1.449	2.000
3	.0868	.1517	.1938	.3490	.4555	.6022	.8994	1.271	1.603	1.930	2.633	3.480
4	.2347	.3624	.4393	.7012	.8694	1.092	1.525	2.045	2.501	2.945	3.891	5.021
5	.4520	.6486	.7621	1.132	1.361	1.657	2.219	2.881	3.454	4.010	5.189	6.596
6	.7282	.9957	1.146	1.622	1.909	2.276	2.960	3.758	4.445	5.109	6.514	8.191
7	1.054	1.392	1.579	2.158	2.501	2.935	3.738	4.666	5.461	6.230	7.856	9.800
8	1.422	1.830	2.051	2.730	3.128	3.627	4.543	5.597	6.498	7.369	9.213	11.42
9	1.826	2.302	2.558	3.333	3.783	4.345	5.370	6.546	7.551	8.522	10.58	13.05
10	2.260	2.803	3.092	3.961	4.461	5.084	6.216	7.511	8.616	9.685	11.95	14.68
11	2.722	3.329	3.651	4.610	5.160	5.842	7.076	8.487	9.691	10.86	13.33	16.31
12	3.207	3.878	4.231	5.279	5.876	6.615	7.950	9.474	10.78	12.04	14.72	17.95
13	3.713	4.447	4.831	5.964	6.607	7.402	8.835	10.47	11.87	13.22	16.11	19.60
14	4.239	5.032	5.446	6.663	7.352	8.200	9.730	11.47	12.97	14.41	17.50	21.24
15	4.781	5.634	6.077	7.376	$\boxed{8.108}$	9.010	10.63	12.48	14.07	15.61	18.90	22.89
16	5.339	6.250	6.722	8.100	8.875	9.828	11.54	13.50	15.18	16.81	20.30	24.54
17	5.911	6.878	7.378	8.834	9.652	10.66	12.46	14.52	16.29	18.01	21.70	26.19
18	6.496	7.519	8.046	9.578	10.44	11.49	13.39	15.55	17.41	19.22	23.10	27.84
19	7.093	8.170	8.724	10.33	11.23	12.33	14.32	16.58	18.53	20.42	24.51	29.50
20	7.701	8.831	9.412	11.09	12.03	13.18	15.25	17.61	19.65	21.64	25.92	31.15
21	8.319	9.501	10.11	11.86	12.84	14.04	16.19	18.65	20.77	22.85	27.33	32.81
22	8.946	10.18	10.81	12.64	13.65	14.90	17.13	19.69	21.90	24.06	28.74	34.46
23	9.583	10.87	11.52	13.42	14.47	15.76	18.08	20.74	23.03	25.28	30.15	36.12
24	10.23	11.56	12.24	14.20	15.30	16.63	19.03	21.78	24.16	26.50	31.56	37.78
25	10.88	12.26	12.97	15.00	16.13	17.51	19.99	22.83	25.30	27.72	32.97	39.44

Duplexing

- **Duplexing = uplink vs. downlink separation :**
  - uplink : from mobile device to the network
  - downlink: from the network to the mobile device
- **« Frequency Division Duplexing »**
  - Parameter : duplex gap (in MHz)
- **« Time Division Duplex »**
  - Parameter : frame duration (in ms)
- **GSM : FDD,**
  UMTS : FDD/TDD, LTE : FDD/TDD; 5G: TDD

