LABORATOIRE D'ELECTRONIQUE ANTENNES ET TELECOMMUNICATIONS

Laboratory of Electronics Antennas and Telecommunications

# LP-WAN Technology

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# Objectives

- Key physical parameters for IoT applications
- Provide a complete view of LoRa protocol from the physical layer to the application layer
- Practical labs using a miniature terminal

# Outline

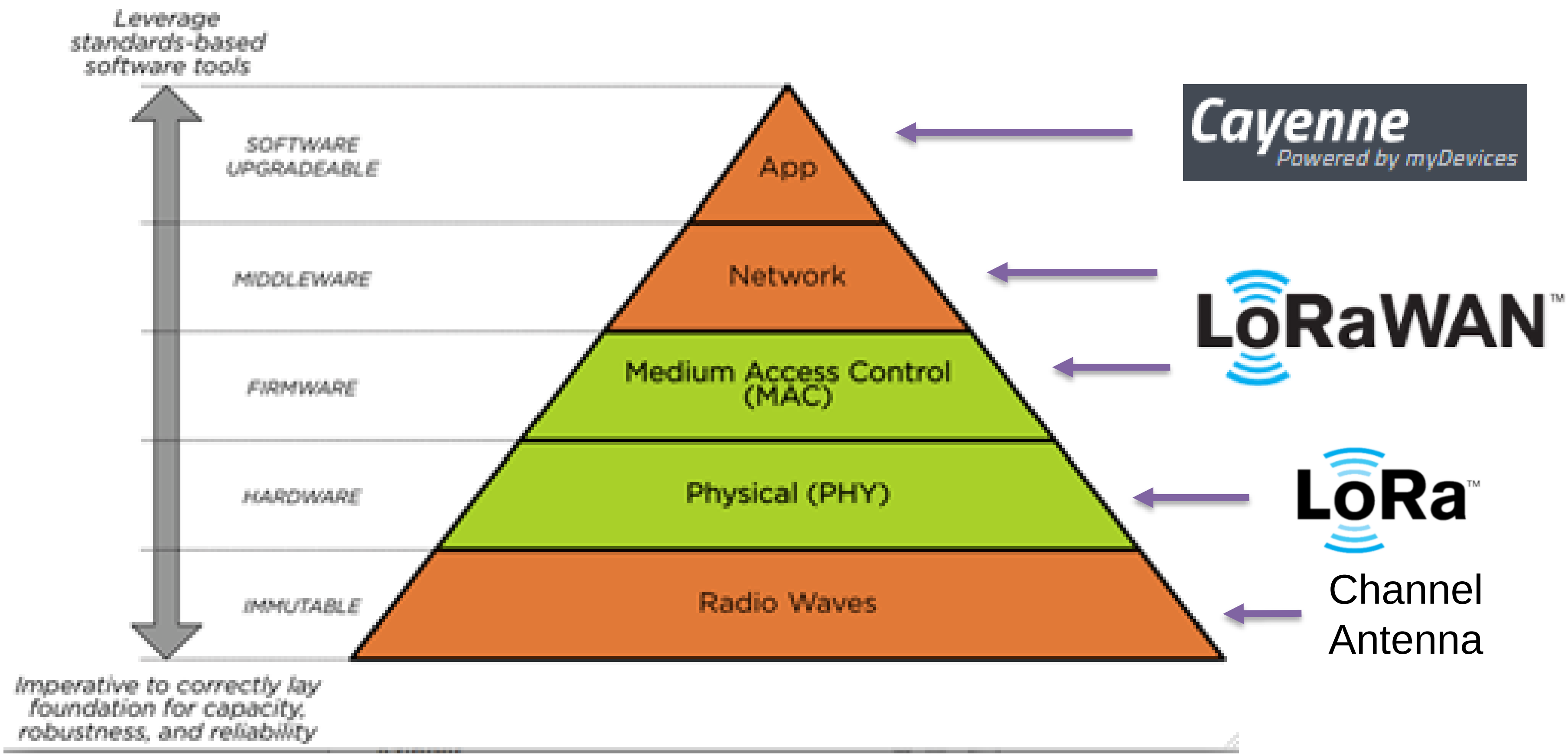
0. Introduction

I. Antenna and channel model

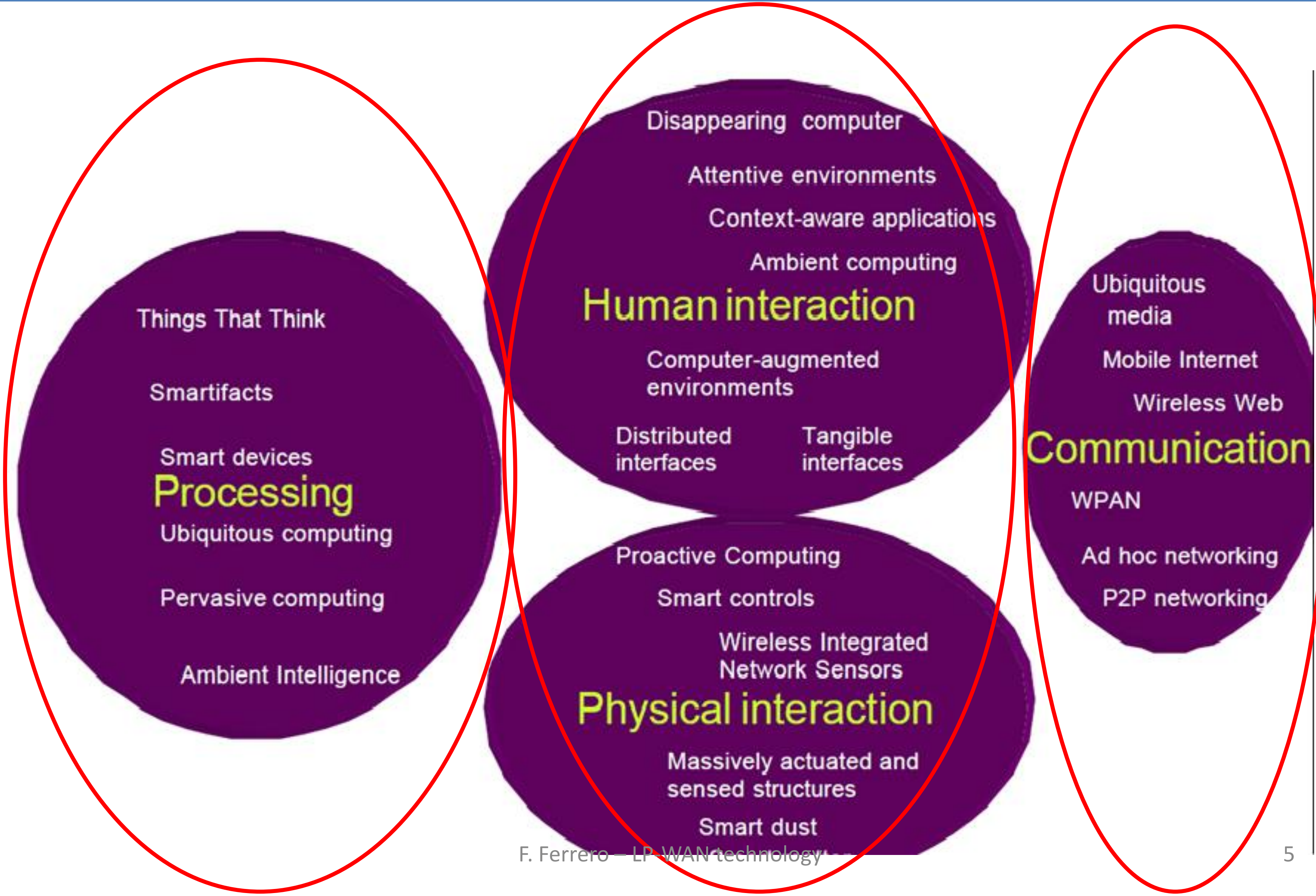
II. Physical layer (LoRa modulation)

