UNIVERSIDAD COMPLUTENSE MADRID

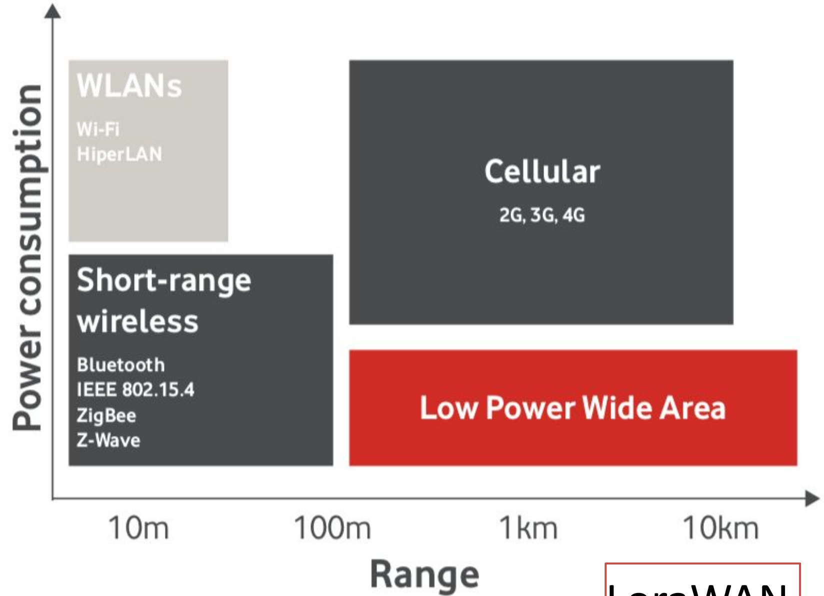
Low Power Wide Area Networks (LPWAN)

Networks and Protocols 1

Facultad de Informática

Low Power Wide Area Networks

- Low Power
  - 25 mW transmission power
  - ~20 years with batteries
- Wide Area
  - 15-50 Km in rural areas
  - 2-3 Km in urban areas or interiors
- Networks
  - Devices interconnected with wireless technologies
  - Generally star topologies with gateways
  - Communication initiated by the device
  - High density
  - Asymmetric links
  - Low bandwidth
  - Licensed spectrum or ISM



LoraWAN
SigFox
NB-IoT

"five 10s" of LPWA

A device must last at least **10 years**

- With distances of **10km** to the base station
- Cost under **$10**
- Transmit **10s of bytes** per hour
- Each base station must support **10k devices**

LPWAN vs other technologies

Wireless Technology	Wireless Communication	Range (m)	Tx power (mW)
Bluetooth	Short range	~10	~2.5
WIFI	Short range	~50	~80
3G / 4G	Cellular	~5000	~500
LoRa*	LPWAN	2000-5000 (urban area) 5000-15000 (rural area) > 15000 (direct line of sight)	~20

LoRa®

- LoRa -> Long - Range
- Radio technologie created by Cycleo (french startup)
  - From 0.3 kbps up to 5.5kbps
  - Gateways can handle hundreds of devices
  - Uses the ISM sub GHz band
    - https://www.thethingsnetwork.org/docs/lorawan/frequencies-by-country.html
    - https://www.thethingsnetwork.org/docs/lorawan/frequency-plans.html

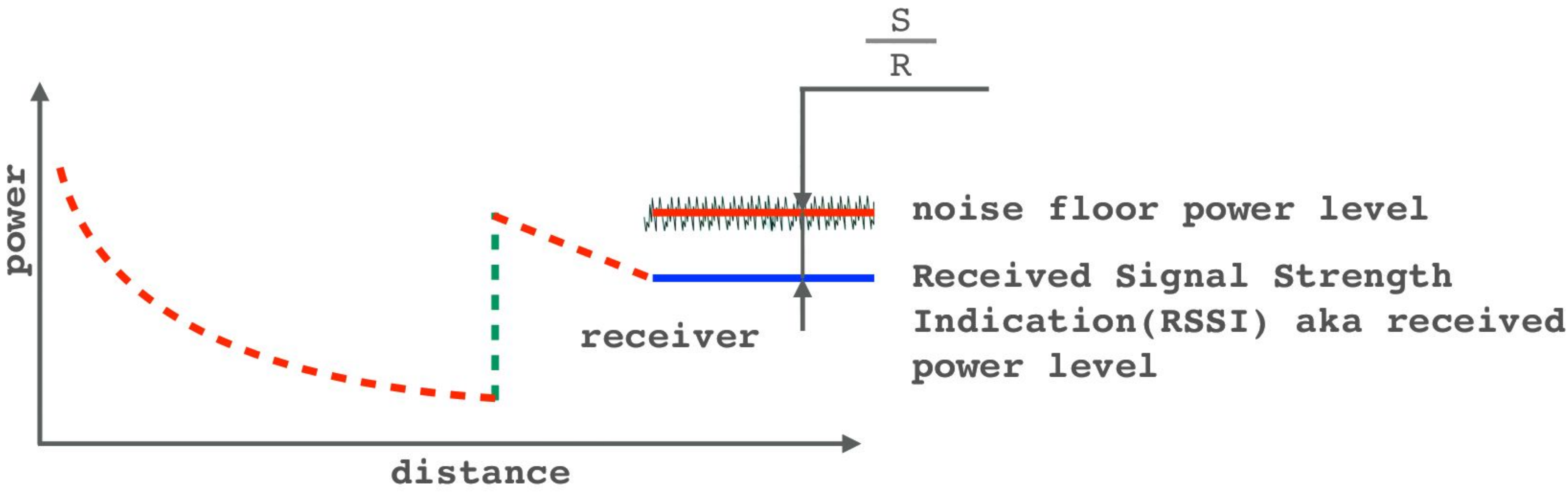
Region	Frequency (MHz)
Asia	433
Europe, Russia, India, Africa (parts)	863-870
US	902-928

Region	Frequency (MHz)
Australia	915-928
Canada	779-787
China	779-787, 470-510

- In 2012 Semtech Corporation acquired Cycleo
  - The LoRa radio is patented
  - Semtech has licenced the intellectual property (ip) to other chip manufacturers like HopeRF, Microchip or Dorji
  - In 2015 Semtech registered the word LoRa as a trademark

LoRa: SNR (dB) < 0

- LoRa receivers have a sensitivity of -148dBm, thanks to the Chirp modulation they use
  - They require a minimum RSSI of -120dBm, i.e. 28dB of margin
- They can operate under the noise level
  - S/N < 1 or SNR (dB) < 0
  - Typical SNR values for LoRa are -20dB to +10dB