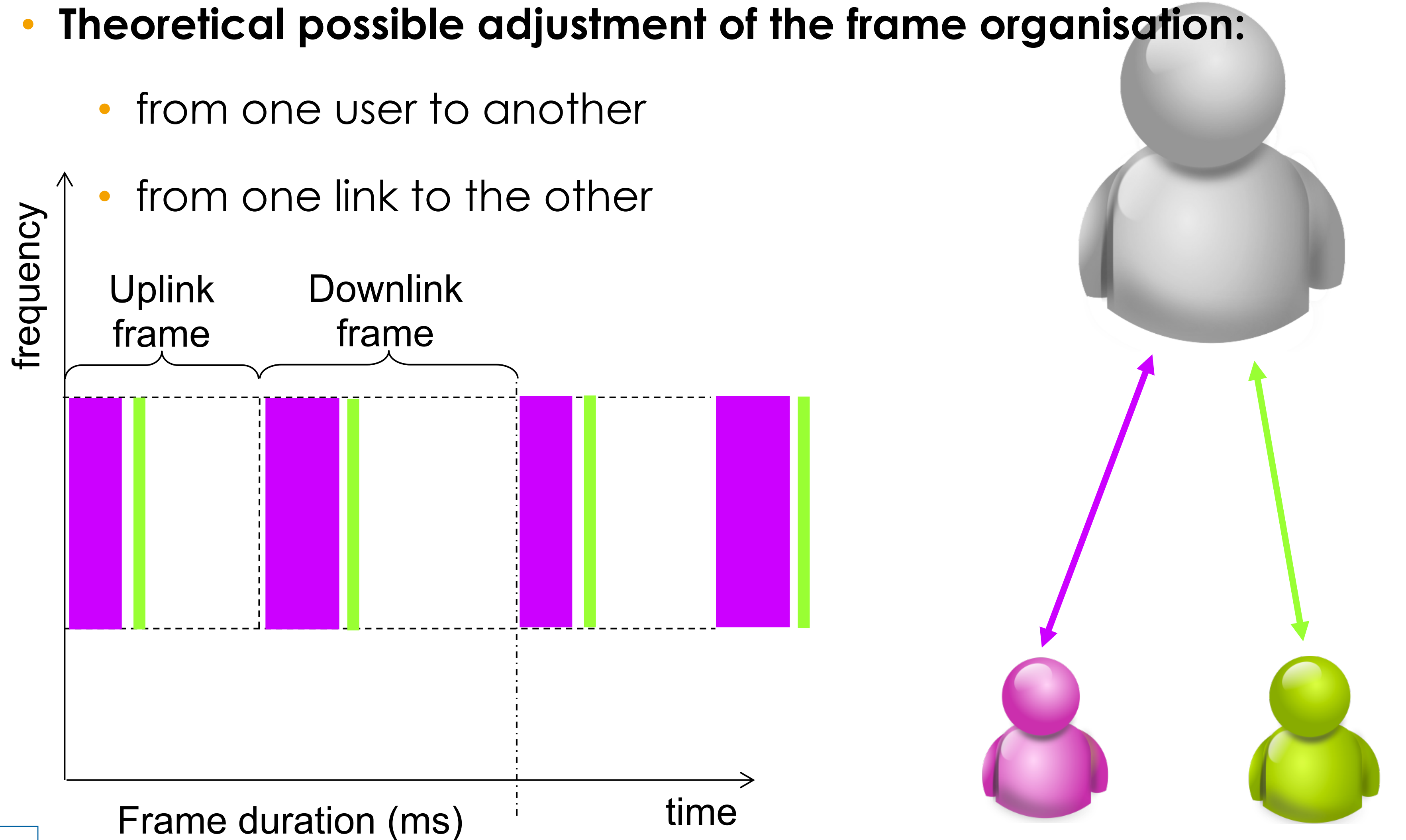
Duplexing : FDD

- **Possible adjustment of the bandwidth:**
  - from one user to another
  - from one link to the other



Duplexing : TDD

- **Theoretical possible adjustment of the frame organisation:**
  - from one user to another
  - from one link to the other



Source coder

- **Caracteristic of digital wireless netwtorks (2G and beyond)**

- **Source coding objective:**
  reduce the information throughput, in order to:
  - reduce the bandwidth to be used…
  - better protect the signal to be transmitted
  - caracterise a voice signal over a 20 to 30 ms period

- **⇒ at the output of the source coder, every 20 ms, the transmitted signal is no more the voice signal, but parameters that characterized this voice signal**

- **Source Coder/Decoder = « Codec »**
  <u>example :</u> throughput at the codec output (GSM / UMTS / LTE) :
  12.2 kbits/s instead of 64 kbits/s (*fixed networks*)

Mobility management: Handover 1/

- **Handover (*handoff*), HO (≠ cell reselection) :**
  - mechanism that makes the mobile device transfer its connection to the network (i.e. DURING THE COMMUNICATION) from one radio channel to another, belonging or not to the same Access Point.
  - commanded after careful analysis of the radio measurements ↑↓

- **Paris : ~ 1 handover / 40 sec. / subscriber**

- **The transfer from one radio channel to another can:**
  - create a short interruption of the connection mobile device ↔ network

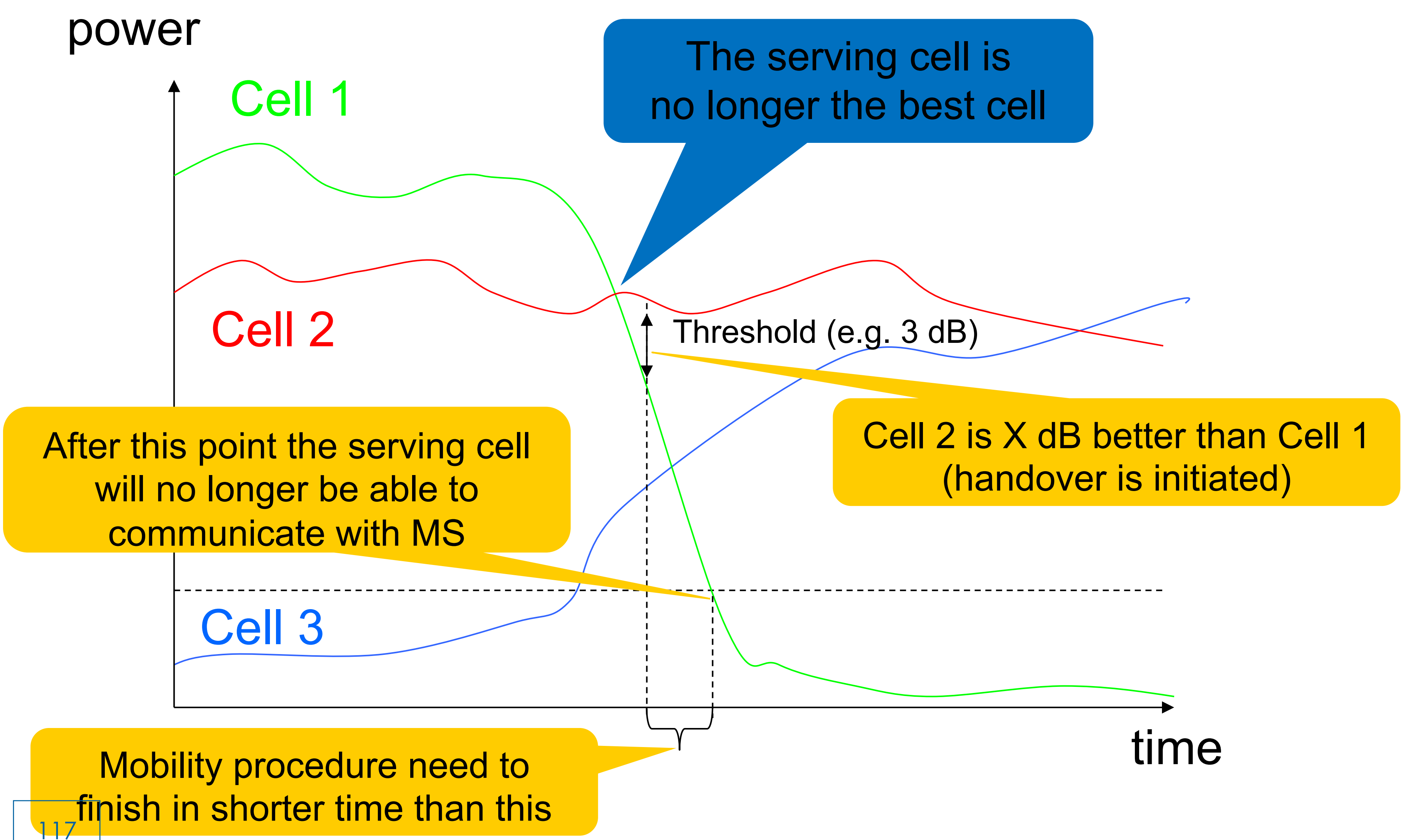
  ⇒ « hard handover » : GSM, UMTS TDD, UMTS inter-bands, LTE