III. MAC layer (LoRaWAN) and security

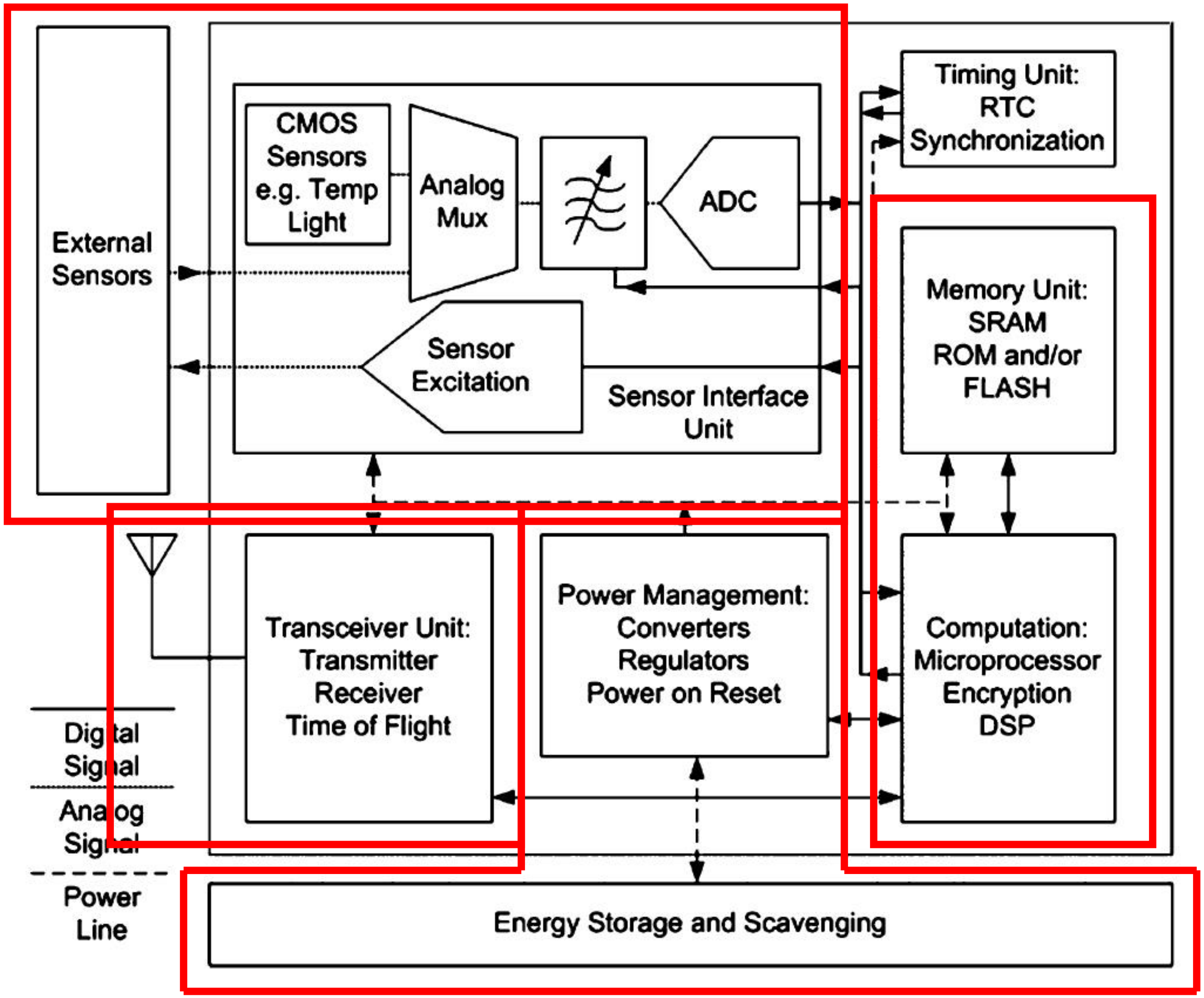
# LoRa vs LoRaWan



# What are we talking about ?



# Anatomy of an IoT device



# Anatomy of our IoT device

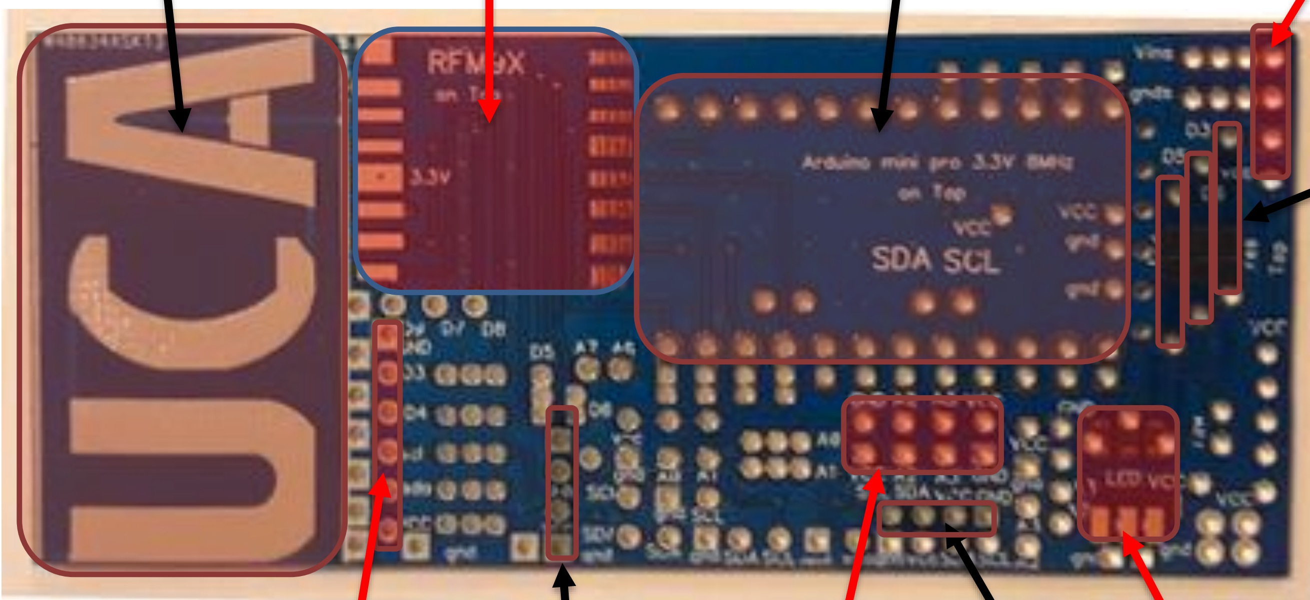
Printed Antenna

RFM95W

Arduino mini pro 3.3V 8MHz

Step-up voltage converter

3 resistors (CMS or THT) for RGB LED




3-axis accelerometer

BMP280 T°C, Pressure, Humidity

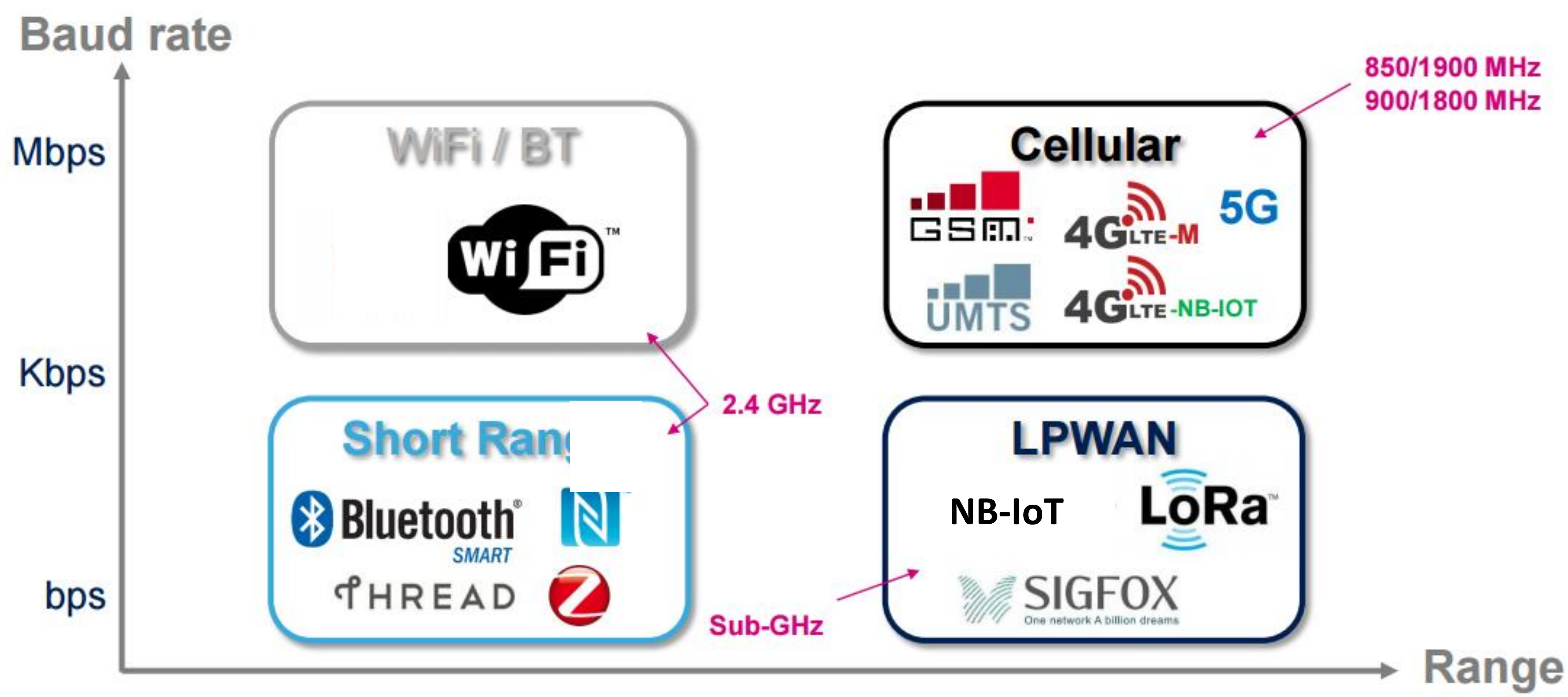
Ultra-sound distance sensor or DHT22

Grove connector I2C

RGB LED

# Communication Technology

Data rate / Range



# Communication Technology

| Techno | Net. Type | Freq | Range | Data Rate | Power |
|---|---|---|---|---|---|
| Wifi | Star | 2.4- 5GHz | 100m | 100Mb/s | 1W |
| BLE | P2P, mesh | 2.4- 5GHz | 100m | 1Mb/s | 10mW |
| Zigbee | P2P, mesh | 2.4- 5GHz | 250m | 250kb/s | 100mW |
| RFID | P2P | 900MHz | 7m | 500kb/s | 2W |
| NFC | P2P | 13.56MHz | 0.1m | 500kb/s | 100mW |
| EDGE | GERAN | 900MHz | 15 km | 384kb/s | 2W |
| UMTS | UTRAN | 2100MHz | 10 km | 10Mb/s | 2W |
| LTE | UTRAN | 700 MHz | 10 km | 100Mb/s | 2W |
| SigFox | Star | 900MHz | 15km | 100b/s | 25mW |
| LoRa | Star | 900MHz | 15km | 290b/s- 5kb/s | 25mw |

# LP-WAN connectivity overview

| | LoRa | SIGFOX | NB-IoT 3GPP |
|---|---|---|---|
| Range (km) | 10km (suburban)<br>3-6km (urban) | 30km (Rural)<br>10km (urban) | |
| Frequency Band (MHz) | Sub GHz (ISM) | 868-900MHz (ISM) | Licensed LTE bands |
| Max. Coupling Loss | 155dB | | 164dB |
| Modulation type | Chirp Spread Spectrum (CSS) | Ultra narrow band / GFSK / BPSK | LTE - OFDMA / SC-FDMA |
| Bandwidth | 125 – 500 kHz | 100 Hz | 180 kHz |
| Datarate | 300 bps – 50 kbps | 100 bps | Up to 250 kbps (UL) – low latency |
| Max /message / day (Uplink) | Unlimited* | 140 msg/day – 12bytesmax/msg | Unlimited (lice. Spectrum) |
| Max /message / day (Downlink) | Unlimited* | 4 msg/day (8bytes max/msg) | Unlimited (lice. Spectrum) |
| Network density | +++ (ADR) | + | +++ |
| Battery peak current | < 50 mA (14dBm) | < 50 mA (14dBm) | ~300mA (@23dBm) |
| Average sensor autonomy | +++ (ADR) | ++ | + |
| Interference immunity | high | Low | Sensitive to downlink jamming |
| Native payload encryption | Yes | Proprietary | Yes |
| Able to create private networks | Yes | No | No |
| Location (w/o GPS) | Yes | No | M1 only, not deployed(**) |
| Commercial availability | Now | Now | Starting in 2017 |

(*) Adaptive Data Rate

(**) Requires optional Location Measurement Units (LMU) in BTS. Not deployed except E911 phase 2 in US

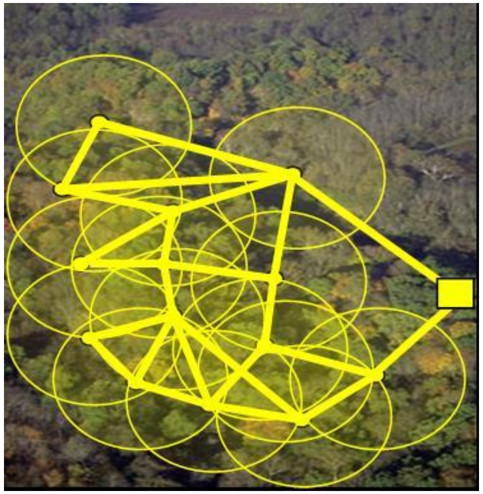
# IoT Physical Key parameters

- Propagation Channel
- Power sources
- Device size
- Security

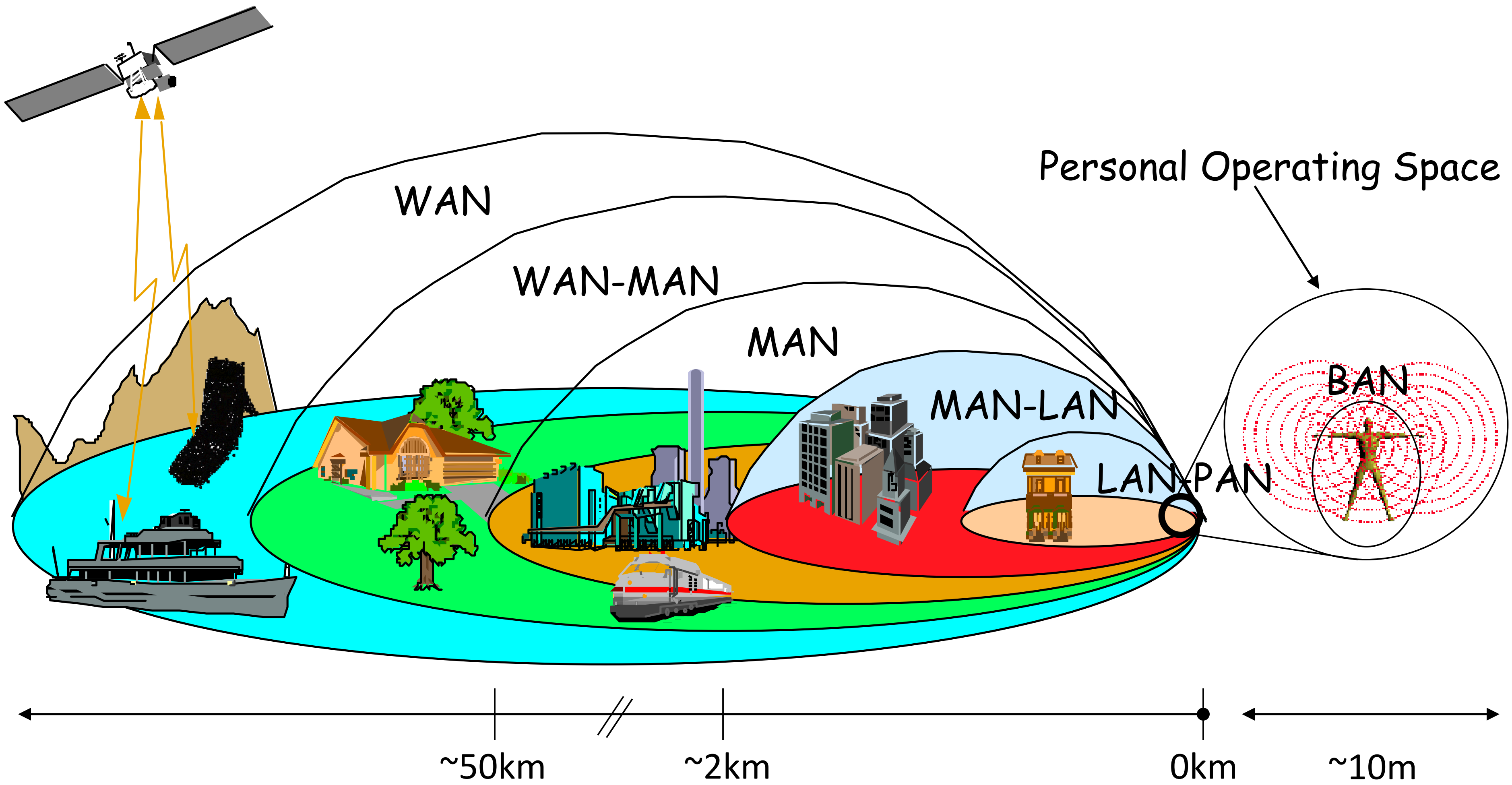
Pictures from Nokia White paper

# Propagation channel

- Type of channel
- Distance among the communicating objects communicants
- Line of sight (LOS) / non-LOS
- Channel noise (interferences)



# Network area definitions



# Network area definitions

- WAN (Wide Area Network)
  - WANs interconnects facilities in different parts of a country or of the world
- MAN (Metropolitan Area Network)
  - MANs shall be capable of operating over an area up to 50 Km in diameter
- LAN (Local Area Network)
  - LANs shall be capable of supporting segments at least 100 meters in length.
- PAN (Personal Area Network)
  - PANs shall be capable of supporting segments at least 10 meters in length.
- BAN (Body Area Network)
  - A Wireless Body Area Network consists of small, intelligent devices attached on or implanted in the body.

# Practically

Carrier frequency ⇧ — Channel losses over the same distance ⇧

Carrier frequency ⇩ — Antenna dimensions ⇧

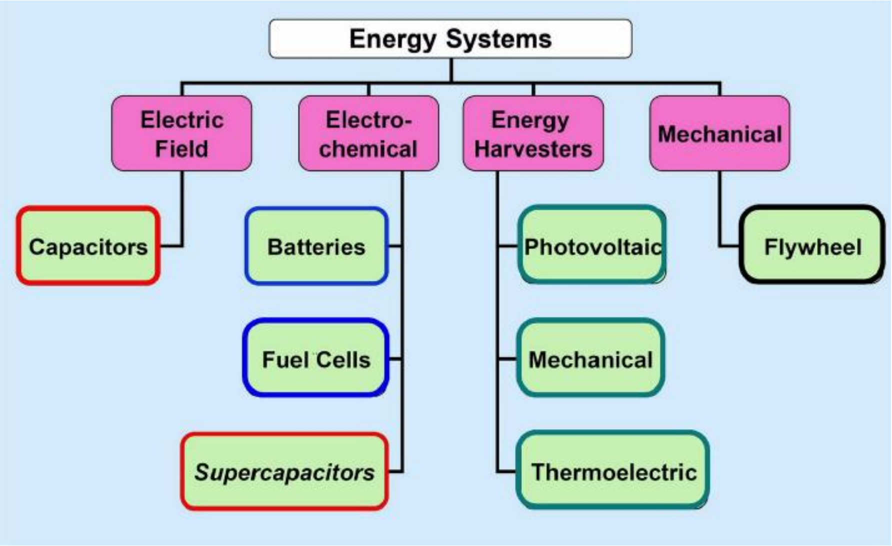
Communication distance X 10

Channel attenuation X 100 Ideally

X 1000 Usually, even more…

# Energy consumption

- How much energy do you need?
- What is the most adapted solution to power your connected object?



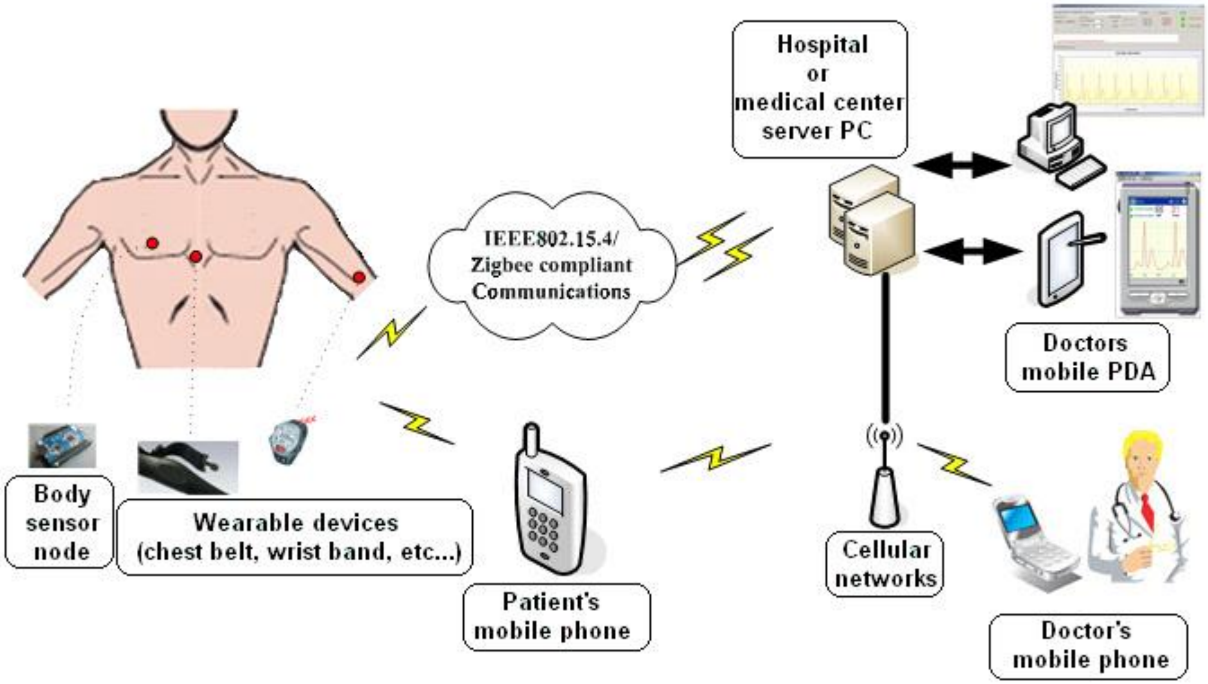

| Battery Lifetime for sensor reporting every minute | | |
|---|---|---|
| | Duty Cycle | Estimated Battery Life |
| Full Time Listen | 100% | 3 Days |
| Full Time Low_Power Listen | 100% | 6.54 Days |
| Periodic Multi-Hop Listening | 10% | 65 Days |
| No Listen (no Multi-hop) | 0.01% | Years |

# Object dimension

- As the dimension of the object decreases, the energy that can be stored decreases as well
  - If the available space is not sufficient for storing enough energy (battery), this should be transferred (RFID) or found locally.
- Small dimensions limit the antenna efficiency. Communication will be still possible but over smaller distances.
- Usually electronics is not an issue in terms of miniaturization. The elements that need space are the antenna and the battery.