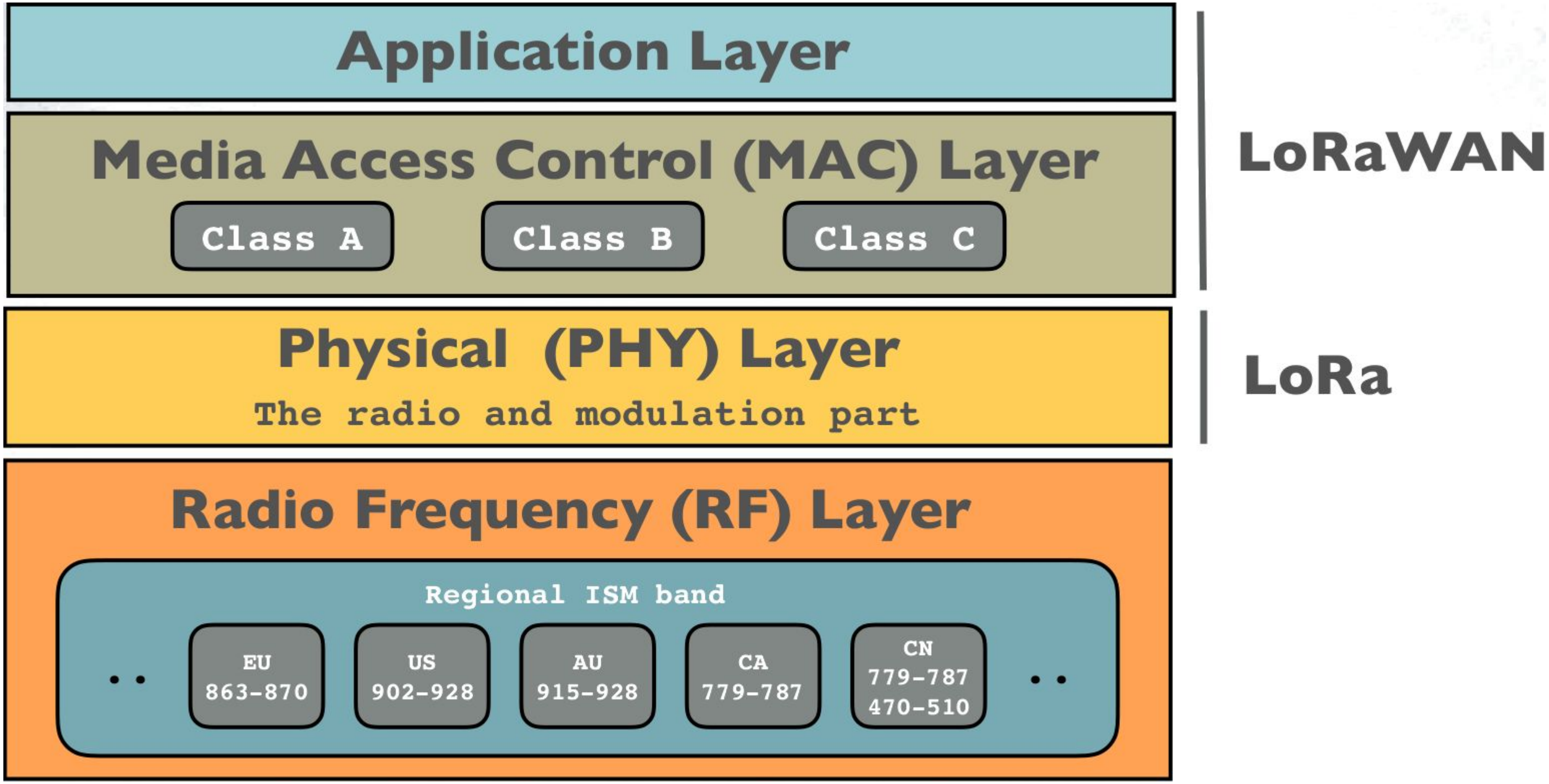
LoRa® range

- Depends on the environment in which it operates
  - The indoor coverage depends on the material used for the building

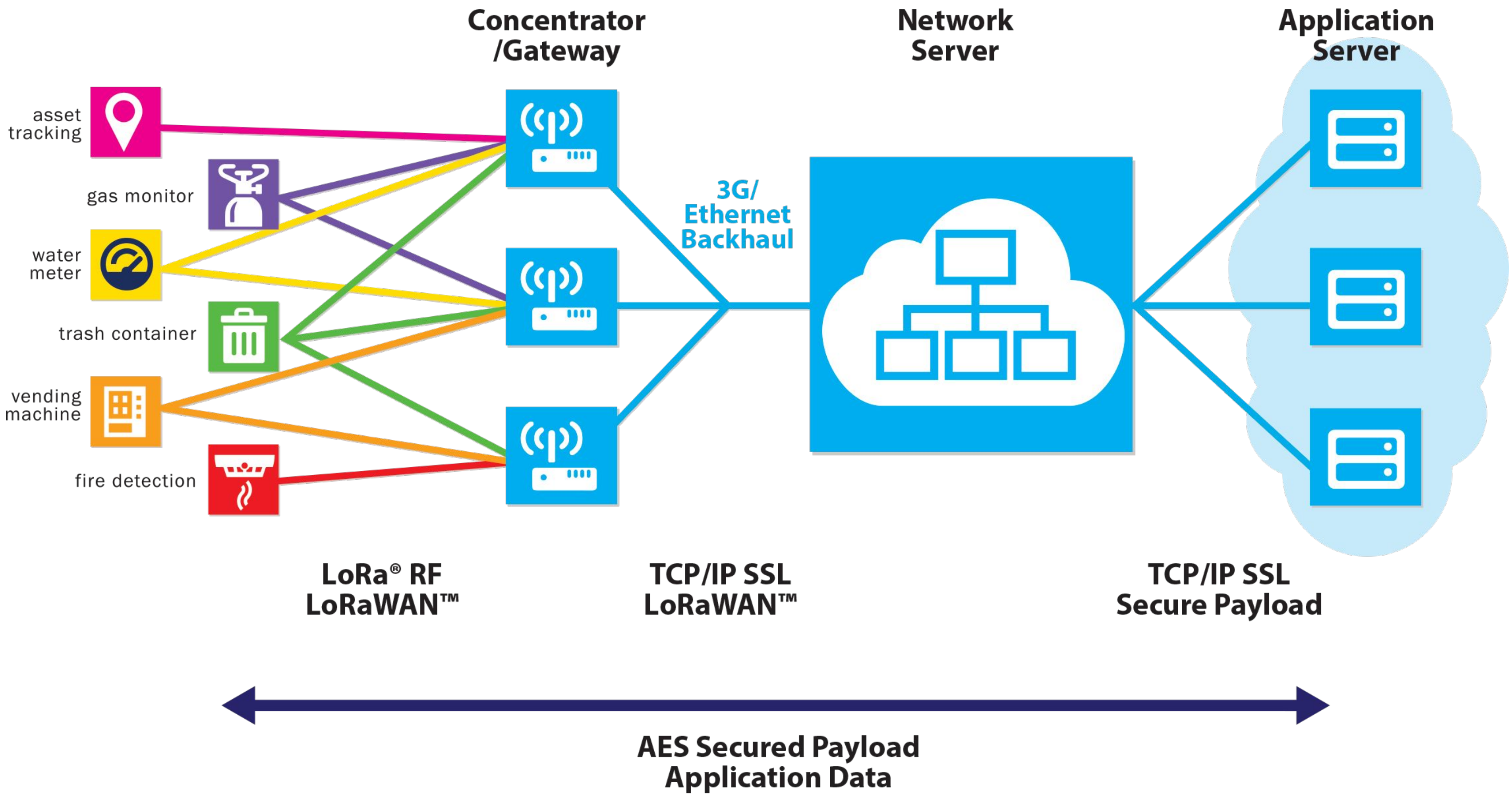
Environment	Range (km)
Urban areas (towns & cities)	2-5
Rural areas (countrysides)	5-15
Direct Line Of Sight	>15

- Some remarkable records:
  - Andreas Spiess, ground to ground connection: 212 km
  - Weather balloon to ground connection: 702.67 km

LoRaWAN Stack



LoRaWAN Network Architecture



- Star topology, no direct communication among nodes
- The gateways send to the network server, that filters duplicates
- Bidirectional communication between servers and nodes

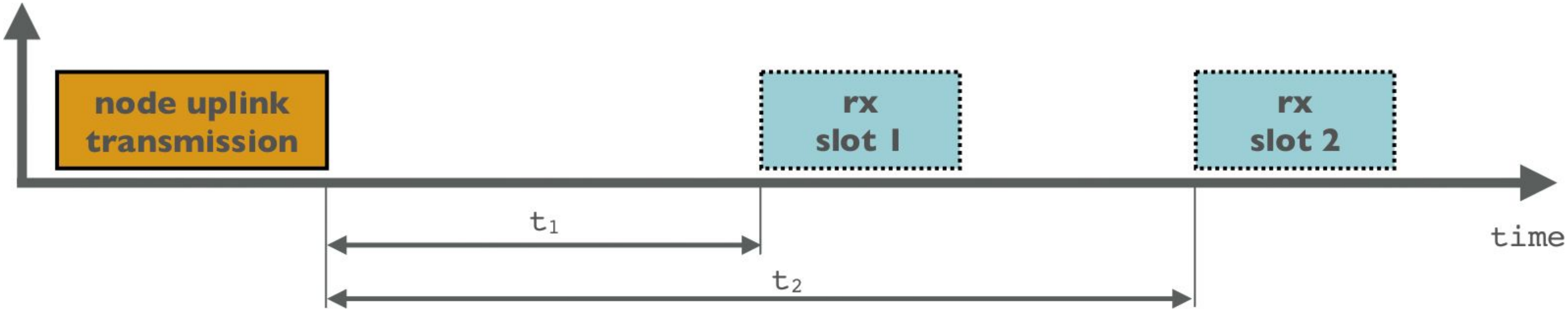
Device classes in LoRaWAN

The LoRaWAN specification defines 3 device classes

Class	Description
A(ll)	Battery powered devices. Each device uplink to the gateway and is followed by two short downlink receive windows.
B(eacon)	Same as class A but these devices also opens extra receive windows at scheduled times.
C(ontinuos)	Same as A but these devices are continuously listening. Hence these devices uses more power and are often mains powered.