  - be completed without any interruption of the connection mobile device ↔ network

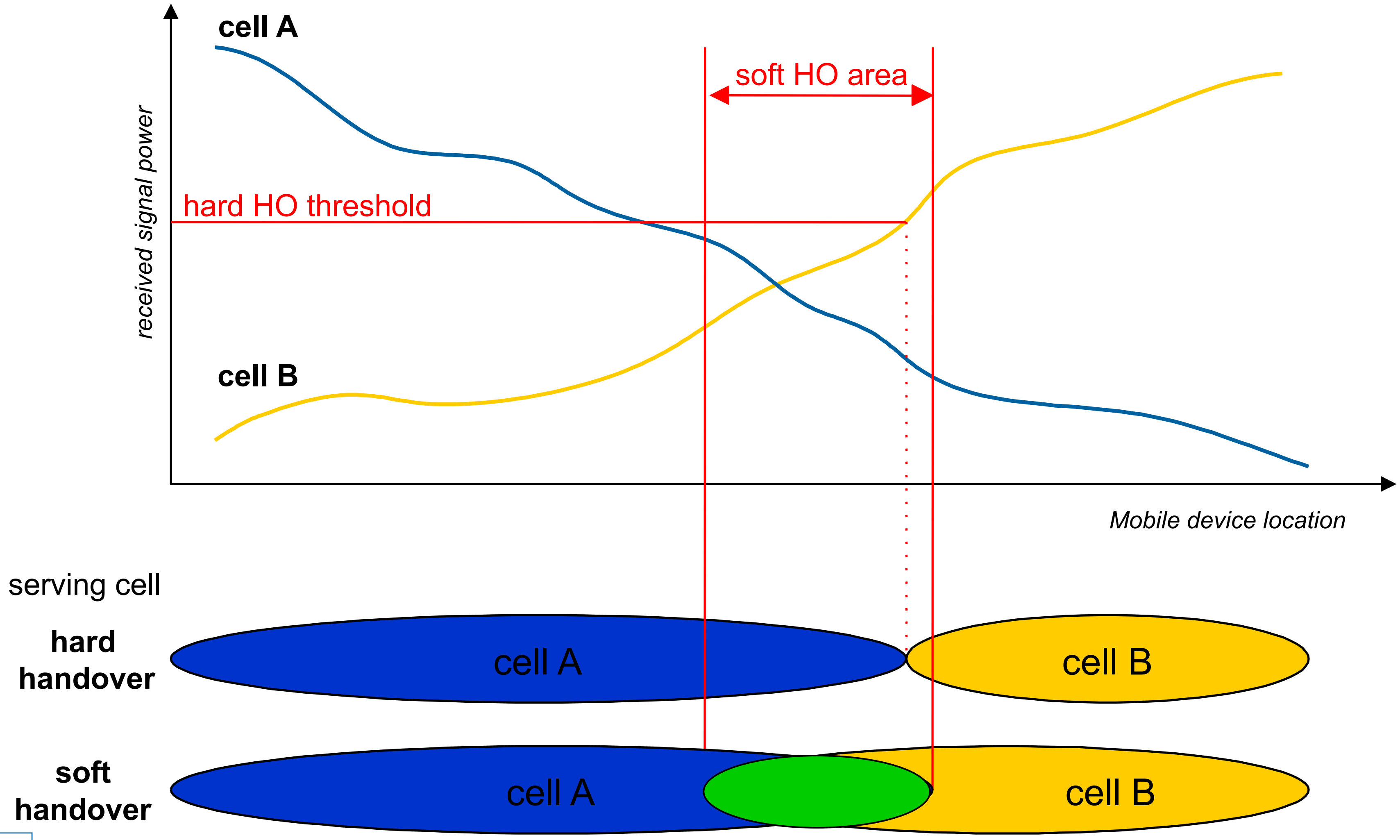
  ⇒ « soft handover » : UMTS FDD

  - result in the mobile device localisation update in the network's databses

Mobility management: Handover 2/



Mobility management: Handover 3/



Mobility management: Localisation areas

- **In presence of an incoming call:**
  - the network can not search the subscriber over the entire covered area of the system!
  - introduction Localisation Area, Routing Area, Tracking Area:

1 Localisation Area =

cells belonging to the <u>same</u> switch

- **Mobility management:**
  localisation update of each subscriber:
  - periodic, or
  - when changing of localisation area