# Security

- What is the level of security needed by your application?
- What is the level of reliability needed by your application?



# What a the key parameters ?

- How much data rate do you need ?
- How is the propagation channel ?
- How small my device need to be ?
- How much energy do you need ?
- What level of security do you need ?

# Outline

0. Introduction

I. Channel model and Antenna

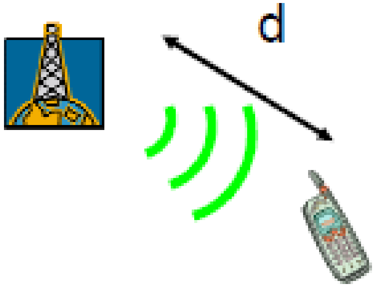
II. Physical layer (LoRa modulation)

III. MAC layer (LoRaWAN) and security

# Channel Ideal model

Free-space propagation

- No obstacles between transmitter and receiver
- The atmosphere is a uniform and non-absorbing medium
- Attenuation $L_p$ depends on the distance *d* and the wavelength of the signal $\lambda$
- $\lambda = c/f$ and $c = 3 \times 10^8$ m/s




$$\frac{P_L}{P_T} = \frac{1}{4\pi r^2} \quad G_T A_R = G_T G_R \left( \frac{\lambda}{4\pi r} \right)^2$$

$$L_p(d) = \frac{(4\pi d)^2}{\lambda}$$

# Real channel model

Real propagation :

- No Line of Sight
- Multiple paths between the transmitter and the receiver
- Attenuation $L_p$ depends **not only** on the distance $d$ and the wavelength of the signal $\lambda$

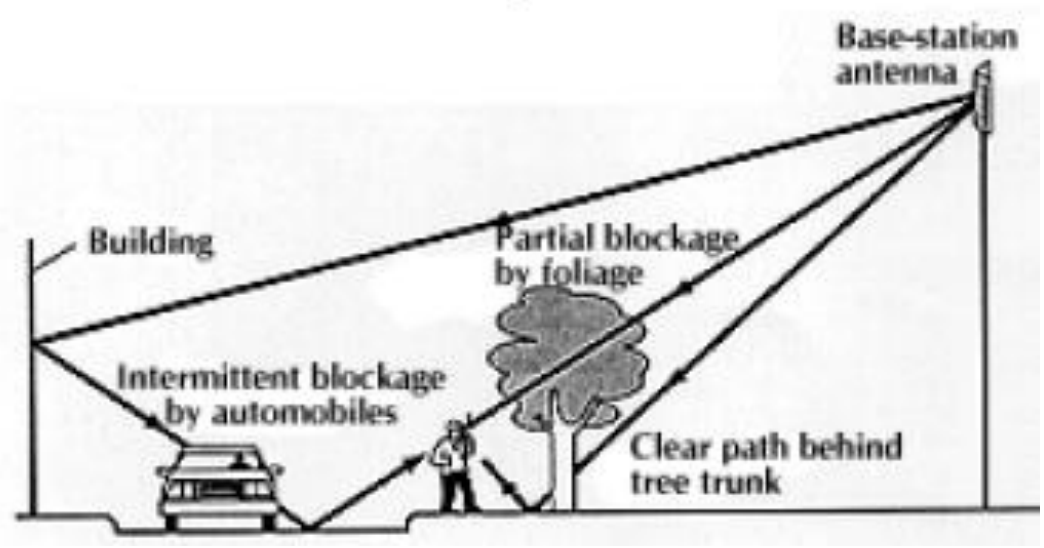
# Real Propagation

Practically, the free-space model is inadequate since:

- Multipath phenomenon
  - Multiple paths between the transmitter and the receiver
- Shadowing phenomenon
  - Obstruction of the direct line of sight between transmitter and receiver
- Fast fading phenomenon
  - Destructive composition of different signal path that are close in time (phase opposition)

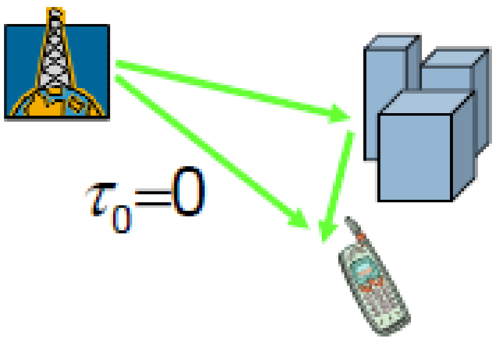
# Multipath

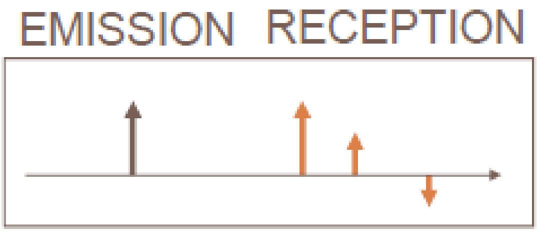
- Macroscopically, the electromagnetic waves are reflected by the obstacles between TX and RX
- The RX receives multiple signals shifted in time



# Multipath

- Signal r(t): sum of N delayed and attenuated versions of s(t)

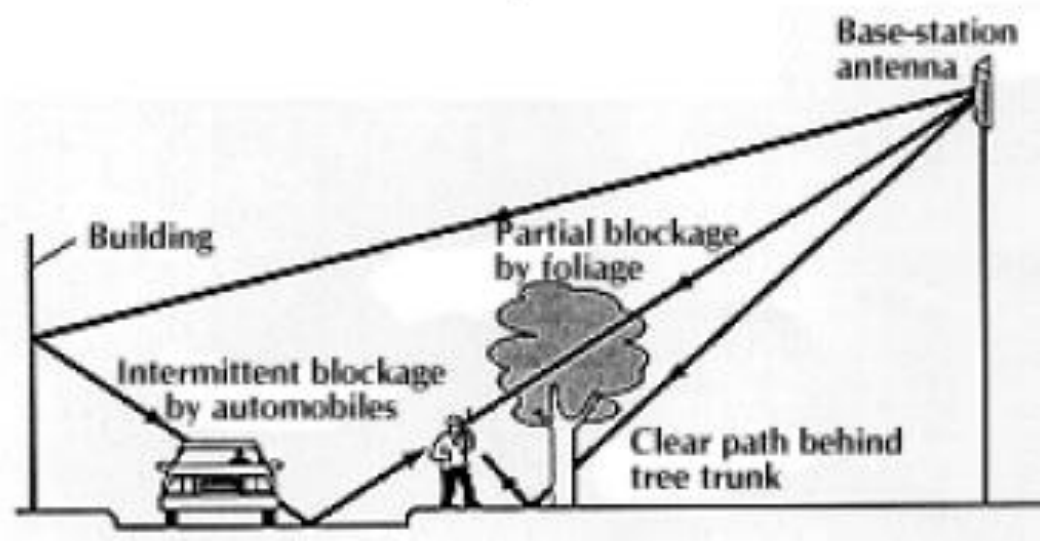



$$r(t)=\sum_{i=0}^{N-1}\alpha_i e^{-j\varphi_i} s(t-\tau_i)+n(t)$$

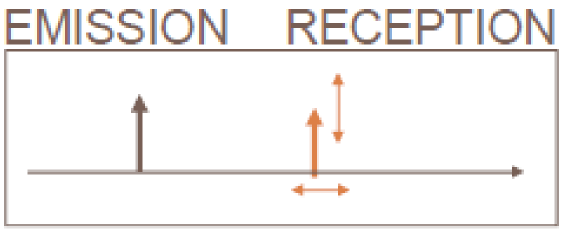
# Fading

- Microscopically, the electromagnetic waves are diffracted and refracted by the obstacles between TX and RX
- Every path is constituted by a continuum of multiple paths



# Fading

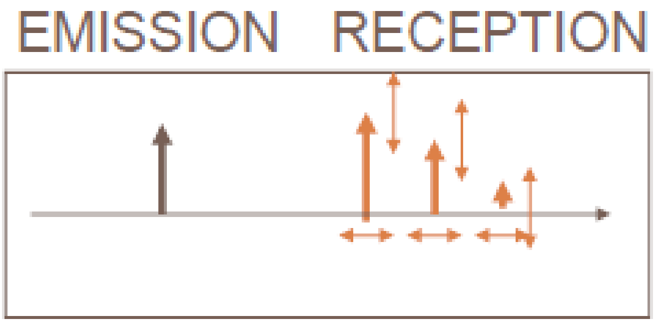
- Signal r(t): copy of s(t) attenuated and randomly delayed




$$r(t)=\alpha(t)e^{-j\varphi(t)}s[t-\tau(t)]+n(t)$$

# Multipath + Fading

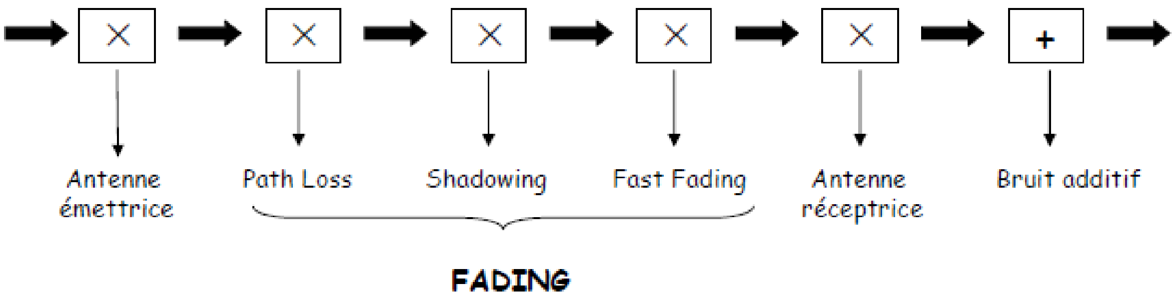
- Signal r(t): sum of N copies of s(t) randomly attenuated and delayed




$$r(t) = \sum_{i=0}^{N-1} \alpha_i(t) e^{-j\varphi_i(t)} s\left[t - \tau_i(t)\right] + n(t)$$

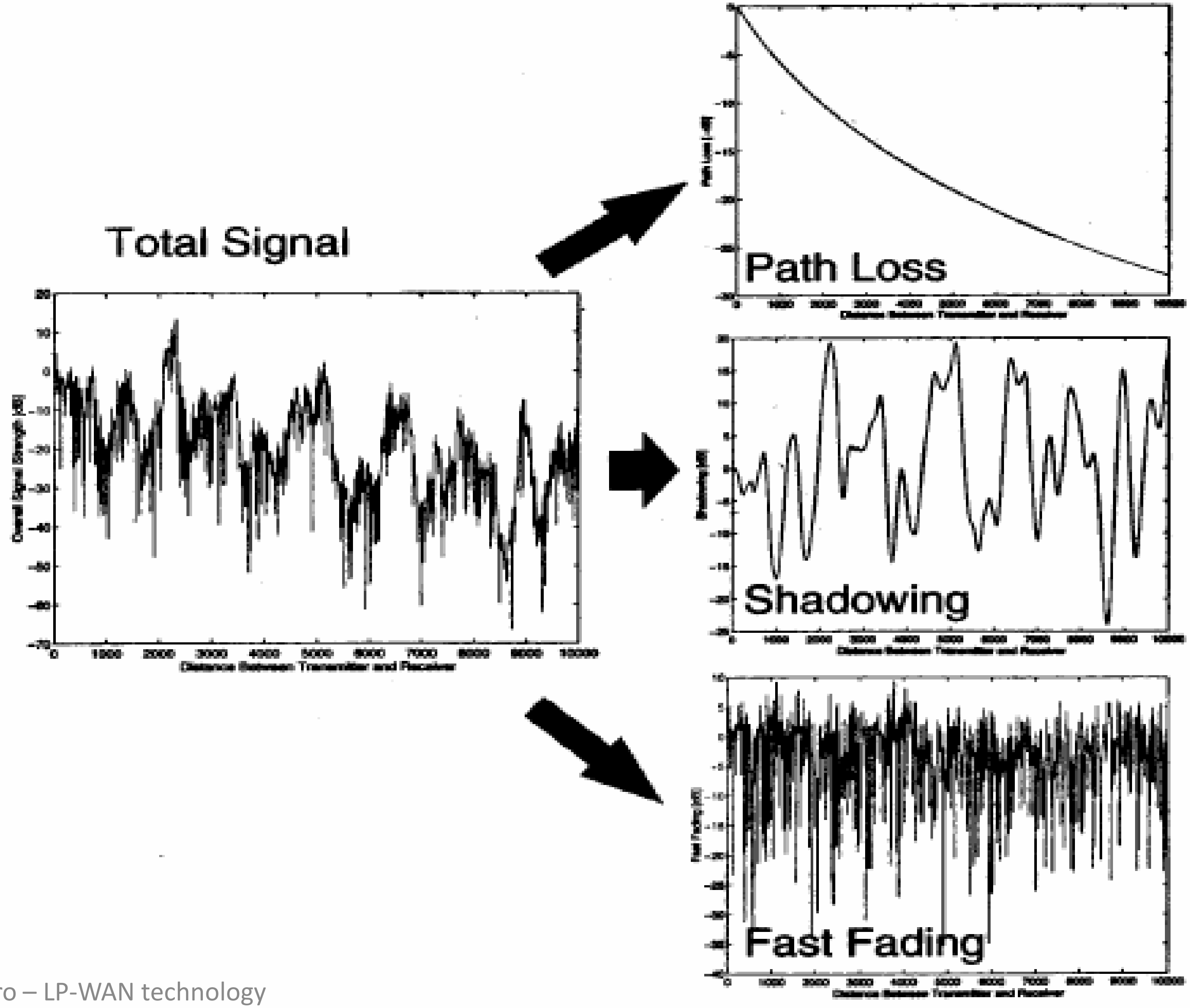
# Attenuation

3 types of attenuation




- ❑ Path loss (distance attenuation)
  - Decrease of the signal power due to the distance (deterministic)
- ❑ Shadowing (or slow fading)
  - Slow variation of the signal amplitude due to large obstacle compare to the wavelength (hills, forest, building,…)
- ❑ Fast fading
  - Fast variation of the signal amplitude (constructive or destructive combination of the electromagnetic waves)

# Attenuation



# Average loss: power law model

$$\frac{1}{L} = \frac{P_R}{P_E} = \frac{k}{d^n}$$

$$L = 10n\log(d) + K \qquad (\text{en } dB)$$

$$L = 10n\log\frac{d}{d_{ref}} + L_{ref}$$

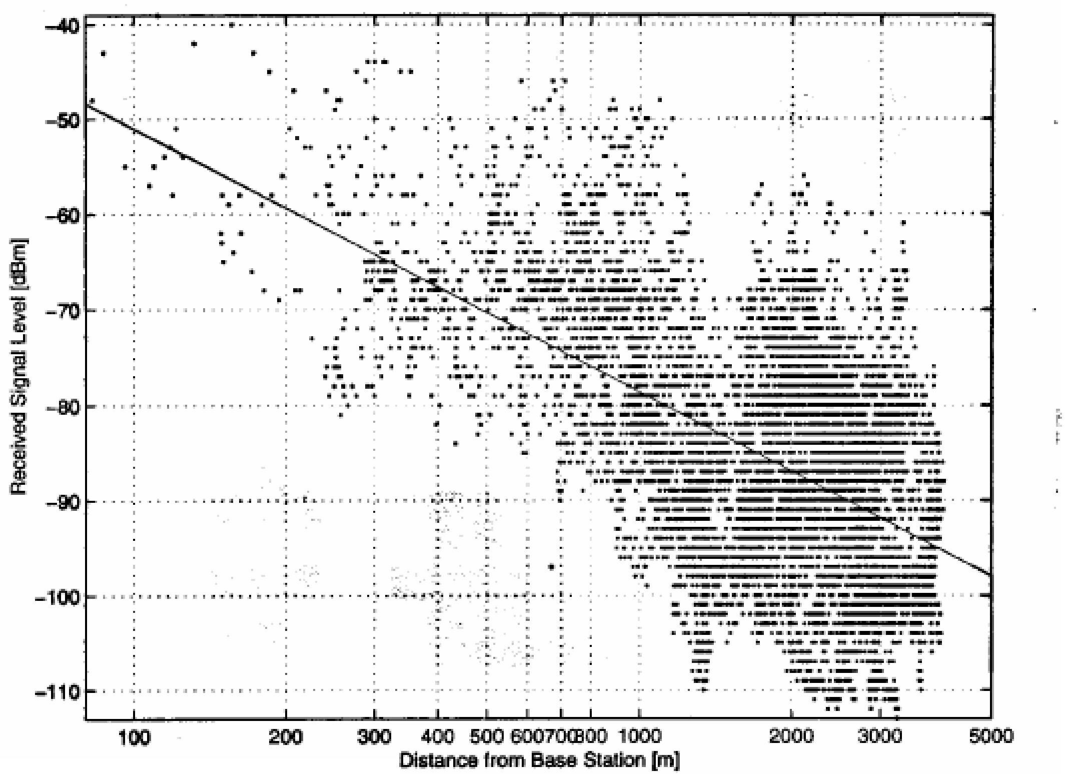
$P_R$ : puissance reçue
$P_E$ : puissance émise

- n : path loss calculated with measurements
- Can be expressed in relative compared to a reference distance
- Most of the time, a distance of 1 m is choosen.