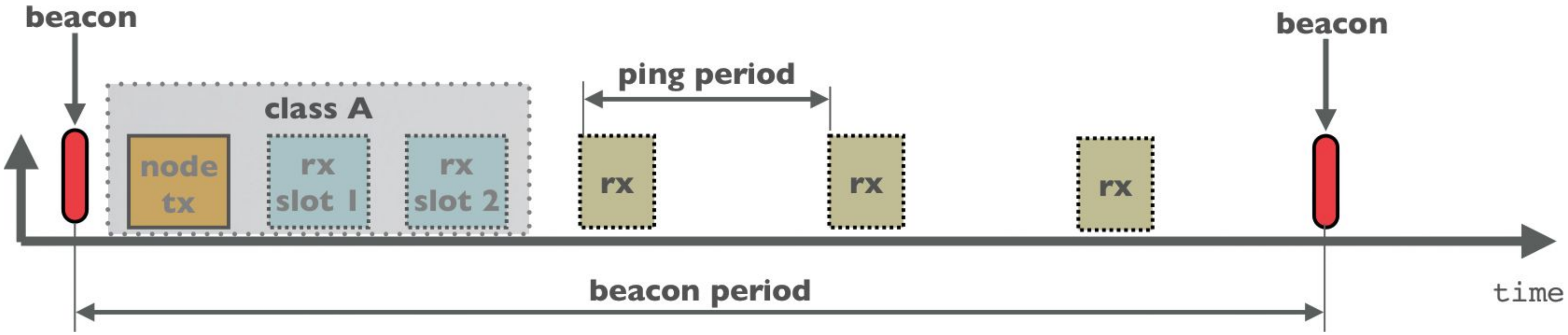
Class A

- A node can send uplink at any moment
- After that it must open two receive windows to listen for downlink messages from the gateway
  - The gateway will use only one of them to send its response
- Devices of class B or C do also support this functionality



Class B

- Class B devices open additional windows for downlink traffic
- Placed in between the beacons of the gateway
- Do not support the functionality of class C devices



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Class C

- These devices listen continuously the medium for downlink traffic
  - usually connected to mains power
- Do not support the functionality of class B devices

LoRaWAN™ addresses

LoRaWAN™ defines a series of identifiers for devices, applications and gateways

- DevEUI -> 64 bits unique id per device (EUI-64)
  - Assigned by the manufacturer
- DevAddr -> 32 bits device address
  - Dynamically generated from 7 bits of the network card (assigned by the Lora Alliance) and 25 bits obtained during activation
- AppEUI -> 64 bits application id (EUI-64, unique)
- GatewayEUI -> gateway EUI-64, unique identifier
  - Assigned by the manufacturer

LoRaWAN™ Security

- LoRaWAN allows the messages to be encrypted and signed using keys known by the gateway and the server
  - Network Session Key (NwSKey)
    - For the interaction between the node and the gateway
    - Used to validate messages (MIC check)
  - Application Session Key (AppSKey)
    - To encrypt/decrypt the payload
- Defines two mechanisms to deploy the keys
  - Over-the-Air-Activation (OTAA)
  - Activation by personalization (ABP)
- Uses *frame counters* to avoid *replay attacks*

LoRa nodes

- Composed of:
  - A microcontroller
  - A LoRa transceiver (radio) with an antenna
- Battery powered
- Usually called "motes" for remote sensor

LoRa Gateway

- Composed of:
  - A microprocessor
  - A LoRa radio module with an antenna
- Connected to mains power
- Connected to the Internet with other technology (e.g. ethernet)
- Multiple gateways can receive the data of a single mote
- Can listen several frequencies simultaneously
  - In all spreading factors for each frequency

Regulations

- ISM Sub GHz Band has usage regulations
  - In the EU we follow the European Telecommunication Standards Institute (ETSI, https://www.etsi.org)
  - In the USA it is the Federal Communications Commission (FCC, https://www.fcc.gov) who establishes the standards
  - The local authorities, including the network operator, can impose additional regulations
- In EU the rules established by the ETSI are:
  - Max uplink power of 25 mW (14 dBm)
  - Max downlink power of 0.5 W (27 dBm)
  - Duty Cycle of 0.1%, 1% or 10% depending on the channel
  - Max antenna gain of +2.15 dBi
- The Things Network (TTN): fair use policy
  - Uplink airtime limited to 30 s per day and node
  - Downlink messages limited to 10 per day and node

Frequencies and LoRa modulation

- Each country follow its own regulations
  - You can check the regulations for your country in:
    - https://lora-alliance.org/lorawan-for-developers
    - https://www.thethingsnetwork.org/docs/lorawan/frequencies-by-country.html
  - The EU863-870 plan regulates the LoRa frequencies in Europe:
    - https://lora-alliance.org/resource-hub/rp2-101-lorawanr-regional-parameters-0
    - https://www.thethingsnetwork.org/docs/lorawan/frequency-plans.html

EU863-870

- Uplink

Channel	Uplink freq (MHz)	SPREADING FACTOR & BANDWIDTH RANGE
0	868.1	SF7BW125 to SF12BW125
1	868.3	SF7BW125 to SF12BW125 and SF7BW250
2	868.5	SF7BW125 to SF12BW125
3	867.1	SF7BW125 to SF12BW125
4	867.3	SF7BW125 to SF12BW125
5	867.5	SF7BW125 to SF12BW125
6	867.7	SF7BW125 to SF12BW125
7	867.9	SF7BW125 to SF12BW125
8	868.8	FSK

- Downlink

Download freq (MHz)	SPREADING FACTOR & BANDWIDTH RANGE
	Uplink channels 0-8 (RX1)
869.525	SF9BW125 (RX2 downlink only)

EU863-870

- All EU686MHz devices must support the first three channels:
  - 868.10 MHz, BW de 125kHz
  - 868.30 MHz, BW de 125kHz
  - 868.50 MHz, BW de 125kHz
- And 5 additional channels can be freely assigned by the network operator
  - For example The Things Network uses adds the next 5 channels: 867.1, 867.3, 867.5, 867.7 y 867.9.
  - The regional parameters used by The Things Network can be looked up in: https://github.com/TheThingsNetwork/gateway-conf
- A LoRa device changes pseudo randomly the channel for each transmission

EU863-870: channels

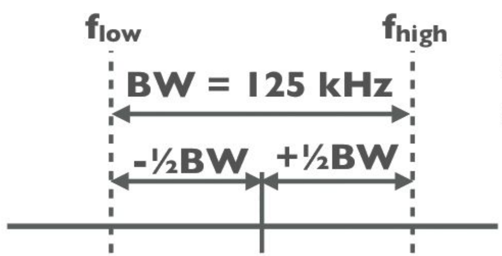
LoRaWan frequencies used in Europe
TTN freq. plan: EU863-870

Bandwidth

- 125 kHz @ SF 1-7, for downlink slot 1
- 250 kHz @ SF7, for downlink slot 1
- 125 kHz @ SF9 for downlink slot 2

Uplink frequencies

Downlink frequencies



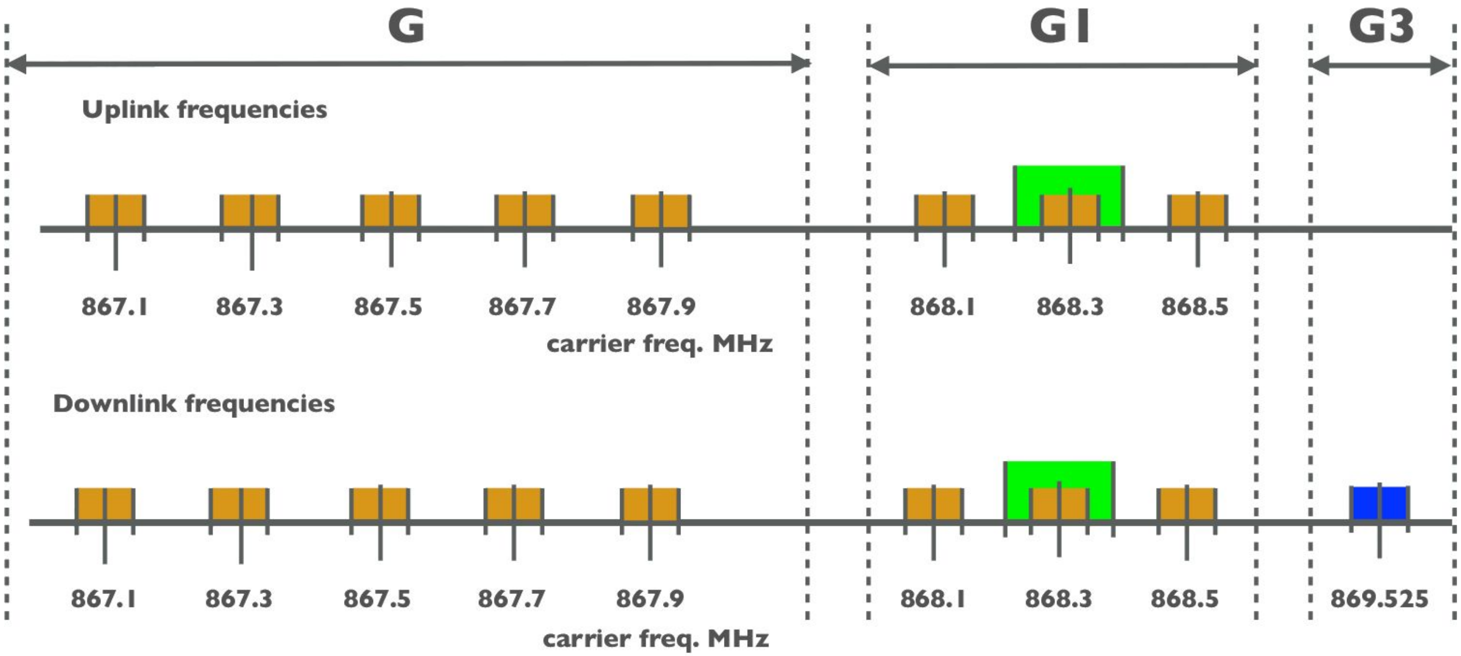
$f_{low} = 867.1 - 0.125 / 2 = 867.0375$ MHz
$f_{high} = 867.1 + 0.125 / 2 = 867.1625$ MHz