Conclusion

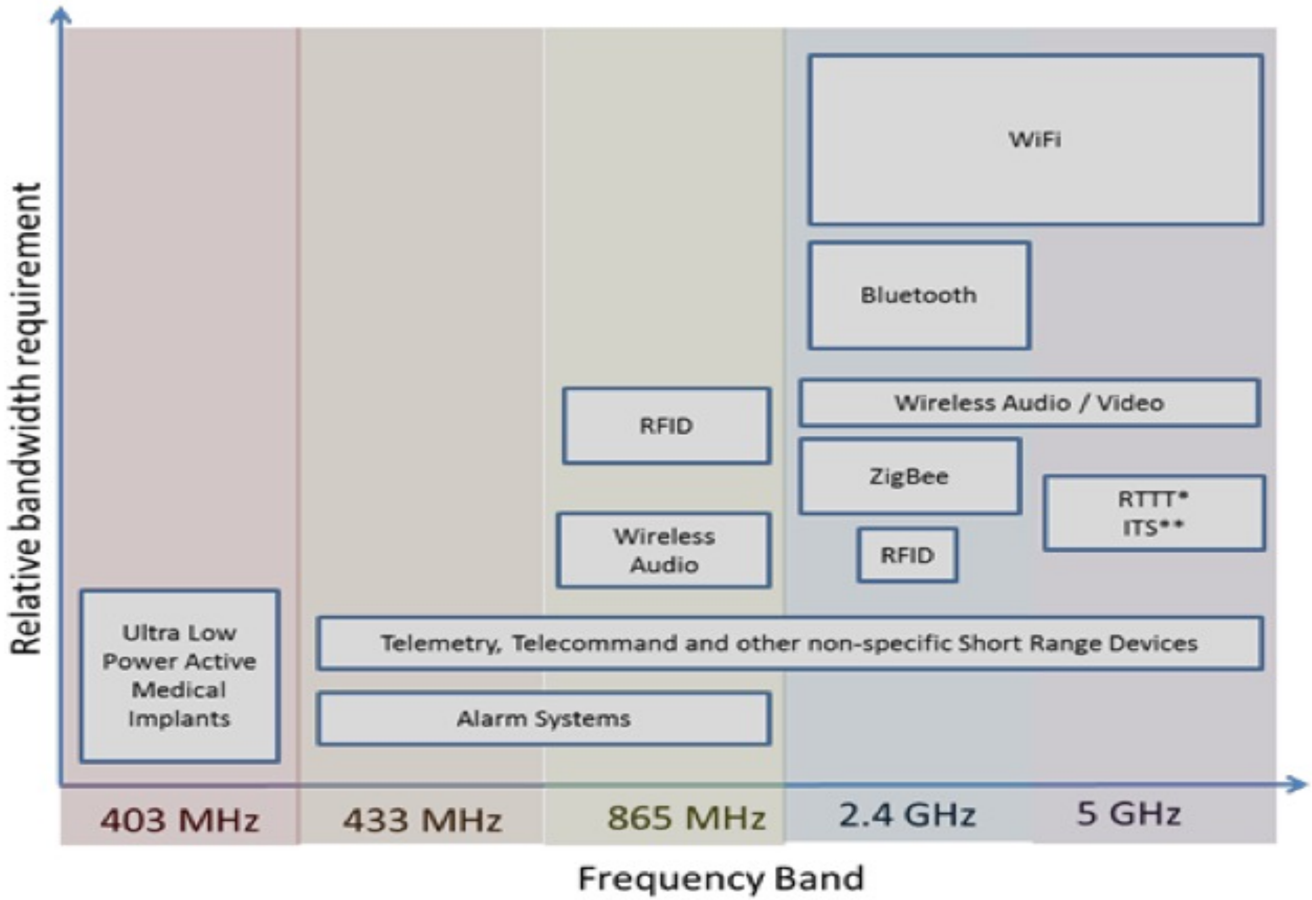
- **Main caracteristics of cellular wireless networks**

- **Specificities of each technologie 3G → 5G presented (again) in the following**

- **2G → 5G technologies standardisation:**

License Exempt Bands for IoT Communications

Unlicensed Band



*Road Transport and Traffic Telematics **Intelligent Transport Systems

License Exempt Bands

- License exempt frequency bands are used by certain devices without the need for prior authorization or an individual right of use.
- The lack of an individual authorization does not mean that these bands are not subject to regulation.
- The access to license exempt bands requires compliance with pre-defined technical rules to minimize the risk of interference between other license exempt devices.
- Short Range Wireless IoT Technologies operate in License Exempt Bands.

User’s Key Benefits

- Greater convenience and flexibility by avoiding the need for lengthy runs of cable in home and work environments.

- Ability to connect mobile devices to a fixed broadband network, reducing dependence on the mobile network and saving costs both for the service provider and the end-user.

- Enhanced convenience, safety and security, e.g. through installation of low cost wire- less alarm systems or ability to unlock vehicles remotely rather than with keys

Service Providers' Key Benefits

- Facilitating market entry: no need to acquire a license to deploy a service
- Providing certainty about spectrum access: there is no need to compete or pay for spectrum access;
- Security of tenure: in general license exemption is not subject to an expiry date;
- Reduced congestion in licensed bands (e.g. through traffic offload from cellular net- works to Wi-Fi).
- The ability to extend the reach of fixed communication networks, by providing wireless local area connectivity in homes, businesses and at public traffic hotspots.

Interference Mitigation Techniques

1. Limiting the Transmitter Power
2. Direct Sequence Spread Spectrum (DSSS)
3. Frequency Agility
4. Carrier Sense Multiple Access with Collision Avoidance (CSMA-CA)

Limiting the Transmitter Power

Band	Applications	Power
2.4 – 2.5 GHz	WiFi	100 mW
2.400- 2.4835 GHz	Bluetooth	10 mW (indoor)
2.446 - 2.454 GHz	RFID	500 mW
5.150 - 5.250 GHz	WiFi	200 mW
5.470 - 5.725 GHz	WiFi	1 W
57 - 64 GHz	Short Range Device	100 mW
57 - 66 GHz	Wi-Gig	10 W

Direct Sequence Spread Spectrum (DSSS)