# Power law model

Set of measurements done in a dedicated environment

Curve interpolation fitting with the measured points



# Propagation

2. Variability of the signal strength in close spatial proximity to a particular location → fading models → small-scale

| Environment | Path Loss Exponent n | Standard Deviation s |
|---|---|---|
| Free space | 2 | 0dB |
| Urban area cellular radio | 2.7 to 3.5 | 10-14dB |
| Shadowed urban cellular radio | 3 to 5 | 11-17dB |
| In-building line-of-sight (LOS) | 1.6 to 1.8 | 4-7dB |
| Obstructed in-building (NLOS) | 4 to 6 | 5-12dB |
| Obstructed in-factories (NLOS) | 2 to 3 | 6-9dB |

Path loss exponent and log-normal shadowing standard deviation

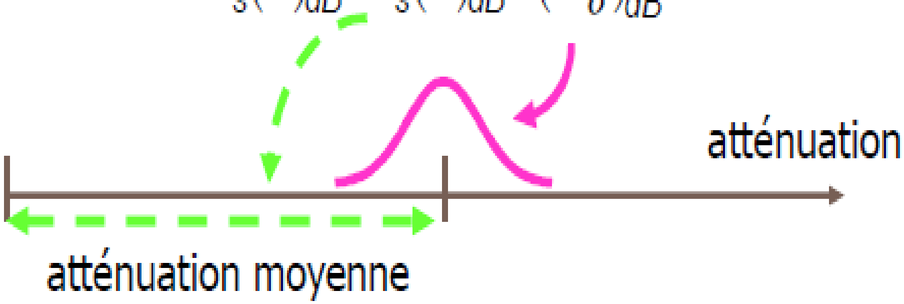
# Log-normal distribution around the average loss

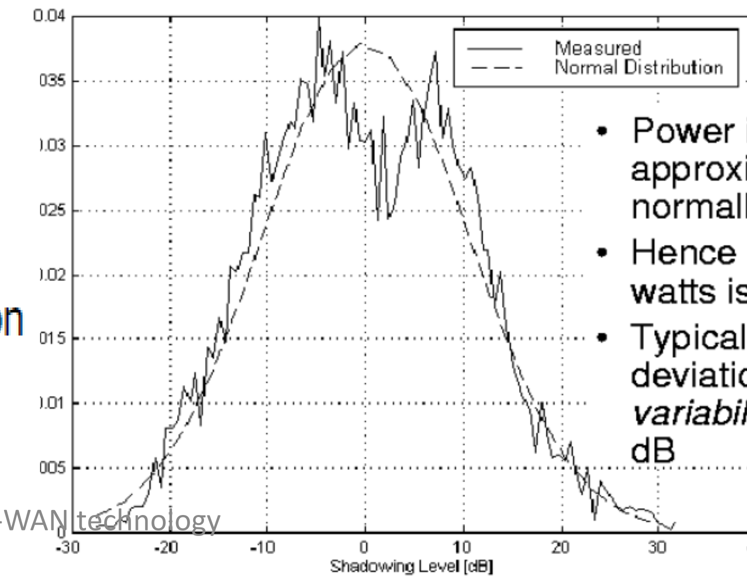
Losses due to shadowing is a random variable Ls(d) composed with a random fluctuation Xs with a log-normal probability density.

- If the fluctuation Xs fits with a log-normal distribution, then, Xs fits a normal distribution N(0,s²) in dB
- Dynamic : from 6 to 13 dB, even more

$$L_s(d) = \overline{L_s}(d) \times (X_\sigma)$$

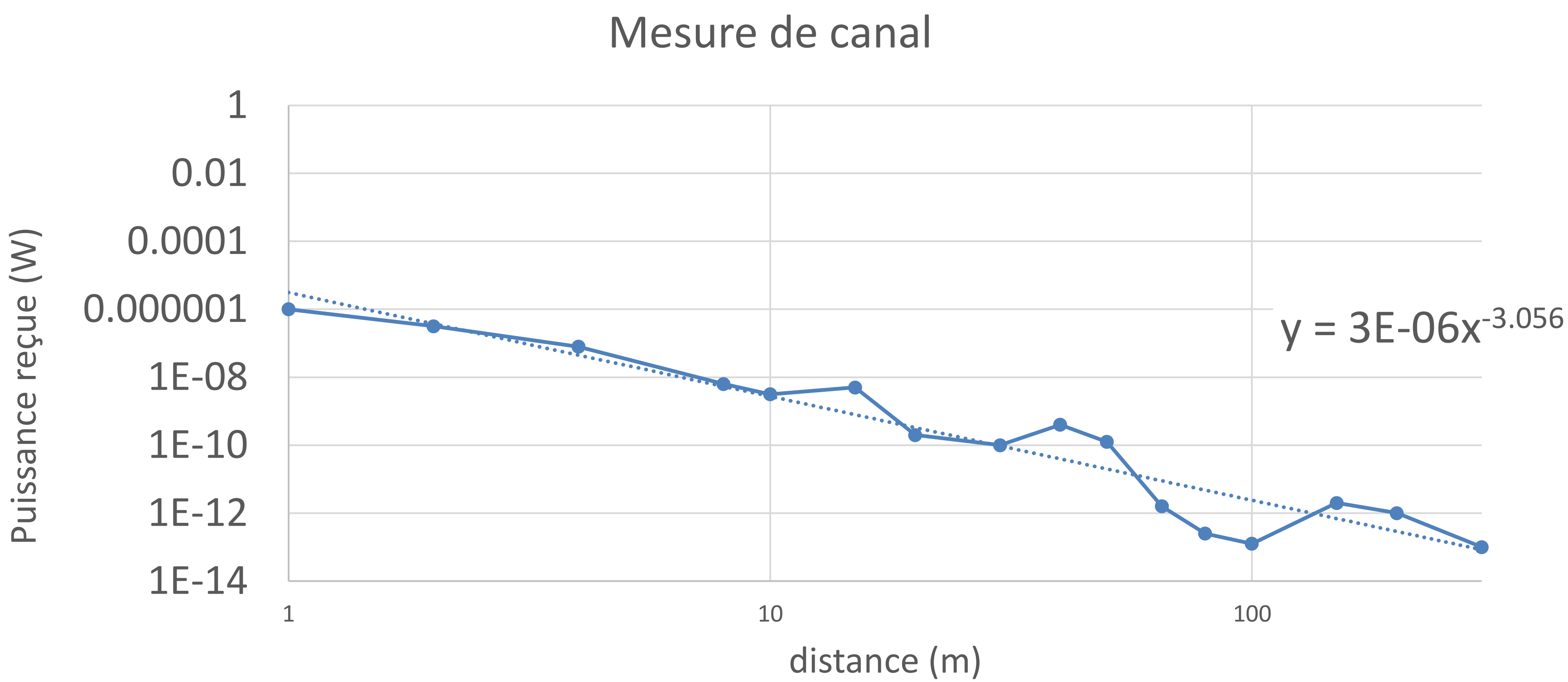
$$L_s(d)_{dB} = \overline{L_s}(d)_{dB} + (X_\sigma)_{dB}$$




- Power in dB is approximately normally distributed
- Hence power in watts is *lognormal*
- Typical standard deviation (*location variability*) of 5-12 dB

# Labs


Mesure de canal
Puissance reçue (W)
1
0.01
0.0001
0.000001
1E-08
1E-10
1E-12
1E-14
1
10
100
distance (m)
y = 3E-06x-3.056

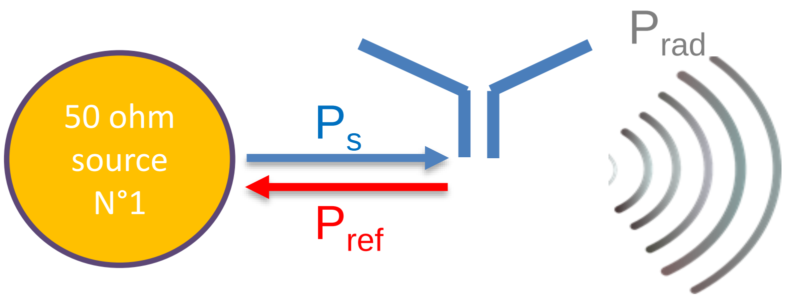

0
100,00 m
200,00 m
303,61 m

# Antenna Outline

- Antenna physical key parameters
- Low-cost Antenna Open Source project

# Antenna performance indicator

- Definition :
  - $P_s$ : Power from the source
  - $P_{ref}$ : Power reflected by the antenna
  - $P_{rad}$ power radiated by the antenna




- Antenna Performance Indicator
  - Reflection coefficient
    - $S_{11}$ is usually plotted in dB scale
    - $S_{11}$ criteria from -10 dB to -6dB (90% to 75% transmitted power)

$$|S_{11}|^2 = P_{ref}/P_s$$

  - Total Efficiency
    - Include **matching** and **radiation loss**
    - Can be plotted in linear or dB scale
    - 30-70% classically observed

$$\eta_t = P_{rad}/P_s$$

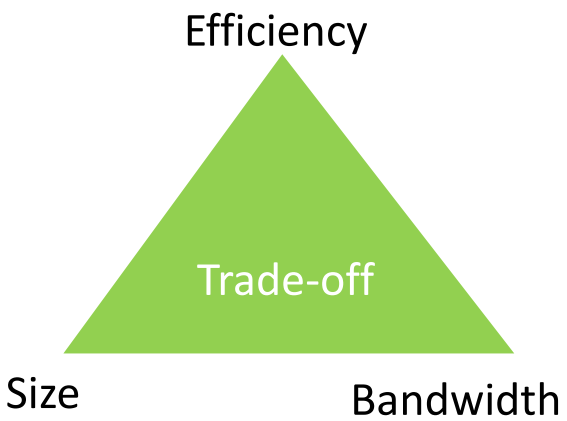
  - Gain
    - Include **matching**, **radiation loss** and **directivity**
    - Plotted in dBi
    - $U(\theta, \varphi)$ is the radiation intensity in a given direction

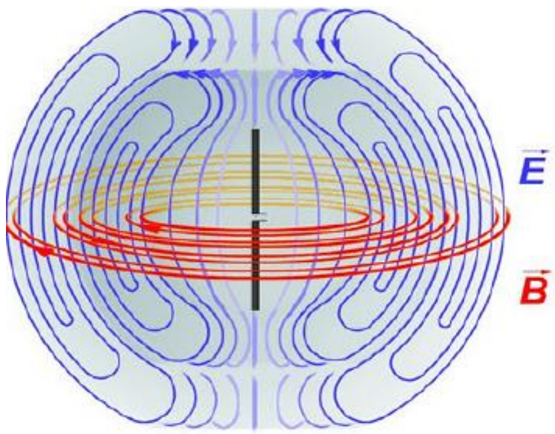
$$G(\theta, \varphi) = \frac{U(\theta, \varphi)}{P_s/4\pi}$$

# Antenna key parameters

- Antenna is a resonnant structure :
  - Input impedance is changing with frequency
  - Limited frequency bandwidth
  - Miniature antenna can have a low efficiency due to metallic or dielectric losses
- Antenna is an open structure
  - Compare to electronic components, antenna is strongly influenced by its surrounding environment
  - For integrated antenna, the electromagnetic wave is generated by the antenna **and** by the terminal ground plane

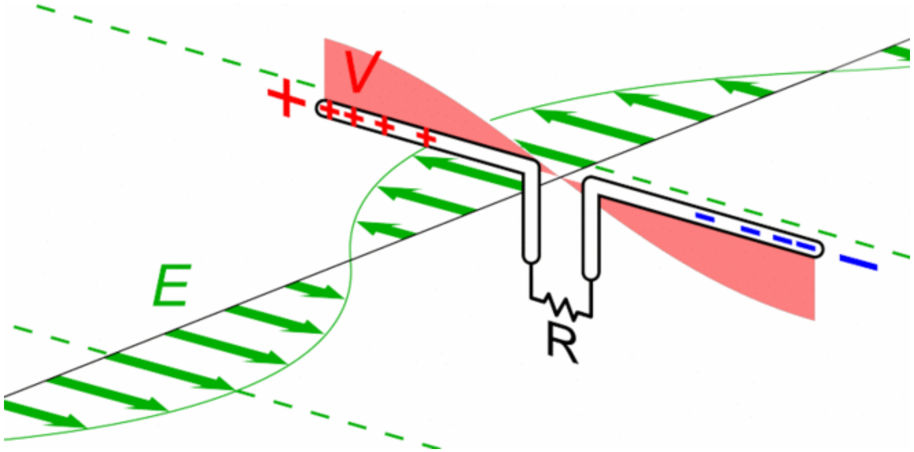
➢ Small antenna has to be carefully tuned