Carrier frequency = 867.1 MHz

Sub-bands in 863-870

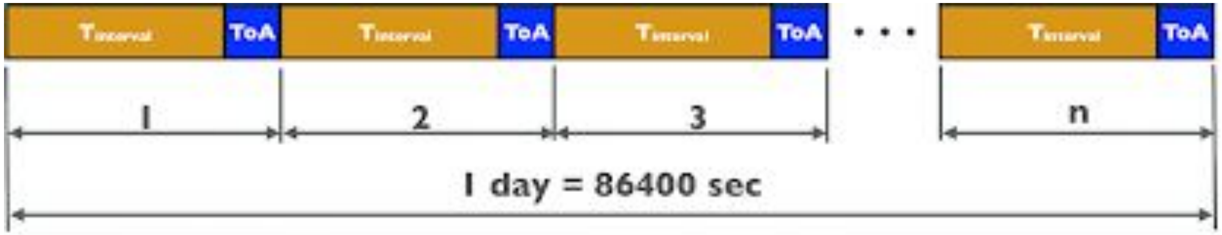
- ETSI divides the band in 5 sub-bands G-G4
  - With different limitations (ERP and duty cycle)

Name	Band (MHz)	Limitations
G	863.0 – 868.0	ERP<25 mW – duty cycle < 1%
G1	868.0 – 868.6	ERP<25 mW – duty cycle < 1%
G2	868.7 – 869.2	ERP<25 mW – duty cycle < 0.1%
G3	869.4 – 869.65	ERP<500 mW – duty cycle < 10%
G4	869.7 – 870.0	ERP<25 mW – duty cycle < 1%



Duty Cycle

- Transmit Interval ($T_{interval}$): Time between transmissions
- Time on Air (ToA): Time in which the transmitter is active transmitting data
- Duty Cycle: portion of time in which a component, device or system is operated



$$ToA = DutyCycle(T_{interval} + ToA) \rightarrow T_{interval} = ToA / DutyCycle - ToA$$

$$= ToA\ (1 - DutyCycle)/DutyCycle$$

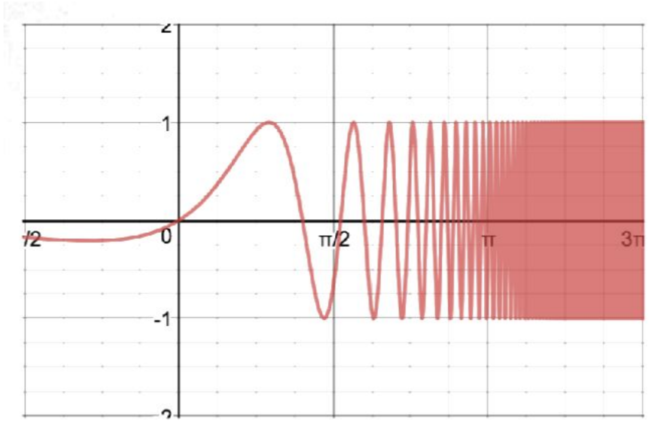
Duty Cycle

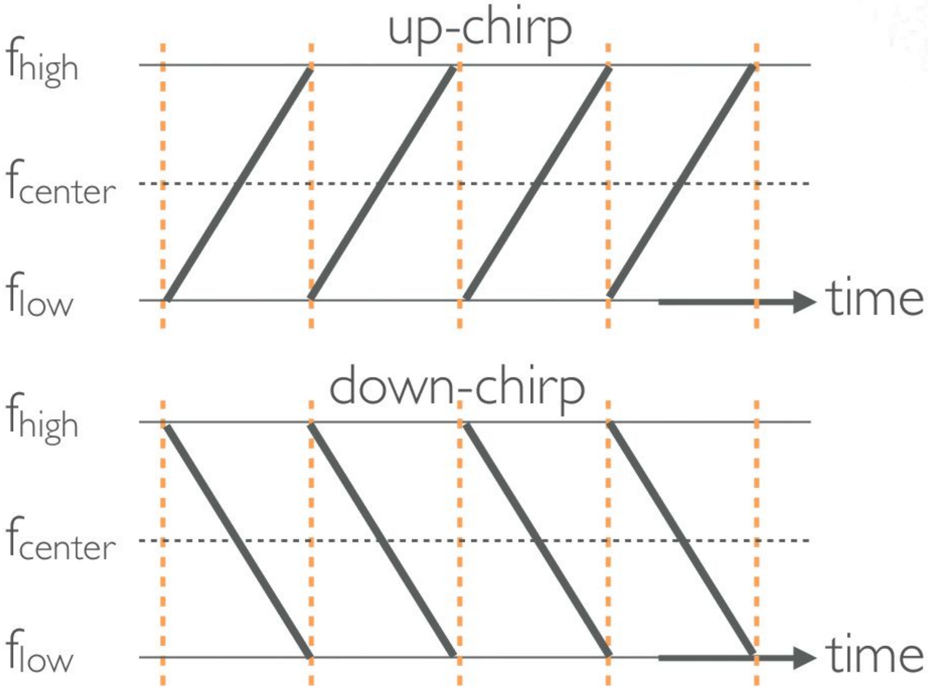
- Example 1:
  - ETSI duty cycle of 1% and ToA of 0.05 s
  - $T_{interval}$= ToA/DutyCycle - ToA = 0.05/0.01 - 0.05 = 4.95 s

- Example 2:
  - The Things Network Fair Policy: 30 s per day
  - Duty Cycle = 30/8400 = 0.00034722
  - $T_{interval}$ = ToA/DutyCycle - ToA = 0.05/0.00034722 - 0.05 = 143.95 s = 2m 23.95 s

Chirp Spread Spectrum (CSS)