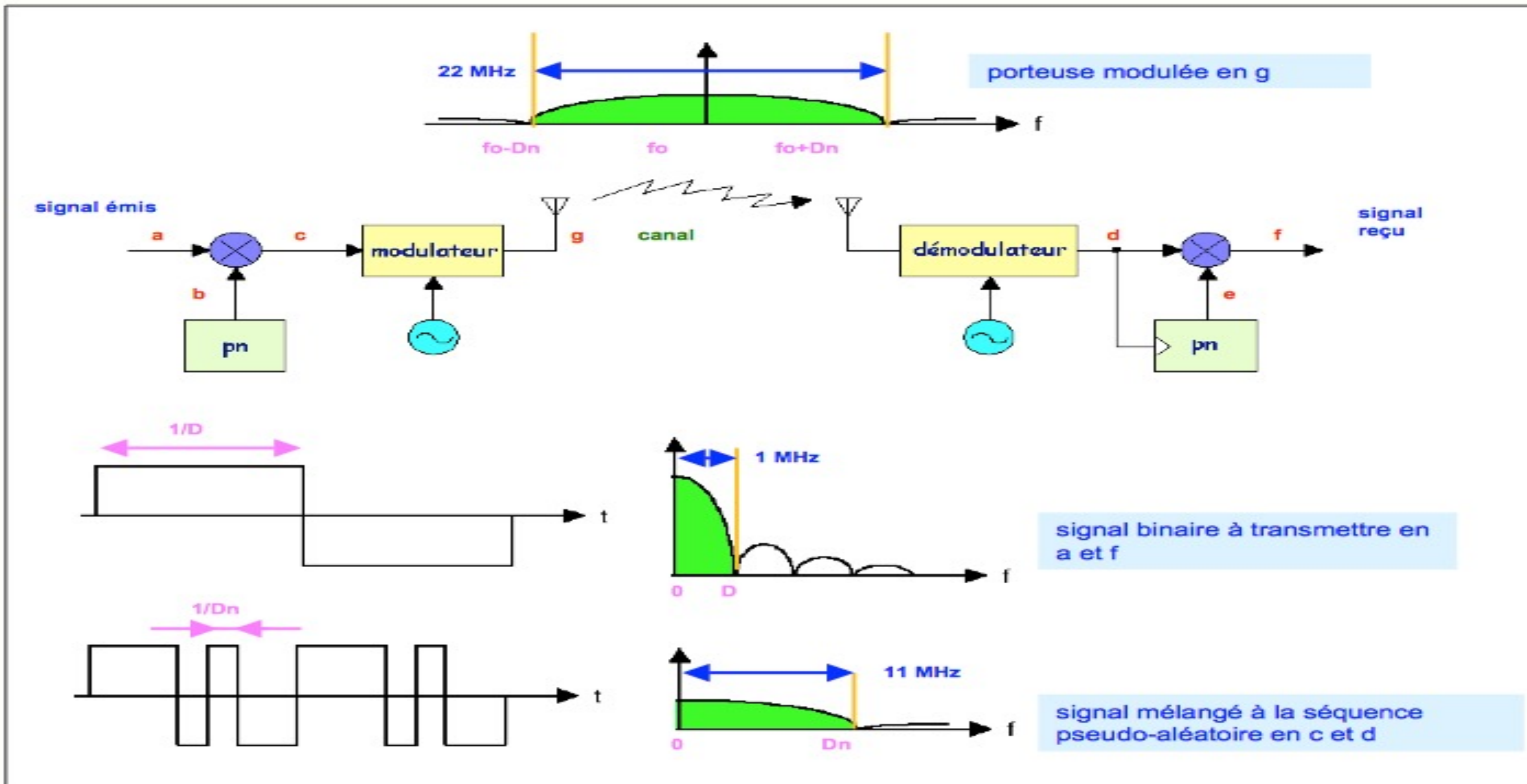
- Spread spectrum systems transmit the message signals using a bandwidth that is in much higher than the bandwidth that is actually needed by the message signal.

- This spreading of the transmitted signal over a large bandwidth make the resulting wideband signal appear as a noise signal.

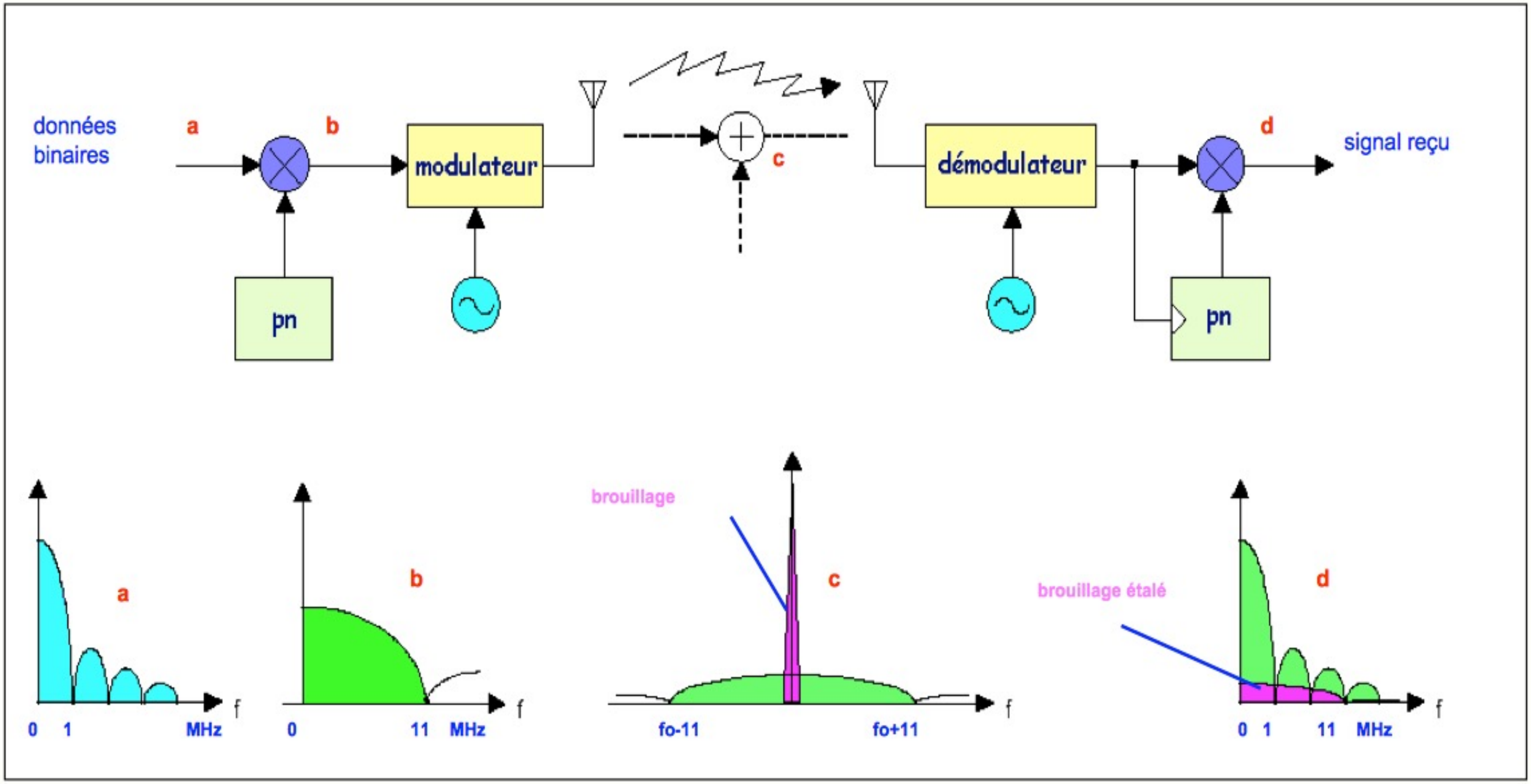
- DSSS techniques allow greater resistance to intentional and unintentional interference with the transmitted signal.