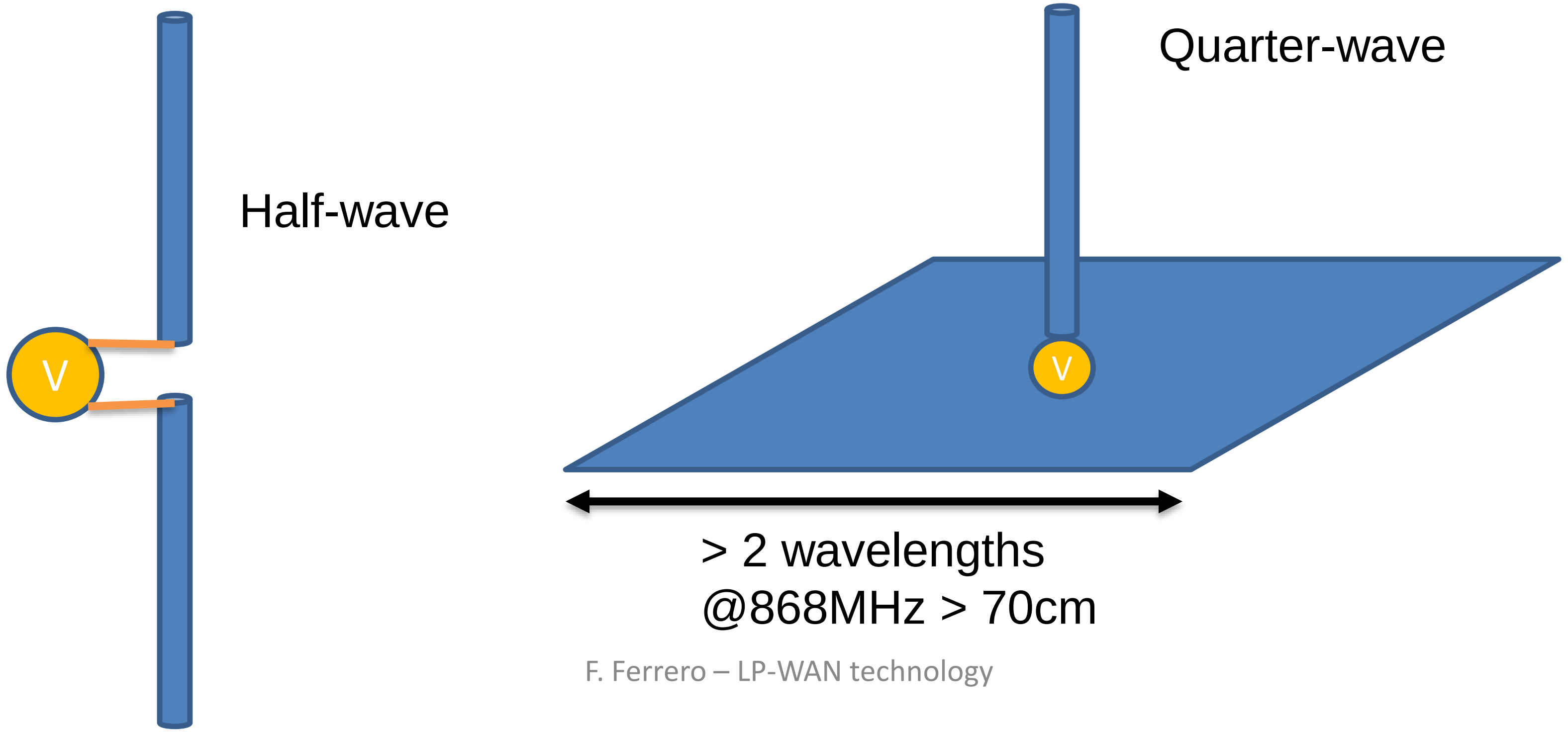


# Effect of terminal chassis

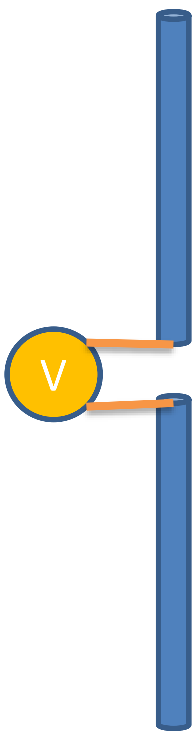
- Antennas can be:
  - Dual-pole : 2 parts will contribute to the radiation
  - Single-pole with a large ground plane



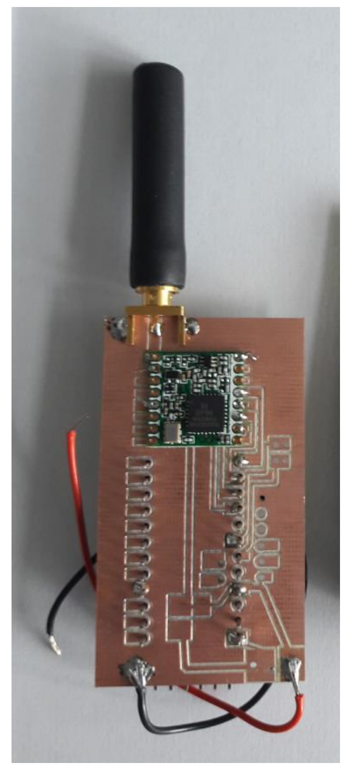



# Effect of terminal chassis

- In most of the case, you will have a dual-pole antenna

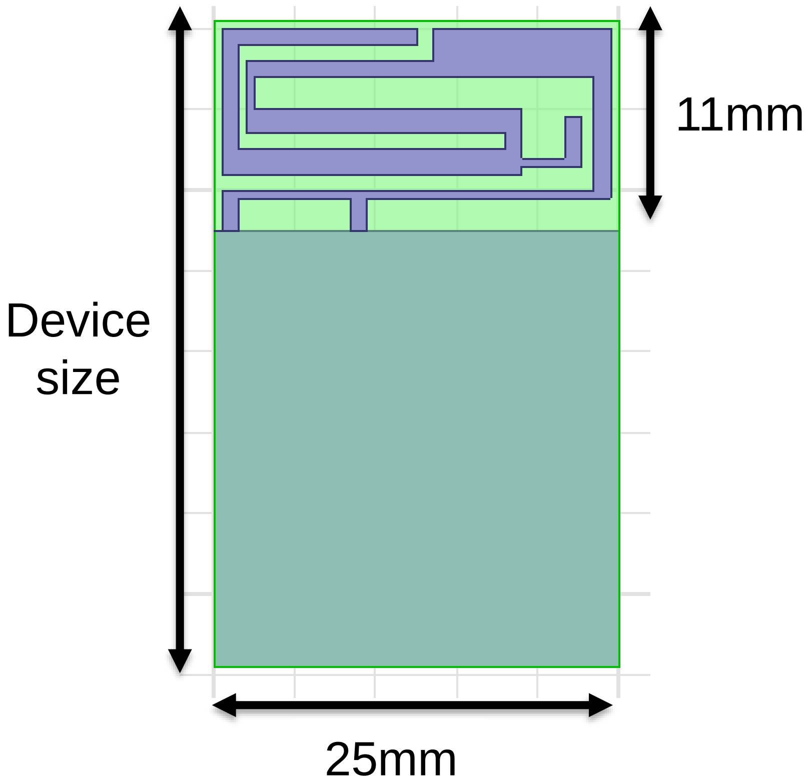


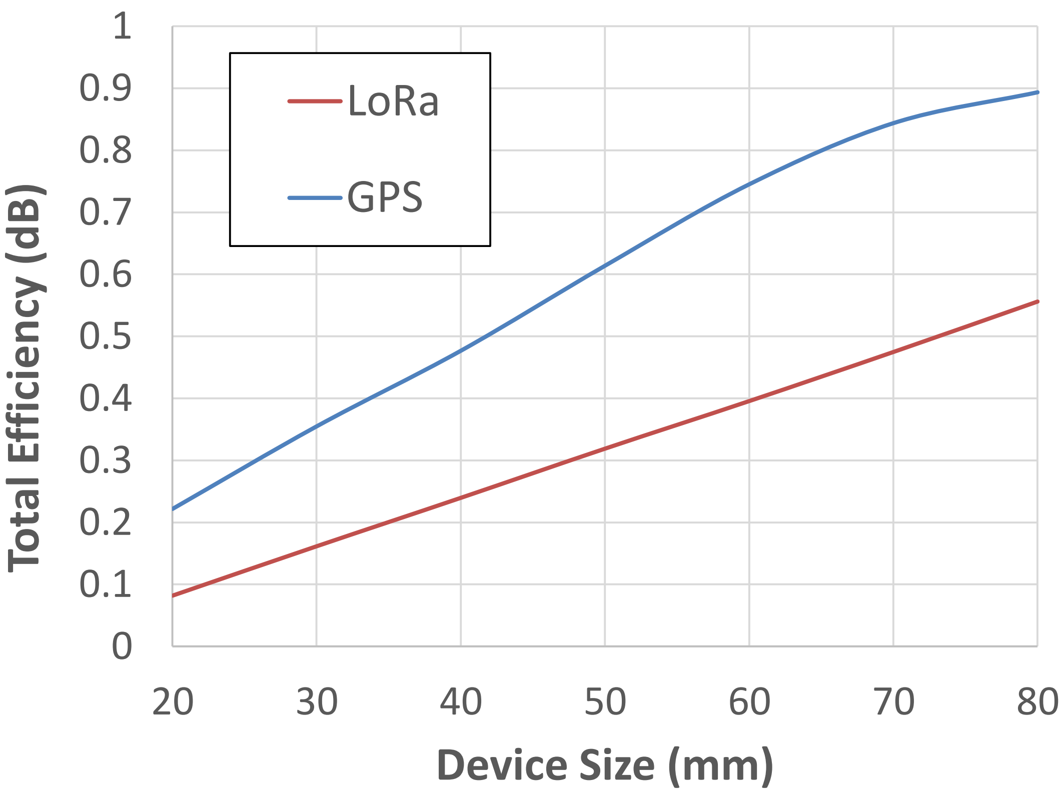

Half-wave



# Effect of terminal chassis

- LoRa (868MHz) and GPS (1575MHz) antenna on small terminal

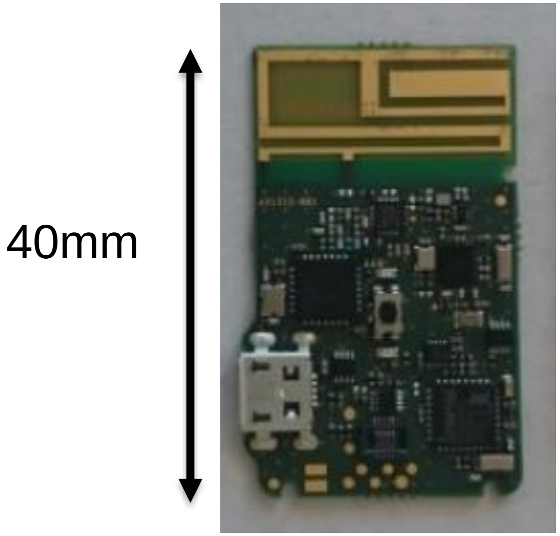


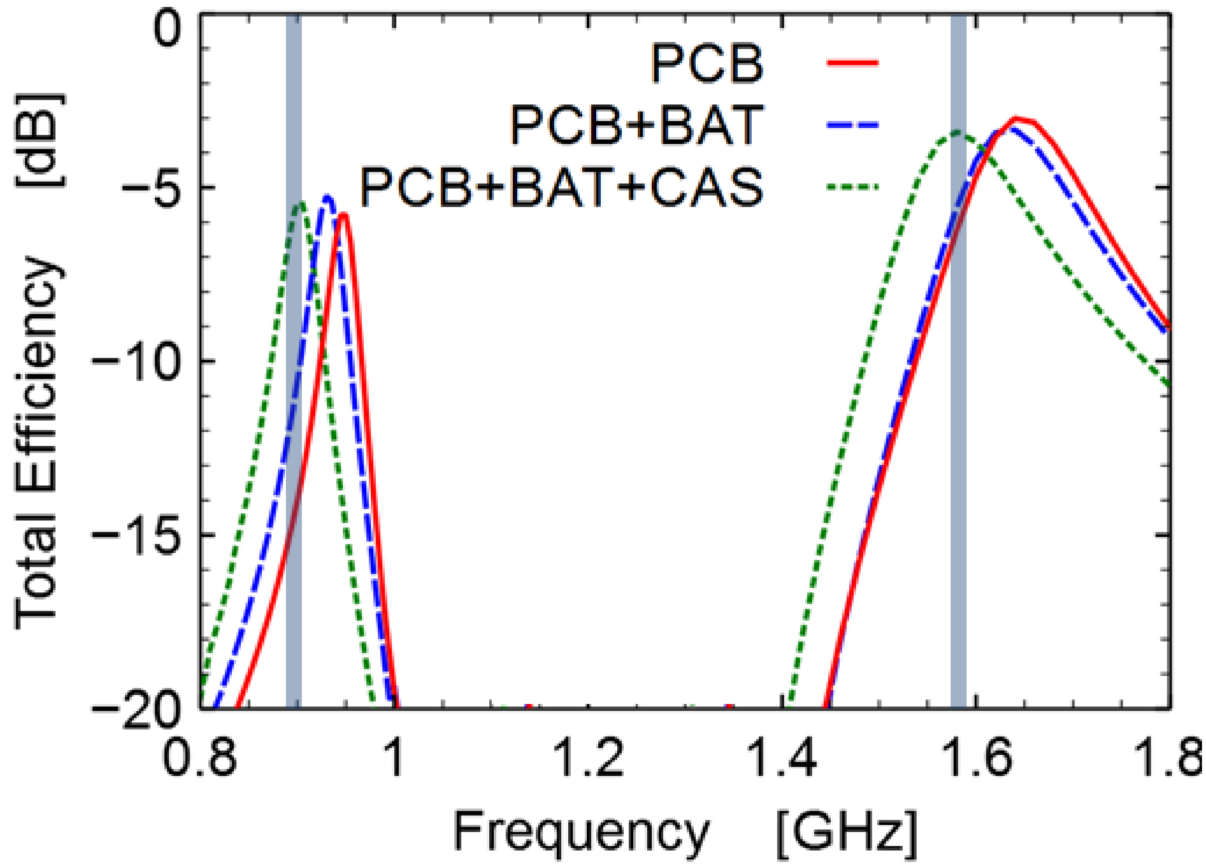




Smart geolocation technology

# Effect of the environment

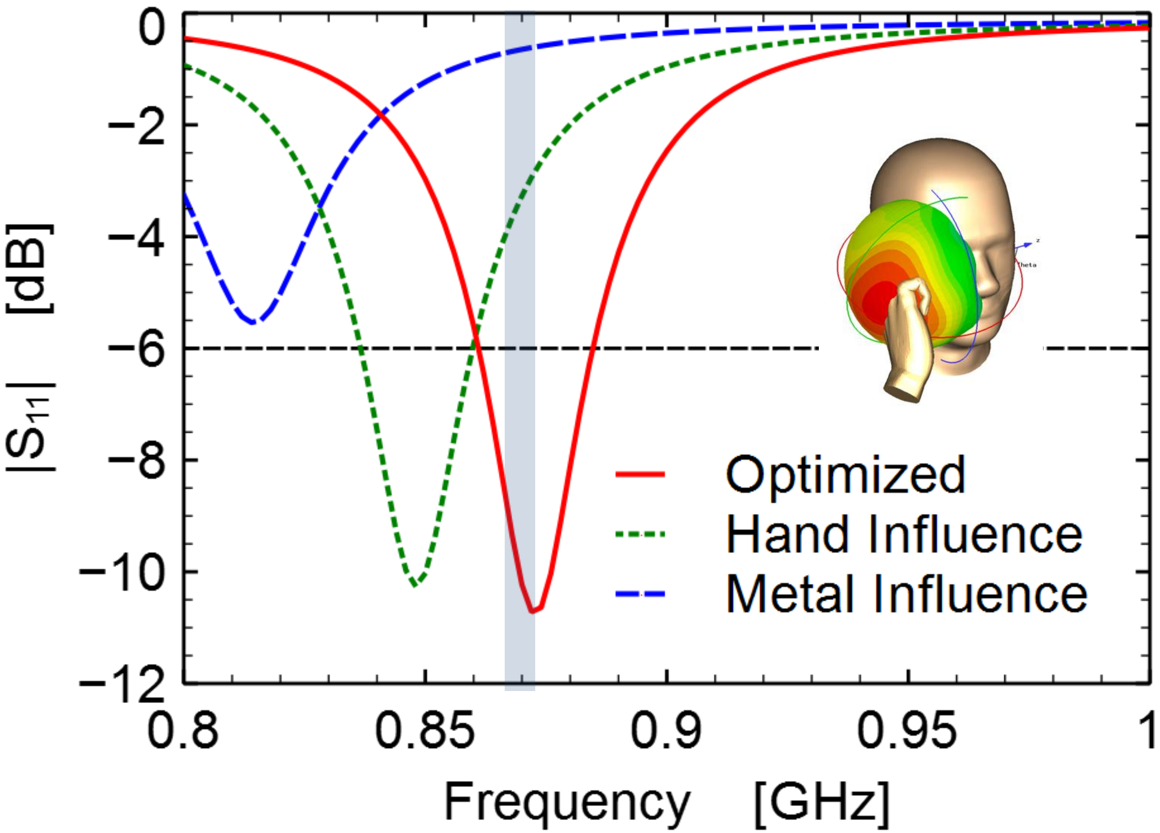
Antenna are strongly influenced by the close environment like the battery or the terminal casing