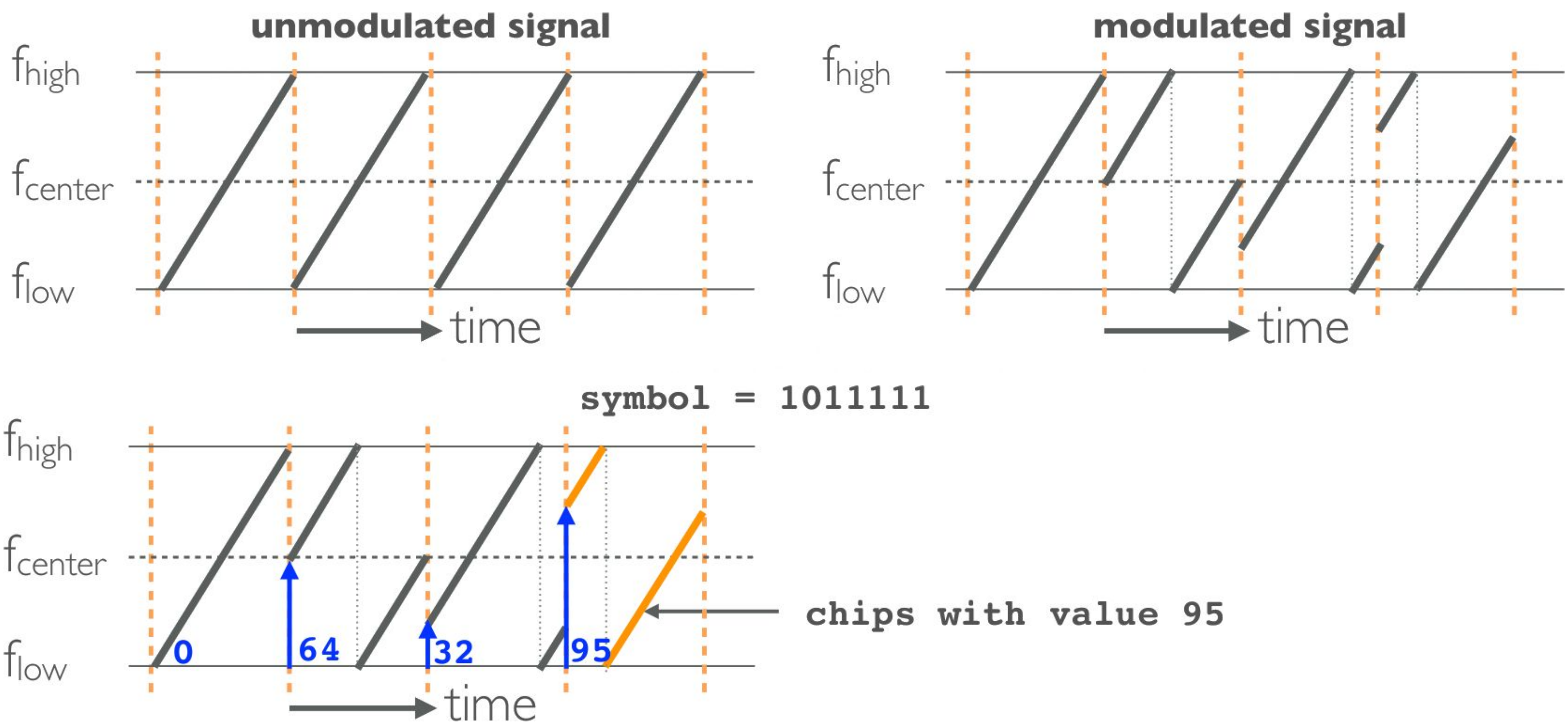
- Modulation Technique in which the bits are represented by signals that increase or decrease linearly their frequency with time





Chirp Spread Spectrum (CSS)

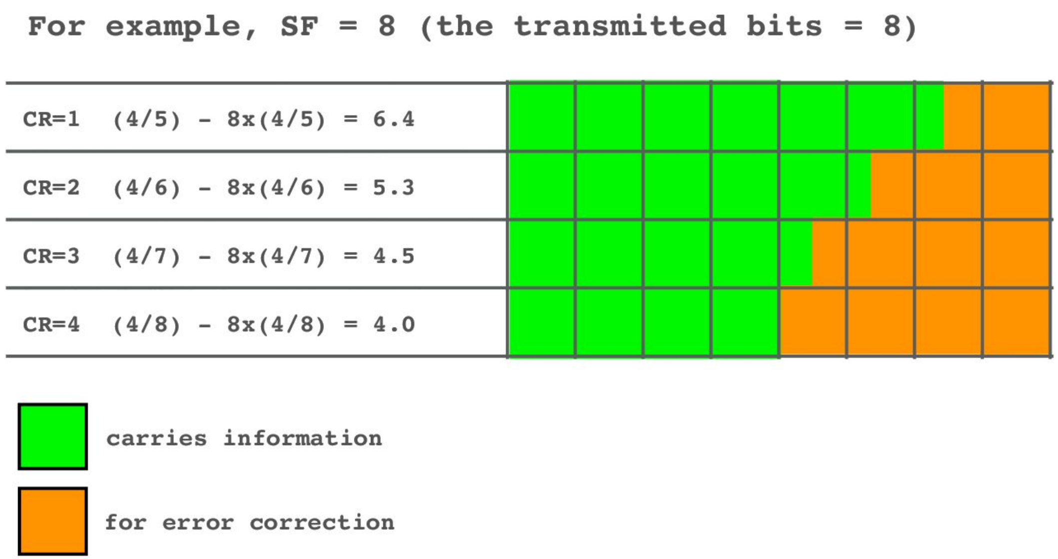
- The **chirps** are divided into 2^{SF} **chips** (SF - Spreading Factor)
- Changing the starting point we obtain 2^{SF} different symbols
  - Thus each symbol encodes SF bits
  - To send data only up-chirps are used



Coding Rate

- Coding Rate (CR): rate of bits that carry data
  - The rest are redundant bits, for error detection and correction
- LoRa allows the following CR: 4/5, 4/6, 4/7 y 4/8
  - Alternative notation: *CR* 1, 2, 3 or 4, for real CR of 4 / (4 + *CR*).

Coding Rate (CR)	CR = 4 / (4 + *CR*)
1	4/5
2	4/6
3	4/7
4	4/8

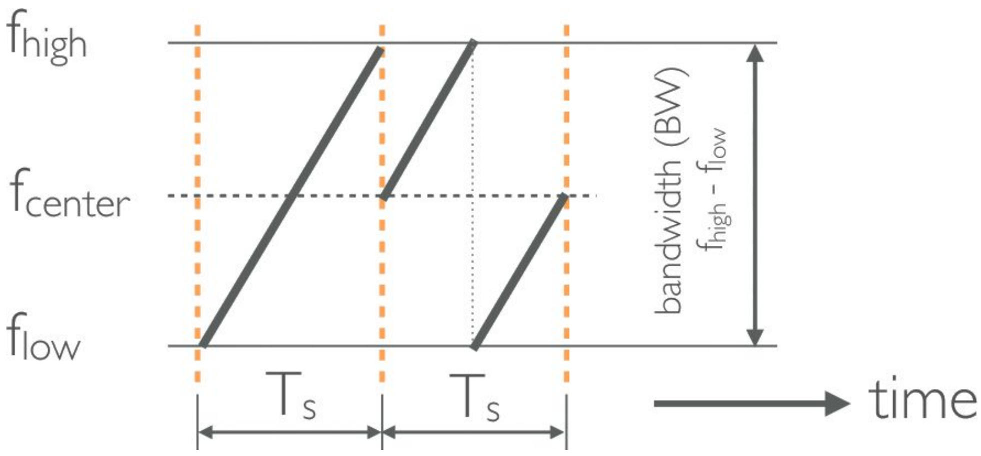


Data Rate

- Each symbol has 2^{SF} chips
- Chip Rate (R_C) is fixed to the BW (LoRa specification)
  - If channel BW = 125 kHz -> R_C = 125000 chips/s
- The chip duration is: $T_C = 1/BW$
- The speed in bauds (symbols/s) is: $R_S = R_C/2^{SF} = BW/2^{SF}$
  - The duration of a symbol is: $T_S = 2^{SF}/BW$
- The data rate or Bit Rate (R_b) is:

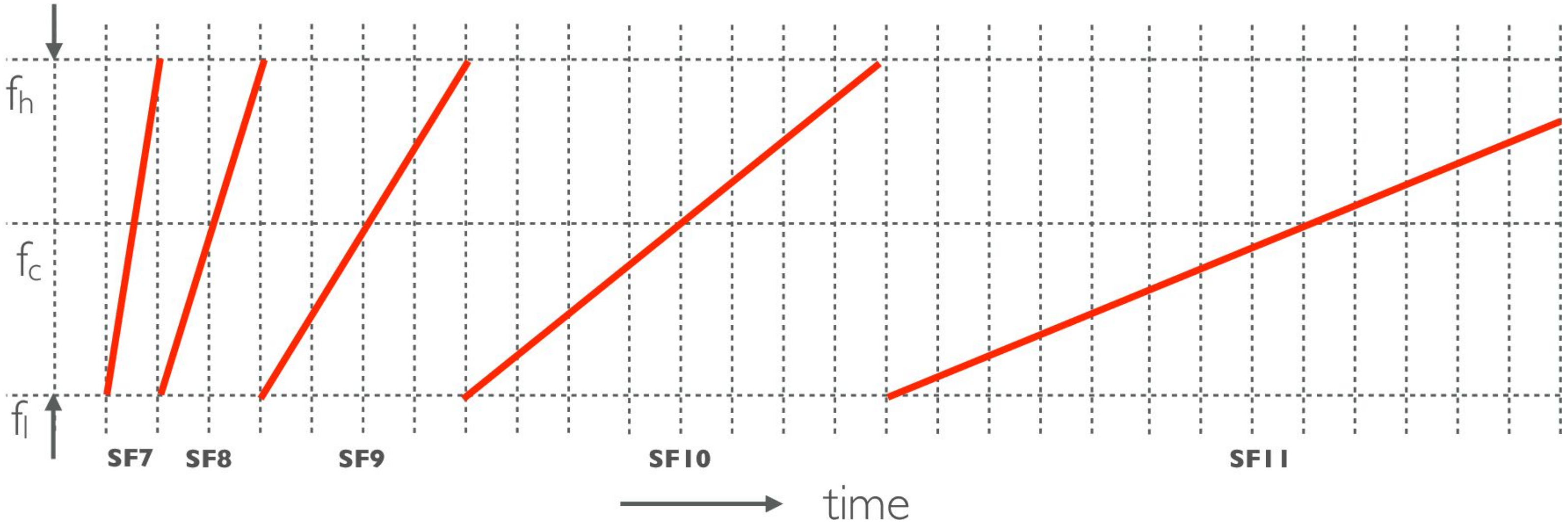
$$R_b = SF \cdot 4/(4 + CR) \cdot R_S = SF \cdot BW/2^{SF} \cdot 4/(4 + CR)$$