Spreading at the transmitter

- **Pn = spreading sequence containing 11 chips**



De-spreading at the receiver



Frequency agility

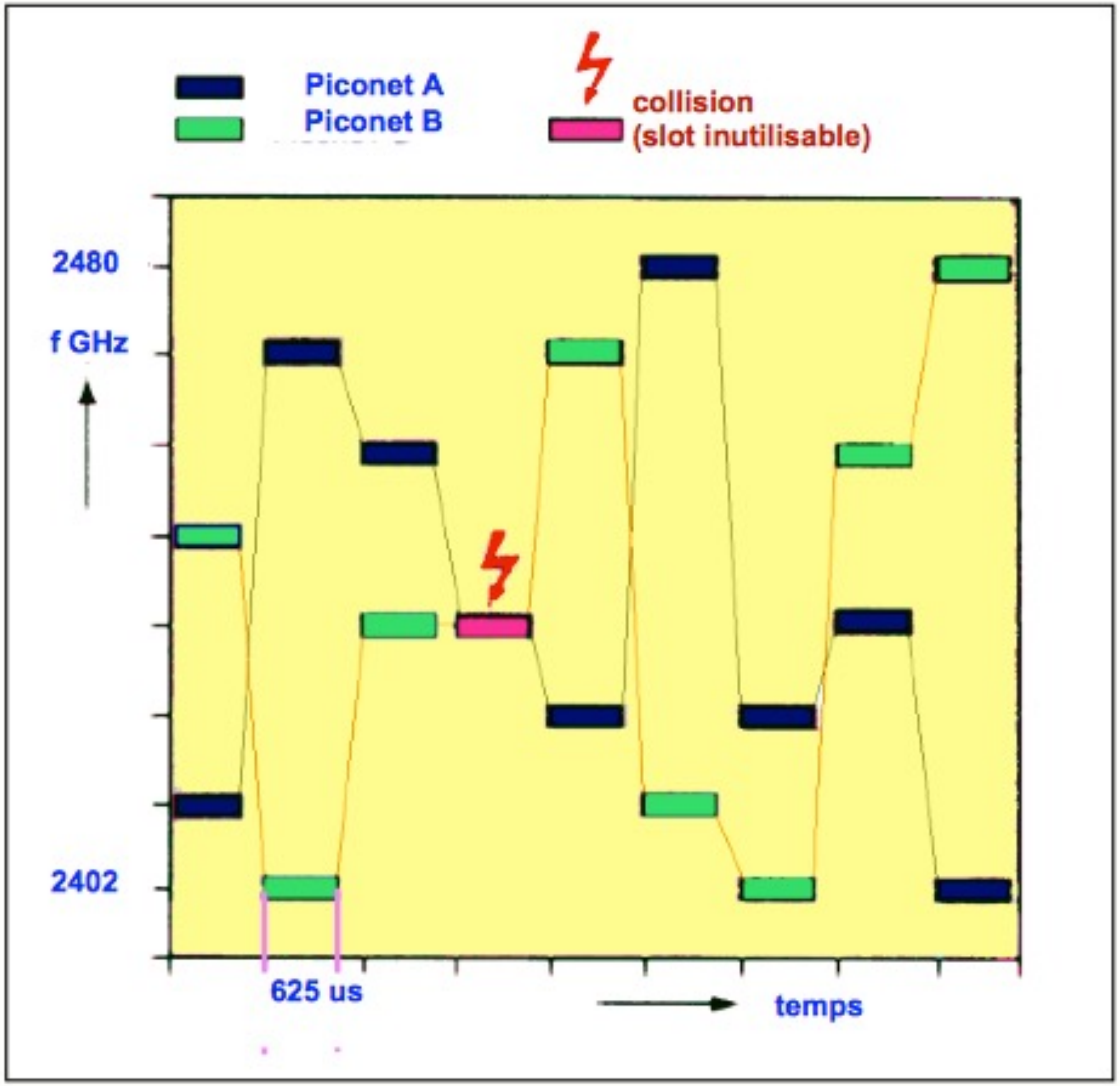
- Frequency agility is a generic term that describes the ability for a device to switch automatically to another frequency if it finds its existing frequency is in use.

- Various approaches to frequency agility have been adopted in license exempt bands:
  - Frequency Hopping;
  - Adaptive Frequency Agility (AFA);
  - Dynamic Frequency Selection (DFS).

FHSS (1/)

- FHSS was used in the earliest implementation of Wi-Fi and is still used by Bluetooth in the 2.4 GHz band.
- FHSS transmits radio signals by rapidly switching a carrier among many frequency channels, using a pseudorandom sequence known to both transmitter and receiver.
- The technique relies on having a relatively large number of frequency channels to accommodate multiple orthogonal hopping sequences;
- FHSS is less suitable for high bandwidth applications.

FHSS (2/)



Piconet A
Piconet B
collision
(slot inutilisable)
2480
f GHz
2402
625 us
temps

Adaptive Frequency Hopping (AFH)

- A specific variant known as Adaptive Frequency Hopping (AFH) is used by Bluetooth devices (IEEE 802.15) to improve co-existence with 802.11 networks.

- AFH allows Bluetooth to adapt to the environment by identifying channels used by 802.11 devices and excluding them from the list of available channels for hopping.