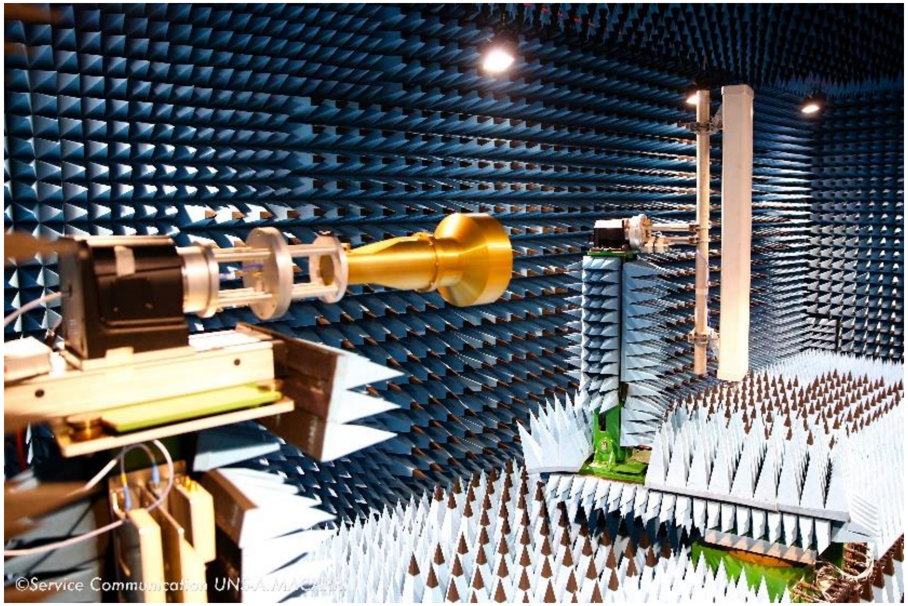
# Effect of the environment

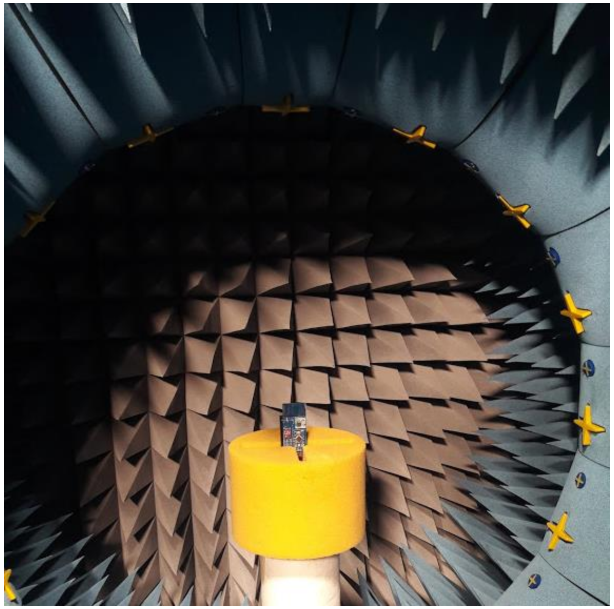
Antenna are also influenced by the surrounding environment



# Antenna measurement

- Reliable antenna measurement is not an easy task
- Very hard to test antennas in a non-anechoic environment
- Cables have a large influence on the measurement
- Only Total Radiated Power (TRP) measurement can be trusted





# Antenna Outline

- Antenna key parameters
- Low-cost Antenna Open Source project
- Micro-tracker Antenna Industrial project

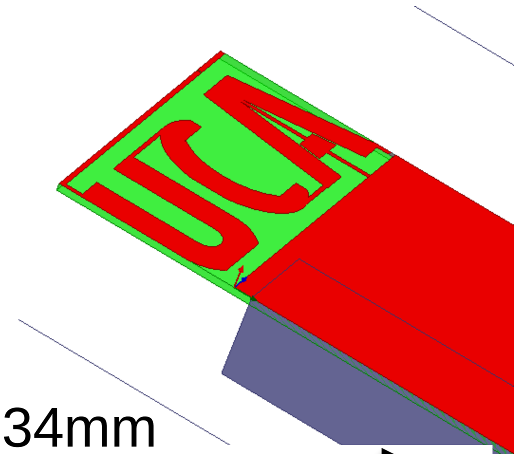
# Design of cost efficient antenna @868MHz

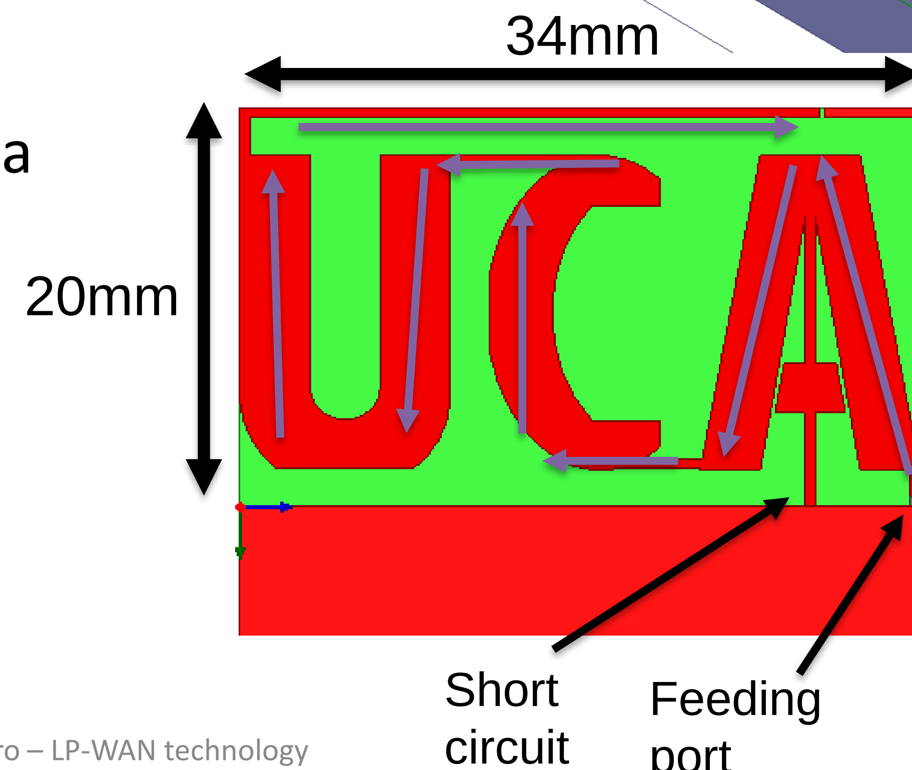
- LoRa collar for Cattle Rustling applications
- Cost reduction
  - Remove RF connectors ( a SMA connector is 4$)
  - Avoid external antenna (cost between 2 and 8 $)
  - A PCB is needed for component integration
  - The cost for an extension of the PCB is negligible, so PCB integrated antenna is very cost efficient

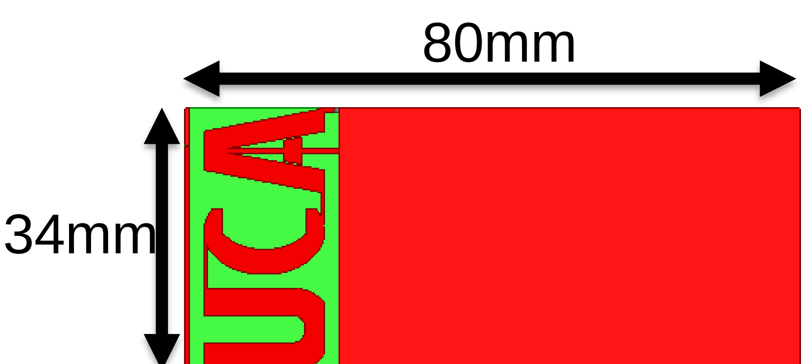

***https://github.com/FabienFerrero/UCA_Board***

# UCA Antenna layout

- Miniaturized Printed Antenna(low cost)
- Based on a meandered **I**nverted **F** **A**ntenna (**IFA**) Structure
- Mounted on a 80*34mm 0.8mm-thick FR4 PCB
- Performance equivalent to a classical printed antenna in this area

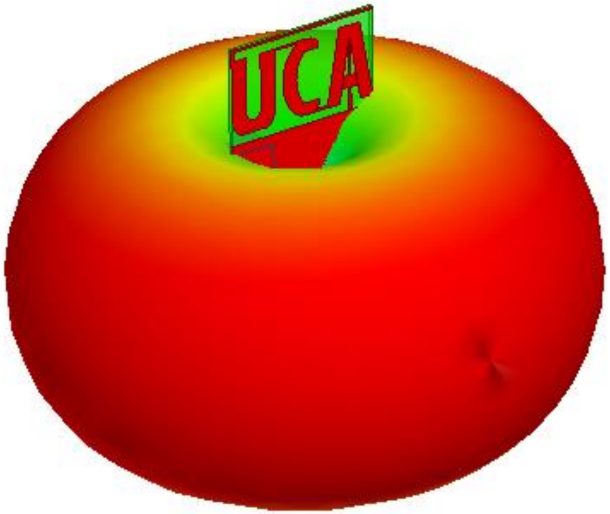




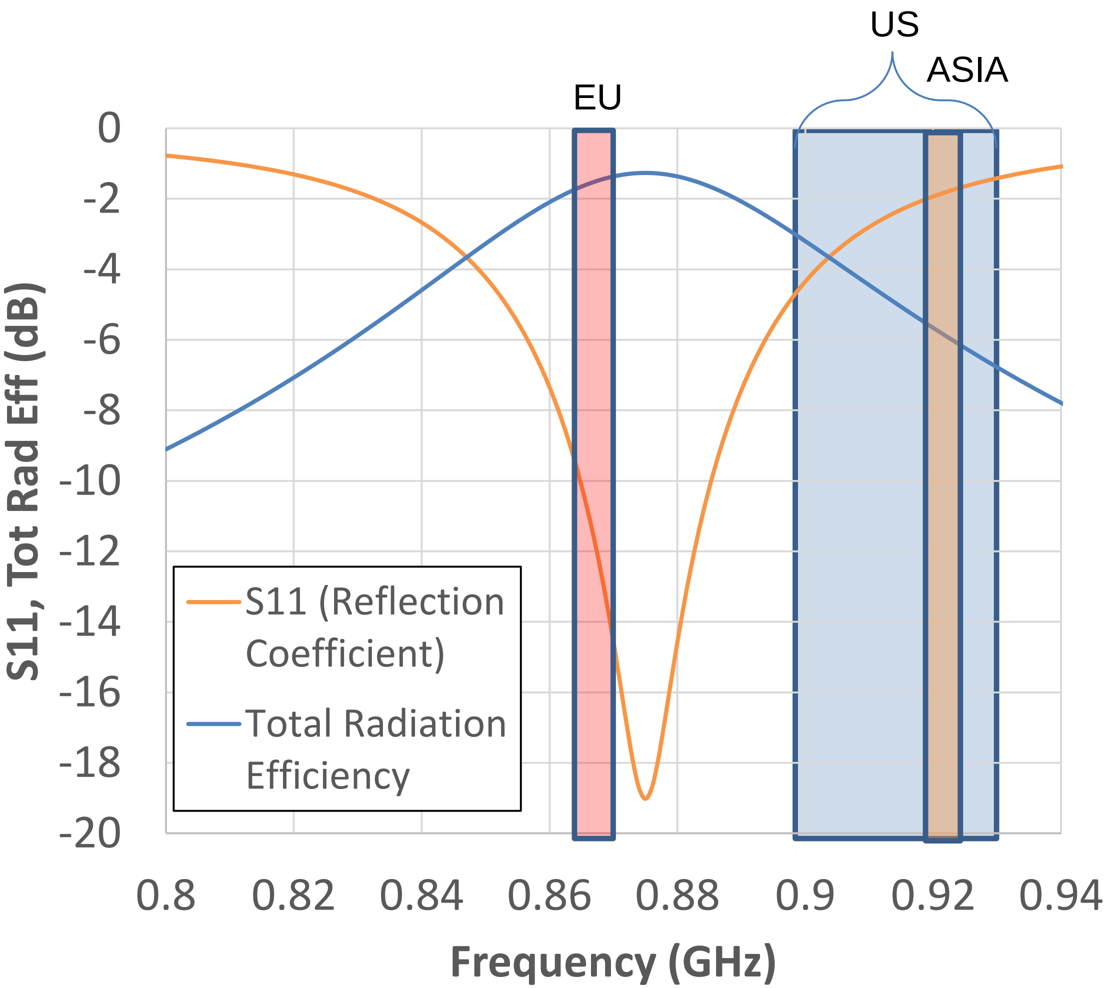
# UCA Antenna tuned for EU band

- Antenna simulation
  - Matched to 50 ohm
  - Bw = 30MHz (@-6dB )
  - -1.2 dB radiation efficiency (75%)
  - Dipole radiation pattern
  - 2.1 dBi peak directivity
  - 0.9 dBi peak Gain



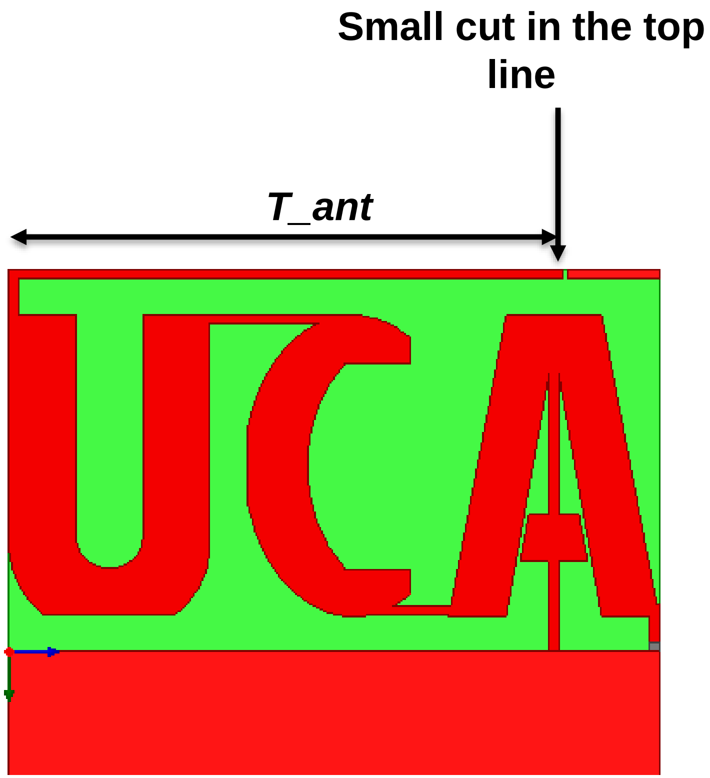
# UCA Antenna tuned for EU band

- Miniature antenna
  - Limited frequency bandwidth
  - If the antenna is matched for European band, the antenna has poor radiation performance in US and ASIA bands