CR: 1-4, SF: 7-12, BW in Hz, R_b in bps



Data Rate and Symbol duration

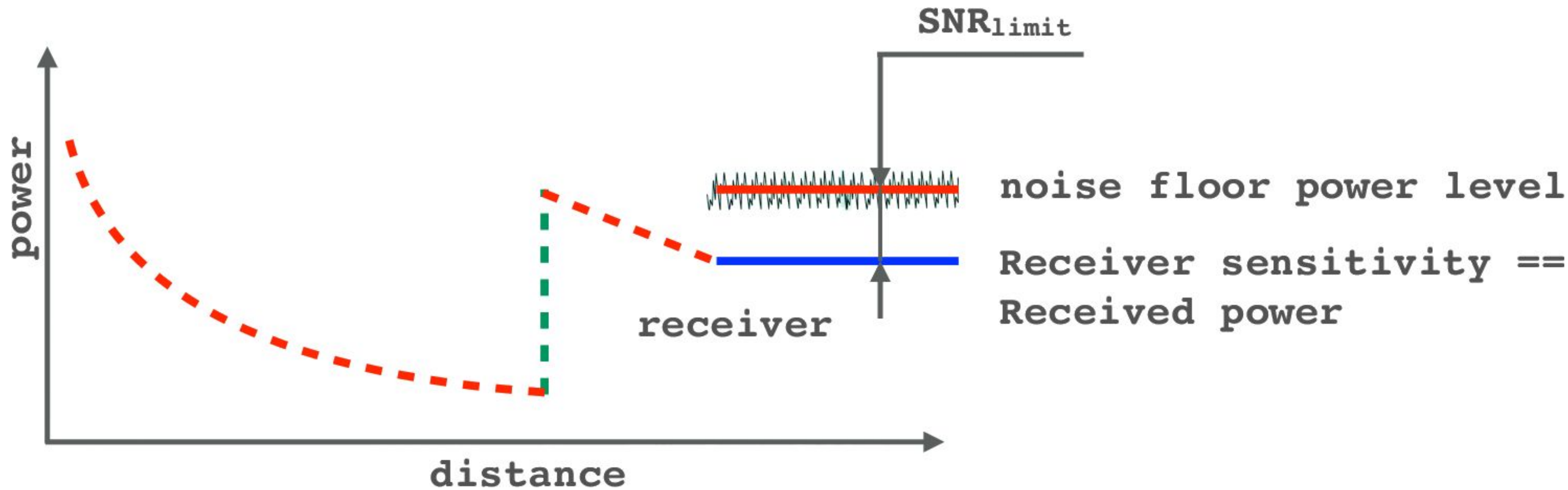
- With CR = 4/5
- If the BW increases, R_b increases and T_S decreases:
  - BW = 125 kHz, Rb = 7 x (125000 / 2^7) x 4/5 = 5.5 kbits/s, T_S = 1.024 ms
  - BW = 250 kHz, Rb = 7 x (250000 / 2^7) x 4/5 = 10.9 kbits/s, T_S = 512 μs
  - BW = 500 kHz, Rb = 7 x (500000 / 2^7) x 4/5 = 21.9 kbits/s, T_S = 256 μs
- If the SF increases, R_b decreases and T_S increases:
  - SF = 7, Rb = 7 x (125000/2^7) x 4/5 = 5.5 kbits/s, T_S = 1.024 ms
  - SF = 8, Rb = 8 x (125000/2^8) x 4/5 = 3.13 kbits/s, T_S = 2.048 ms
  - SF = 9, Rb = 9 x (125000/2^9) x 4/5 = 1.76 kbits/s, T_S = 4.096 ms



SF and SNR_{limit}

- SNR_{limit} is the lowest SNR for which the receiver can demodulate the signal
  - Depends on the SF
  - Increasing the SF in 1 reduces the SNR_{limit} in -2.5dB

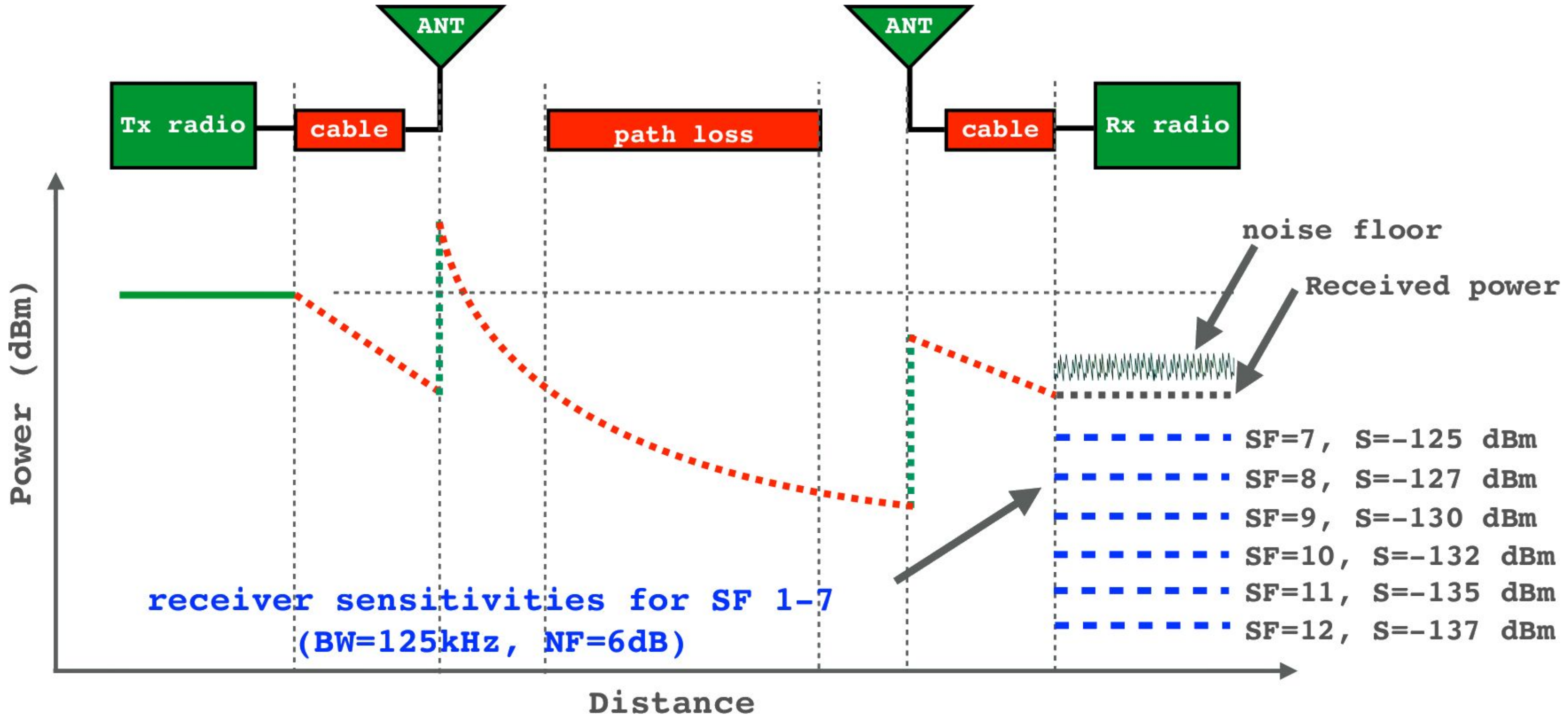
Spreading Factor	chips/symbol	SNR limit (dB) [2]
7	128	-7.5
8	256	-10
9	512	-12.5
10	1024	-15
11	2048	-17.5
12	4096	-20