- There are different methods for identifying channels occupied by 802.11 networks, for example measuring received signal strength or packet error rate.

Dynamic Frequency Selection (DFS)

- DFS is a technique used by WiFi systems operating in the 5 GHz bands to scan continuously for the presence of radar signals within the band.
- If a signal is detected on a particular radio channel, that channel is flagged as unavail- able and the WiFi system must switch to another channel.
- Once a radar signal has been detected the affected channel cannot be used for at least 30 minutes.
- The key objective is to protect radars from interference by moving away from the channels they occupy.

CSMA-CA (1/)

- CSMA-CA is used by Wi-Fi networks.

- Prior to transmitting, a Wi-Fi device must first check whether any other transmissions are present on the same frequency channel.

- The channel is free if the detected energy level is below a pre-defined threshold during a specified period of time, referred as the Distributed InterFrame Space (DIFS).

CSMA-CA (2/)

- If the channel is free during DIFS, the device is allowed to transmit. If the frequency channel is busy:
  1. the device waits until the channel becomes free (the DIFS duration);
  2. The device chooses a random back-off counter to determine the amount of additional time the device needs to wait before it can transmit.
- This idle period after the DIFS duration is known as the contention window.

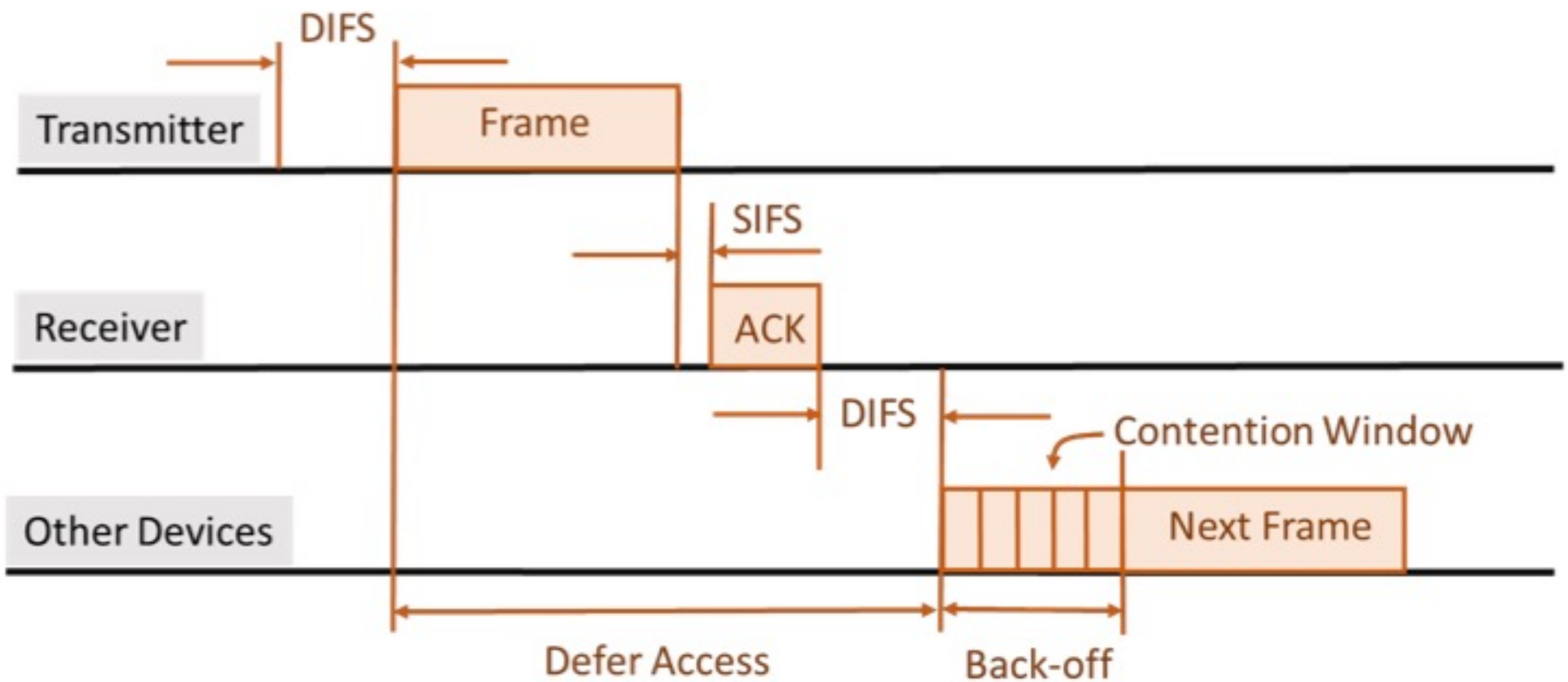
CSMA-CA (3/)

- During the idle period, the device decreases its back-off counter until it is zero and then the transmission can take place.
- The receiver sends an acknowledgement packet after a short interframe space (SIFS) duration if no collision has occurred and the data is successfully received.
- In case of a collision, no acknowledgement is received and the transmitter attempts to re-transmit the data.