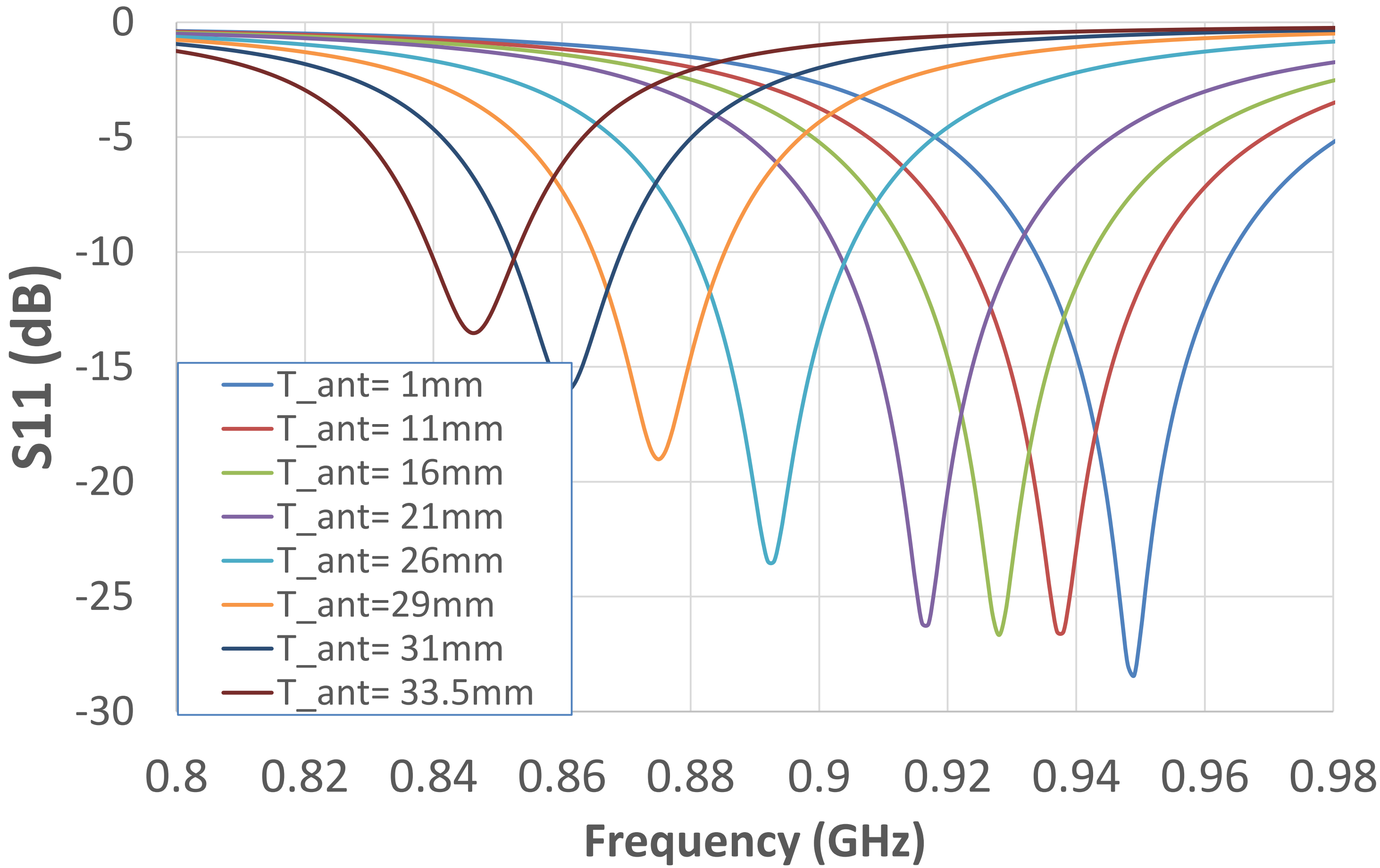


# Antenna design

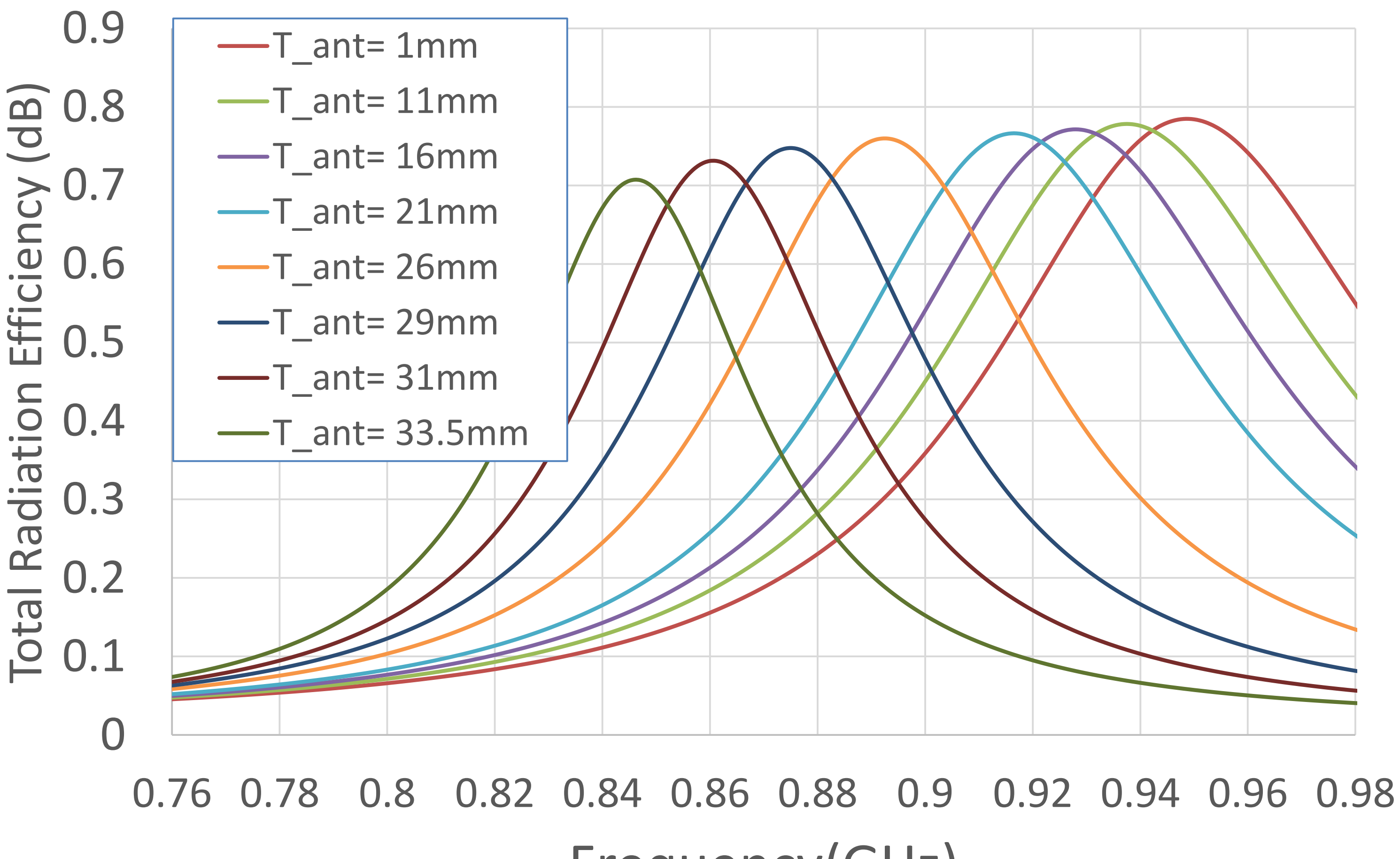
- The antenna shape can be easily tuned to different frequencies
  - The top line can be cut at different position to change the antenna trace length
  - *T_ant* parameter can be tuned from 0 to 34mm
  - Antenna resonance frequency can be tuned from 845 to 950MHz



# UCA Antenna tuning : Reflection coefficient



# UCA Antenna : Linear Total Rad. Efficiency



# II. Physical layer (LoRa modulation)

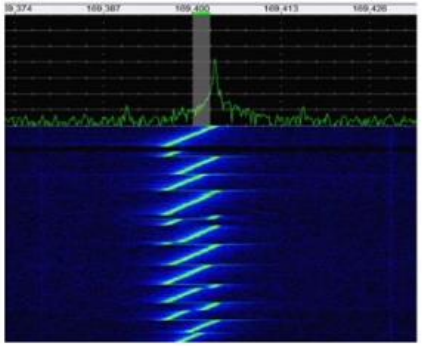
- Spread Spreading technique
- Chirp Spread Spectrum
- LoRa Spreading factor

# LoRa modulation

**Spread spectrum technique :**

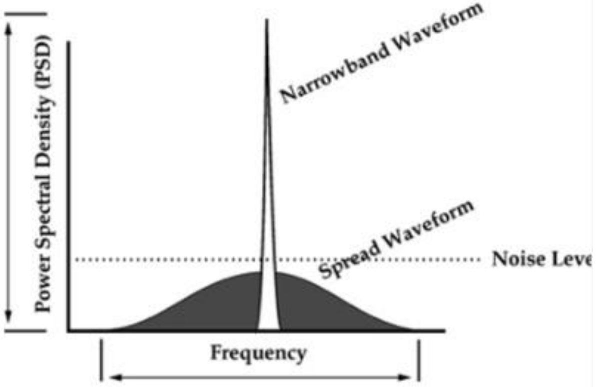
Increase communication distance by increasing energy per bit :

- Increase transmit power
- Lower modulation rate

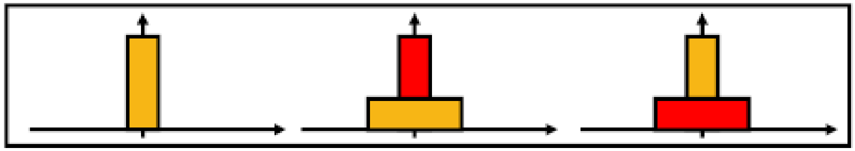


3 types of spread spectrum technique :

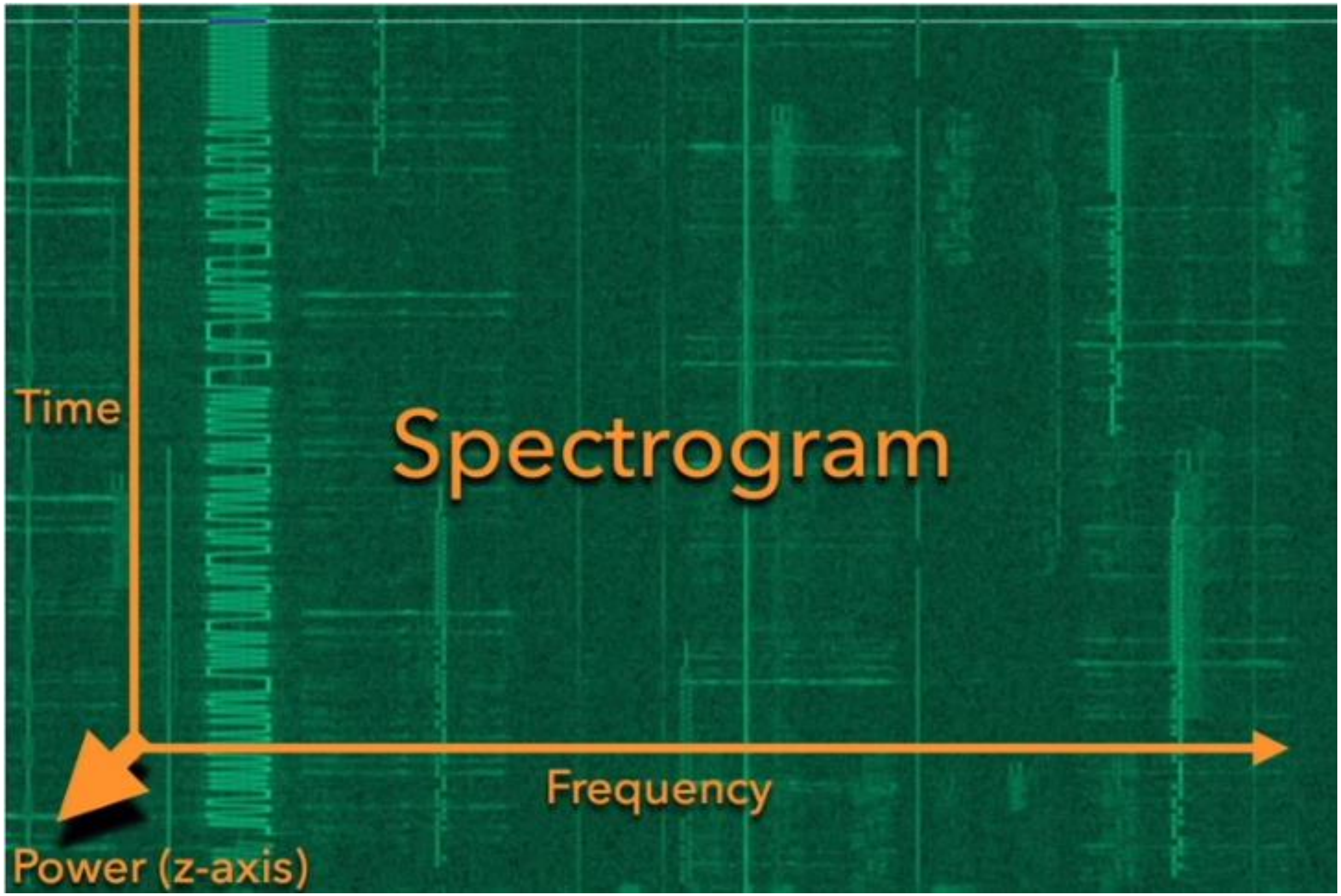
- FHSS : Freq Hopping (used in Bluetooth)
- DSSS : Direct Sequence (UMTS and Zigbee)
- CCS : Chirp Spread Spectrum (LoRa)