Receiver Sensitivity

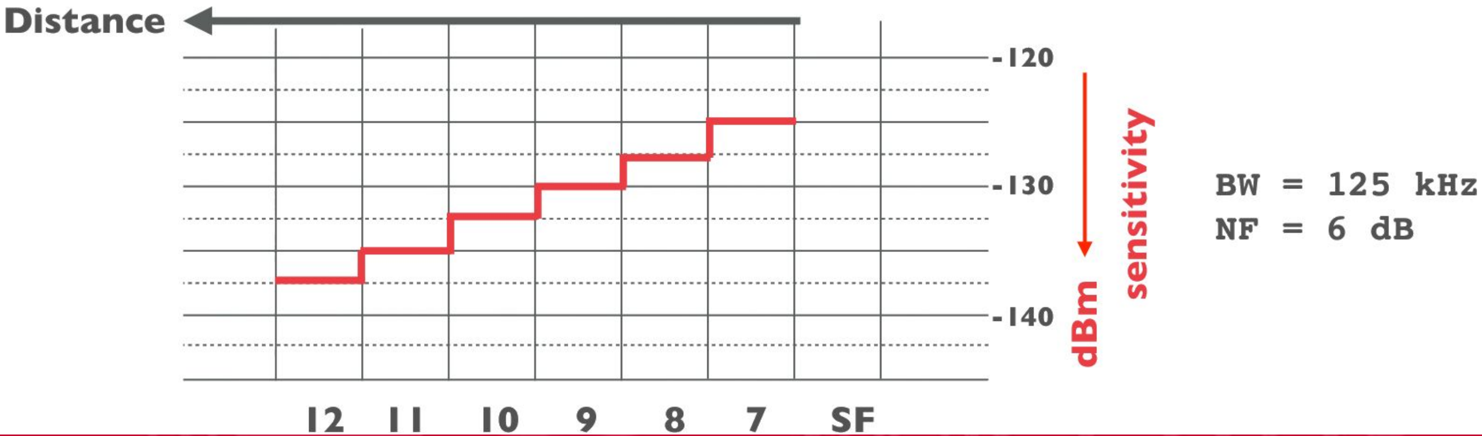
$$S = -174 + 10\cdot\log_{10}(BW) + NF + SNR_{limit}$$

- S: receiver sensitivity in dBm
- BW: bandwidth in Hz
- NF: noise factor, fixed for a give receiver
  - E.g.: SX1272 and SX1276 have a NF of 6dB
- SNR_{limit}: lowest SNR acceptable in dB



SF impact

- If we increase the SF in 1:
  - The symbol duration (T_S) is duplicated, R_b divided by two aprox.
  - The ToA and the achievable distance increase
  - E.g.: ToA for a payload of 10B, with BW of 125kHz
    - SF7 => ToA = 41ms
    - SF12 => ToA = 991ms
    - ToA online calculator: https://www.loratools.nl/#/airtime
- The greater the distance the more sensibility required, the larger SF required => lower Rb
  - The LoRa devices use a large SF for weak signals (far away or many obstacles) or in the presence of high noise power

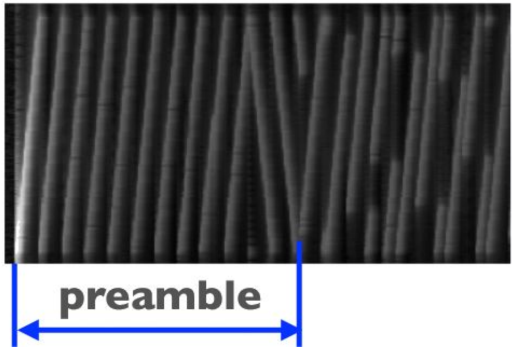


LoRa packets

- The LoRa packets are composed of 4 elements:
  - Preamble: used to train and synchronize the receiver
  - Header (optional): contains the payload length, the coding rate used for the payload and a flag for CRC present
    - In implicit mode the length of the package, the CR and the CRC flag are preconfigured and are not sent in the header
  - Payload: coded with the CR indicated in the header
  - 16 bits CRC (optional)

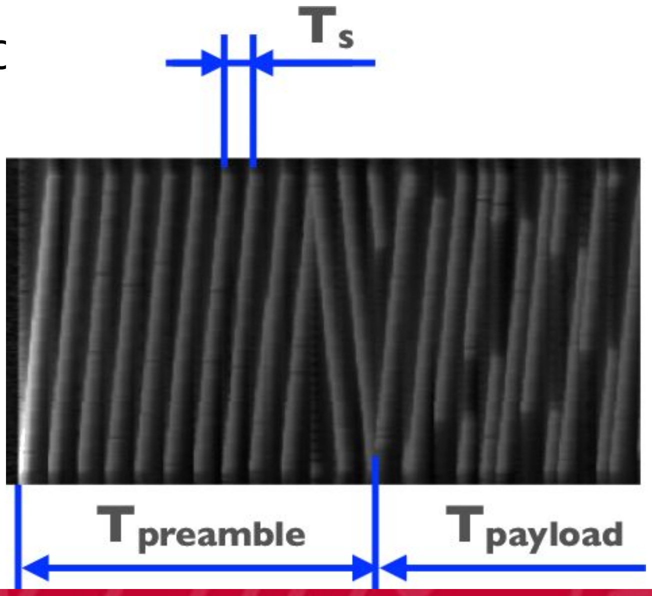
Explicit header mode

Implicit header mode

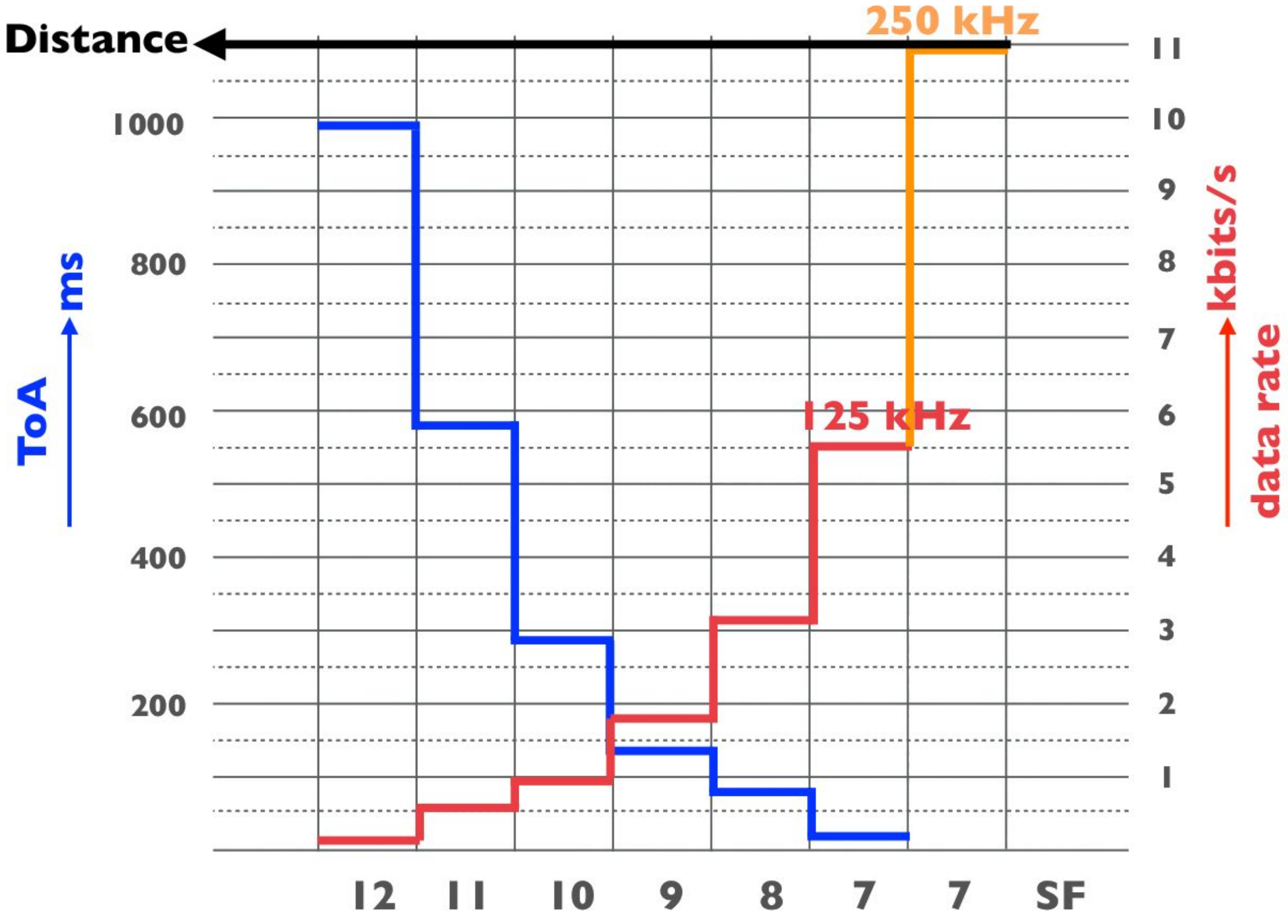


Time on Air (ToA)