Size of Contention Window

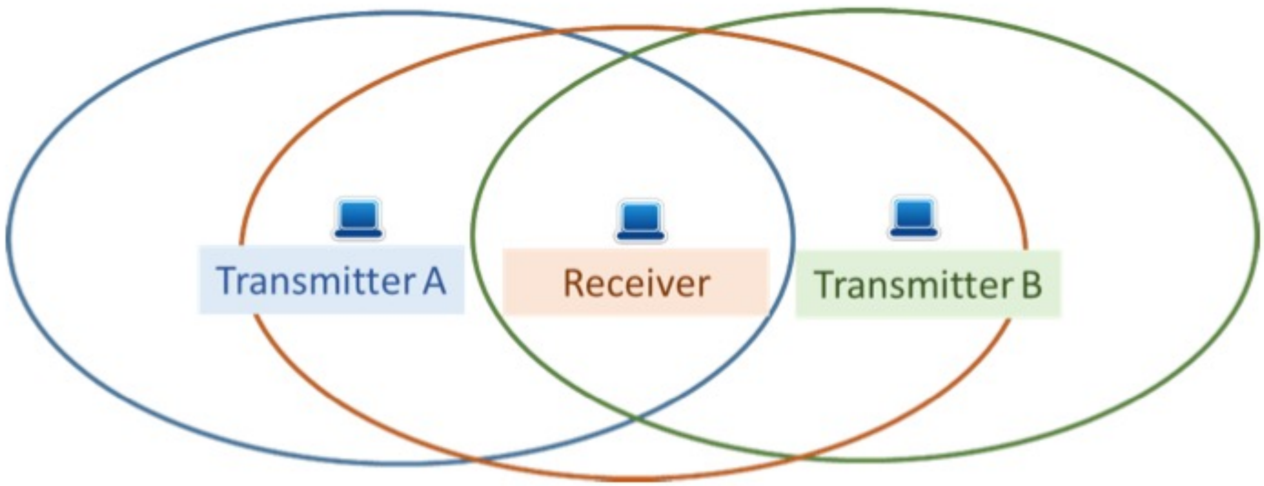
- The contention window is initially assigned a minimum size;
- At each failed attempt to transmit the contention window size is doubled in a process referred to as exponential back-off, until a maximum value is reached.
- It then remains at this value even if further transmission attempts fail due to collisions.
- A packet is eventually discarded if it cannot be transmitted successfully after the threshold for maximum number of re-transmissions is exceeded.
-

Illustration of CSMA-CA Process



Hidden Node Problem

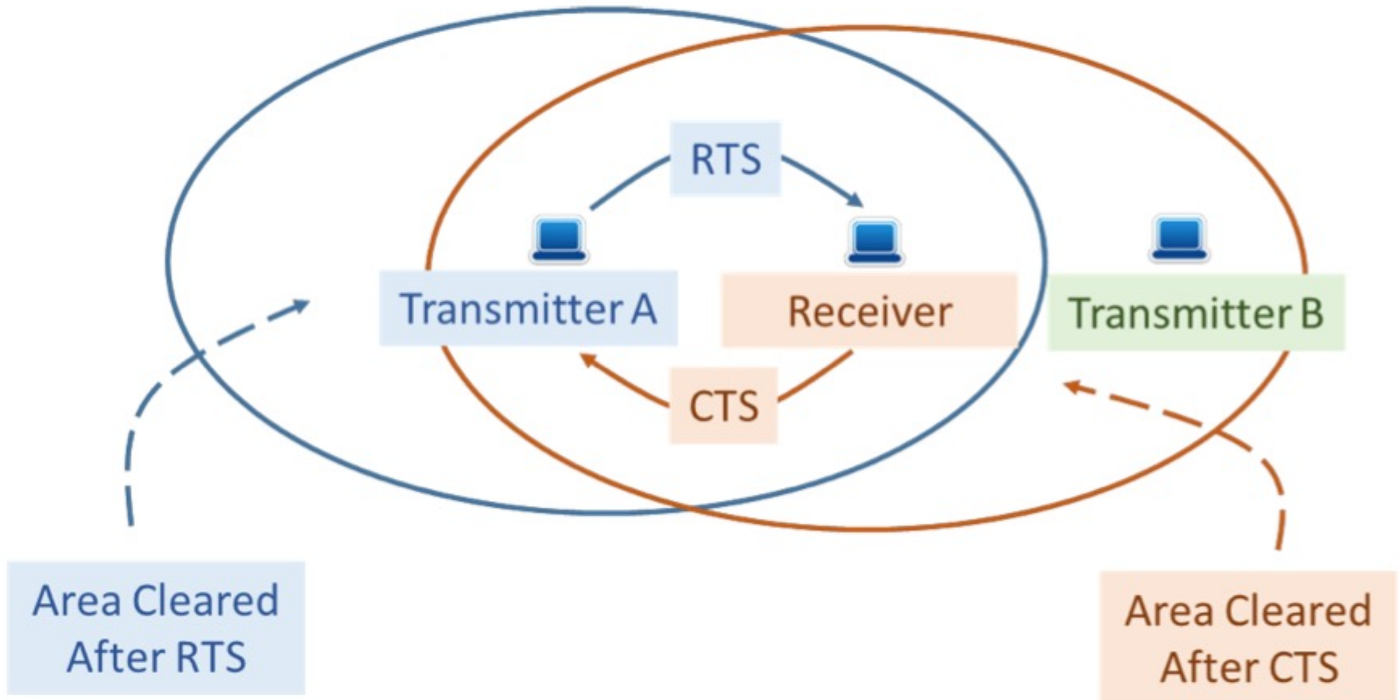
- Devices attempting to access a channel may sometimes not detect each other.
- When both transmitters attempt to send data to the receiver collisions may occur as transmitters are not aware of each other.



Virtual Carrier Sense Method RTS/CTS

- In order to reduce the probability of collisions caused by the hidden node problem, short control packages: Request to Send (RTS) and Clear to Send (CTS) are used.
- The transmitter first sends an RTS message (which includes the source, destination and duration of following data transmission) and the receiver replies with a CTS.
- The actual data and acknowledgement exchange can then take place.
- Neighboring devices that receive either the RTS or CTS set their Network Allocation Vector (NAV) to reserve the channeL.

Virtual Carrier Sense Method RTS/CTS



WiFi Use Case

- Two nodes A and B transmit simultaneously a WiFi packet to the same access point on the channel 6. A collision occurs during this transmission. The WiFi uses the CSMA-CA protocol to manage the access to the shared Medium.
- For the the back-off window size W is in the interval $0 \leq W < 2^{1+i}$, with i being the transmission trial number.. The time duration corresponding to the window is then WT with T being defined by the WIFI standard
  - Find the probability of collision after the first retransmission trial.
  - Assume that a collision occurs after the first transmission trial, find the probability of collision during the second trial.
  - Deduce the average delay to access to the network in function of W and DIFS.

Bluetooth Use Case

- **Find the average delay that induce a collision between two Bluetooth Communication**