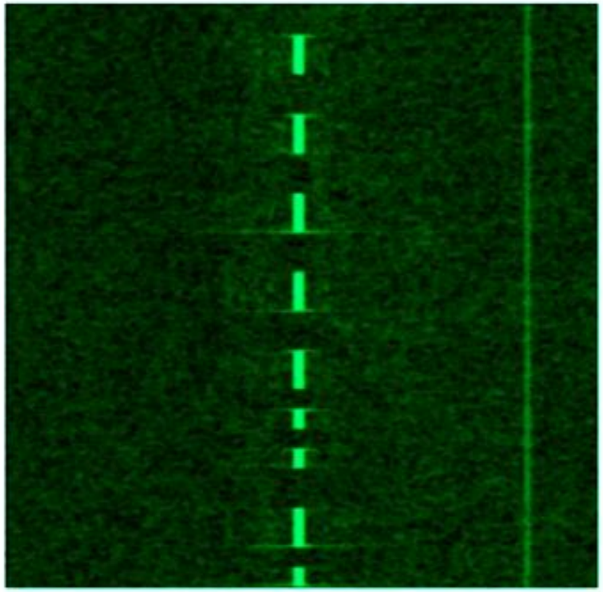

Robust to interference, multipath and fading



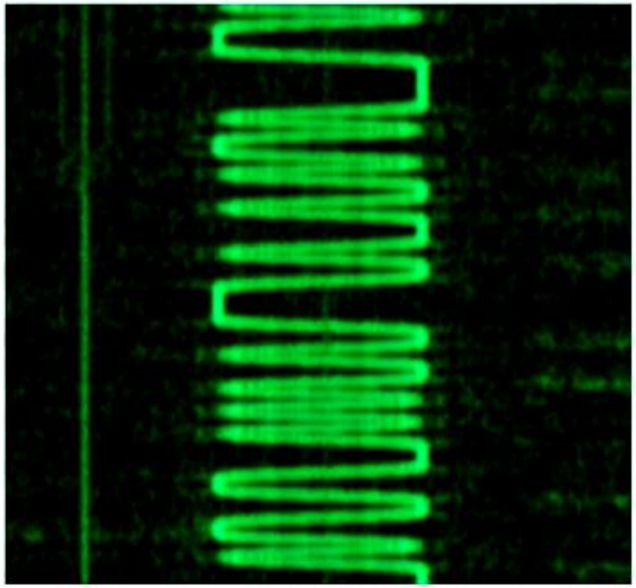
# CSS : Chirp Spread Spectrum



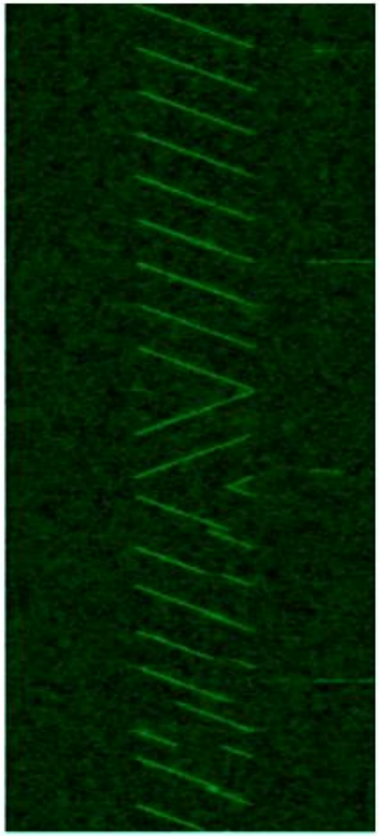
# CSS : Chirp Spread Spectrum



On-Off Keying



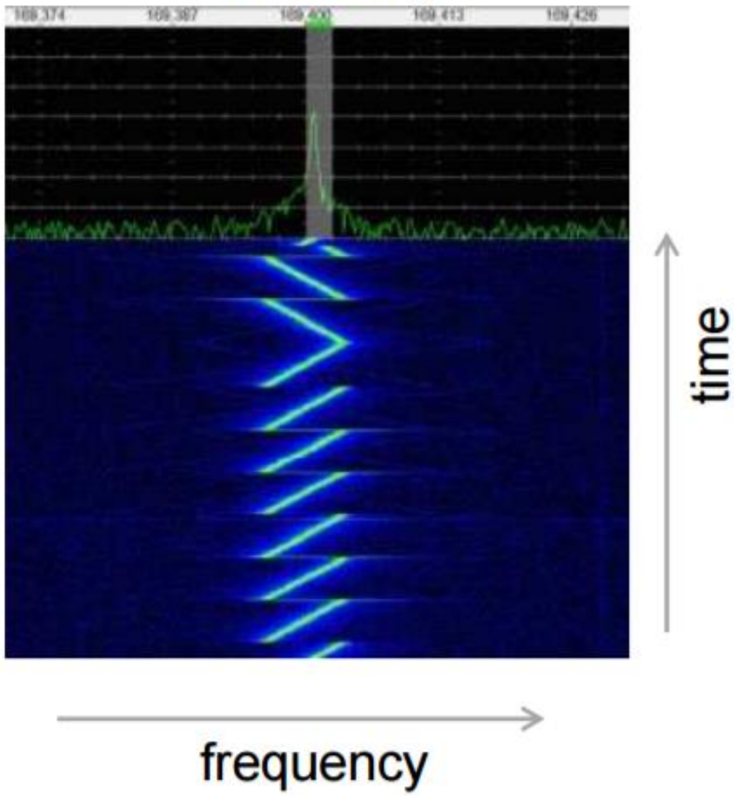
Frequency-shift Keying



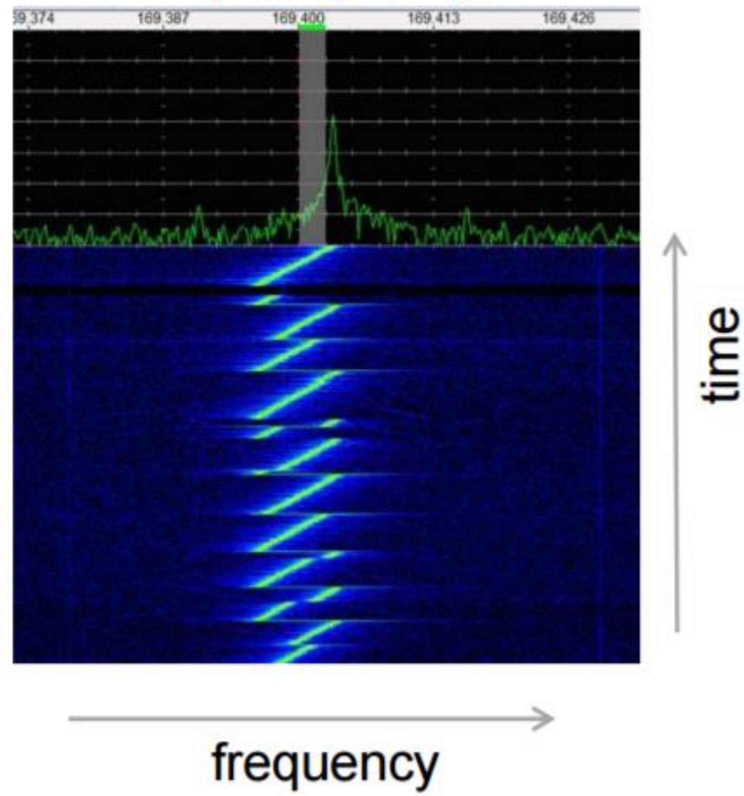
LoRa

# LoRa Chirp Spread Spectrum (CSS)

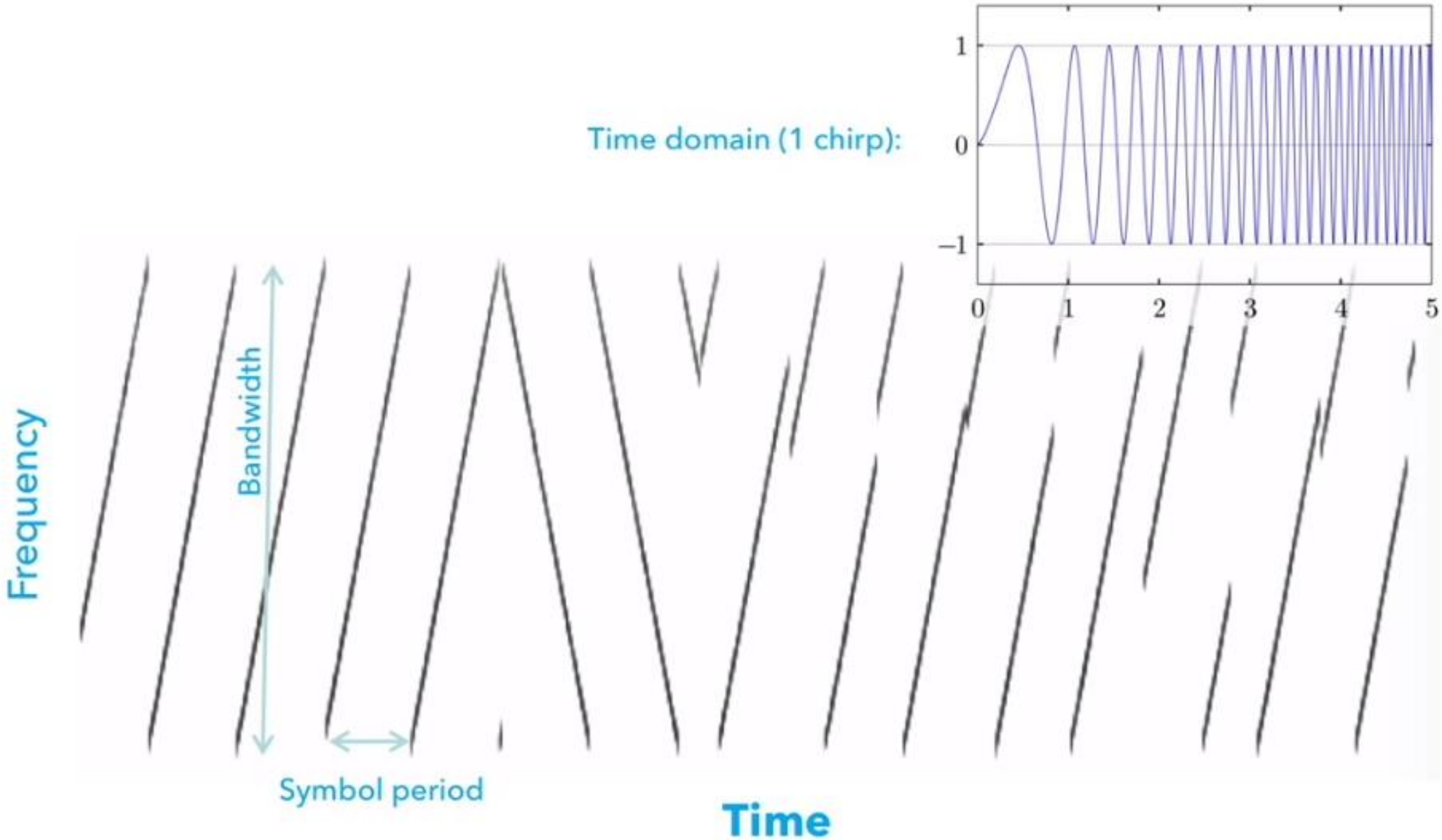
LoRa pre-amble signal:
10 symbols or "chirps",
2 reverse "chirp".




LoRa data signal:
A symbol is a "chirp" with
a frequency "hop".



# LoRa Chirp Spread Spectrum (CSS)



# LoRa Bit rate

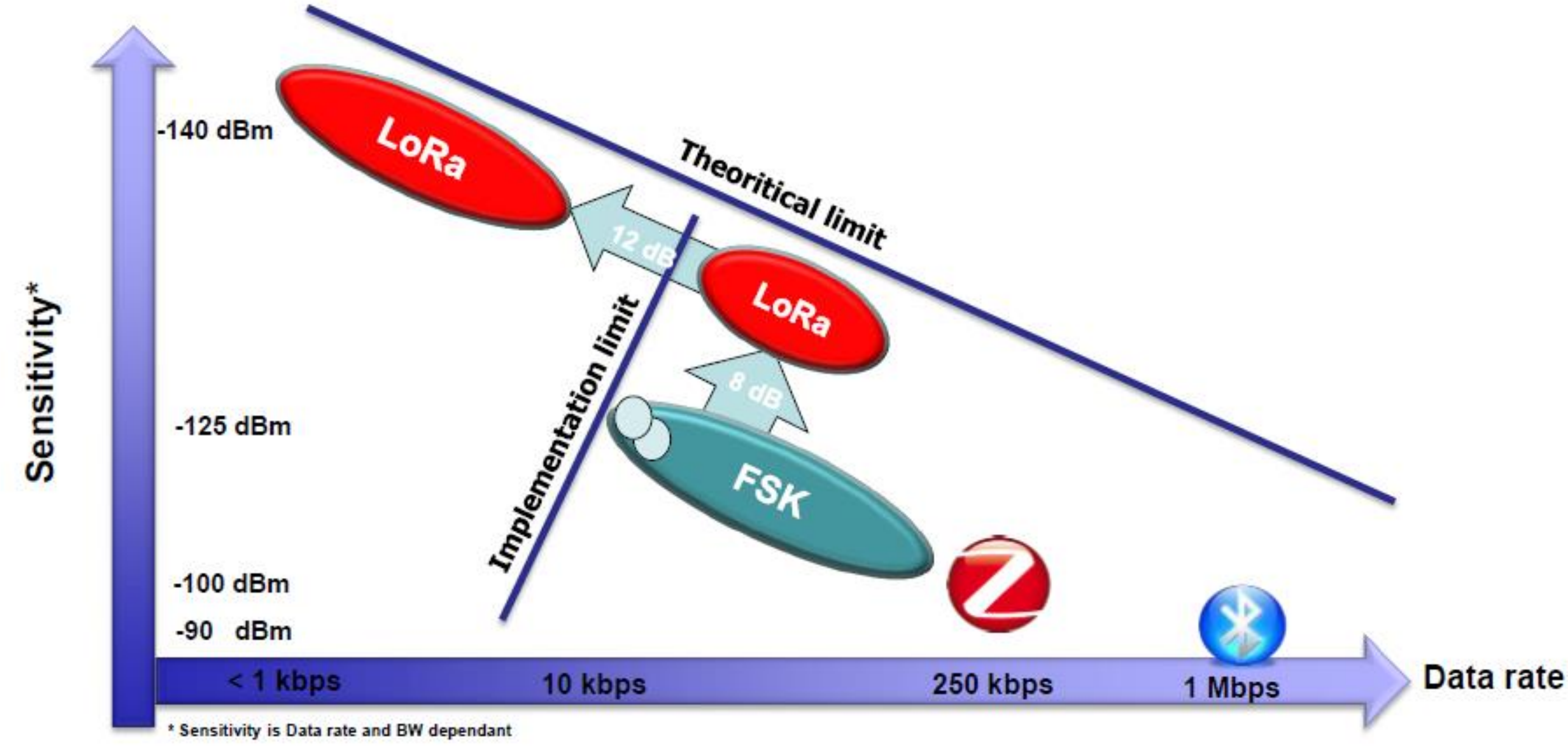
## Some LoRaWAN data rates

| | | $T_{Symbol} = 2^{SF}/BW$ | | ohne FEC | 4/5 FEC (CR=1) | |
|---|---|---|---|---|---|---|
| BW / kHz | SF | $T_{symbol}$ / ms | $R_{symbol}$ / Hz | $R_{bit}$ / bps | $R_{bit}$ / bps | Sensitivity |
| 125 | 7 | 1.024 | 976.56 | 6835.94 | **5468** | $S_{ref}$ = -125 dBm |
| 125 | 8 | 2.048 | 488.28 | 3906.25 | **3125** | - 2.4 dB |
| 125 | 9 | 4.096 | 244.14 | 2197.27 | **1757** | - 4.9 dB |
| 125 | 10 | 8.192 | 122.07 | 1220.70 | **976** | - 7.5 dB |
| 125 | 11 | 16.384 | 61.04 | 671.39 | **537** | - 10 dB |
| 125 | 12 | 32.768 | 30.52 | 366.21 | **292** | - 12.7 dB |

using SF = 12 rather than SF = 7

- improves the sensitivity by ~**13 dB**
  or the range by a factor of ~**2.3** (assuming a path loss of 35 dB/decade)
- but increases the symbol time $T_{symbol}$ by a factor of **32**
  (and, thus, the "time on air" and the current consumption)

# LoRa CSS modulation

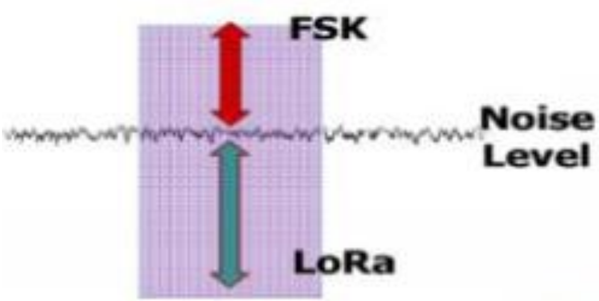


# LoRa Modulation : Synthesis

**Benefits :**

- Simple to implement (Constant enveloppe)
- Bandwidth scalable
- Very resistant to in-band and out-of band interferences
- High immunity to multi path and fading

- Doppler shift resitance
- Moving devices
- High clock tolerances




- Orthogonal with other non-LoRa communications (OFDM, narrowband FSK…)
- Orthogonal with LoRa systems using a different Spreading Factor

- Good sensitivity
- Lora reception is simple