- The ToA or frame duration is computed as
  - $ToA = T_{packet} = T_{preamble} + T_{payload}$
  - $T_{preamble} = T_S(n_{preamble} + 4.25)$
    - $n_{preamble}$: number of additional symbols in the preamble
    - for EU868 $n_{preamble}$ is 8, the preamble has a total of 12.25 symbols
  - $T_{payload} = T_s(8+max(ceil((8PL- 4SF+28+16CRC-20H)/4(SF-2DE))(CR+4),0))$
    - T_S: Symbol duration in seconds
    - PL: number of payload bytes
    - SF: Spreading Factor
    - CRC: 1 with CRC, 0 without. For LoRaWAN CRC
    - H: 1 implicit format, 0 explicit format
    - DE: 1 Low Data Rate Optimize enabled
      - Mandatory if ToA > 16 ms
      - Enabled with BW 125 kHz and SF >= 11
    - CR: coding rate 1-4
- ToA online calculator:
  - https://www.loratools.nl/#/airtime



ToA, Bit Rate & Distance



BW = 125 kHz
CR = 1
Payload = 10 bytes

ToA data see Tutorial 17

Data rate data see Tutorial 15, slide 7

Large ToA:

- longer distance and higher power consumption
- lower bit rate

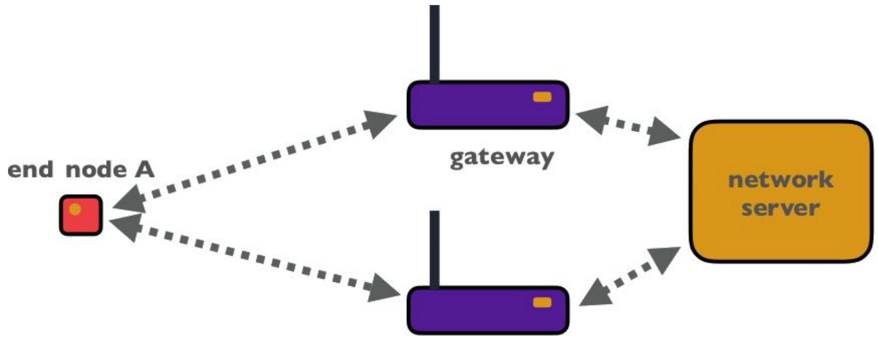
Distance and Duty Cycle

- The Things Network, 30 s for uplink per day and node
  - DutyCycle = 30/86400 = 0.00034722
  - Distance to the gateway 5 km
    - SF = 12
    - BW = 125 kHz
    - CR = 4/5
  - Payload of 13 bytes: “Hello, world!”
  - ToA (https://www.loratools.nl/#/airtime) 1155.07 ms
  - $T_{interval}$ = ToA/DuctyCycle - ToA = 1.15507/0.00034722 - 1.15507 = 3325.47 s = 55:25 (mm:ss)

Adaptive Data Rate

Adaptive Data Rate (ADR):

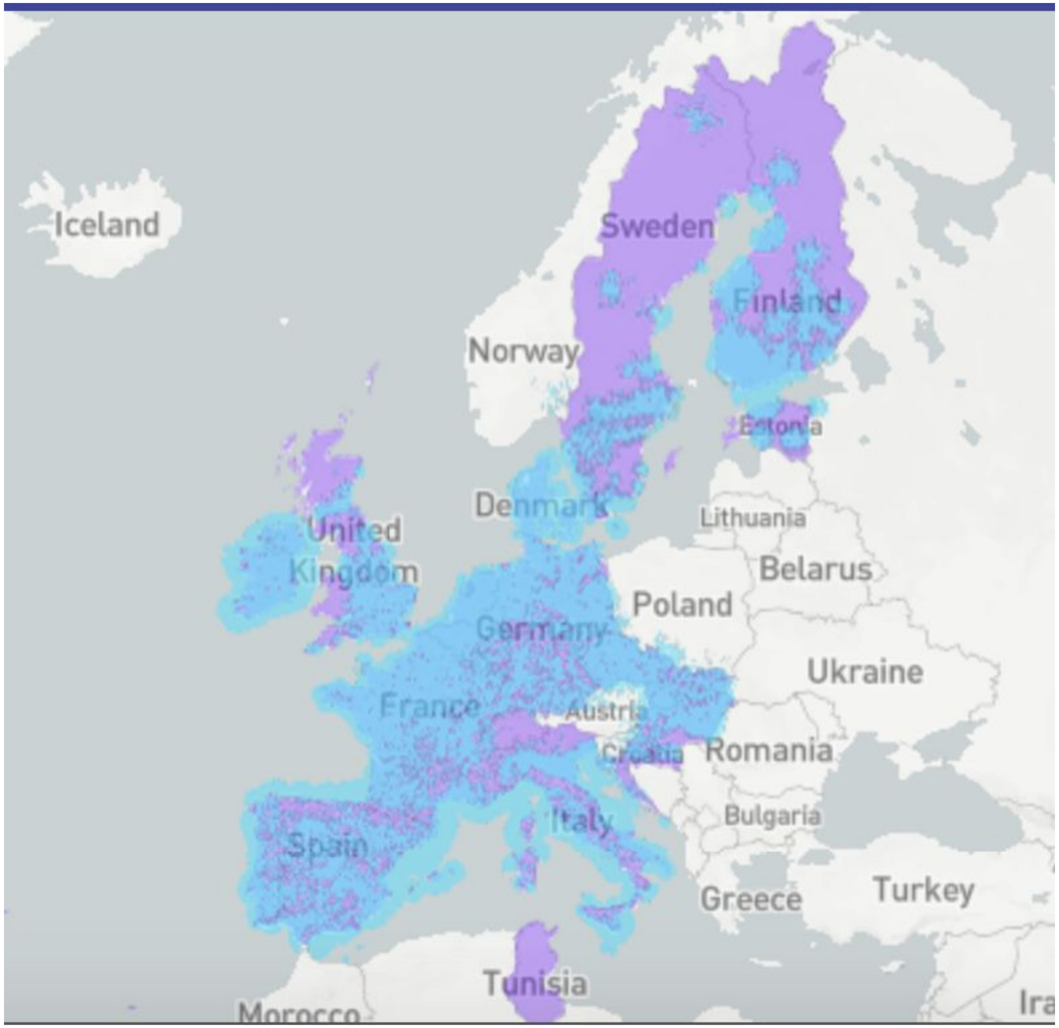
- Control scheme defined by LoRaWAN to adapt the uplink transmission parameters of the nodes:
  - Spreading Factor (SF)
  - Bandwidth (BW)
  - Transmission Power (P_{Tx})
- Requested by activating the ADR flag in the uplink packets
  - Convenient with static nodes (at least temporarily)
  - The server determines the most convenient parameters from the last 20 packets transmitted uplink by the node



20 most recent uplink transmissions data from end node A
#01: data rate = SF12BW125, SNR=5
#02: data rate = SF12BW125, SNR=1
#03: data rate = SF12BW125, SNR=5
:
#20: data rate = SF12BW125, SNR=1

SigFox

- Proprietary technology
  - Few open details
- Uses ultra-narrowband
- ISM band
  - 868.180 MHz-868.220 MHz with 400 subbands of 100Hz in EU
- Operator based model
  - Sigfox network deployed by sigfox
  - You pay for subscription and/or bytes transmitted



Sigfox Characteristics

- Cloud-based: all the data received by the sigfox gateways are sent to the sigfox servers
  - They offer web services to connect these data with other clients
- Range of 20-50km in rural areas, 3-10 km in urban areas
- Max. Payload of 12 bytes (uplink) (+14 overhead), and 8 bytes for downlink
- Max. packets per day depends on the subscription
  - 140 for the Platinum subscription
  - 1-2 for the basic subscription
- Power consumption is similar to LoRa
  - In LoRa it really depends on the distance to the Gateway, not so in Sigfox

SigFox vs LoRa (data from SigFox)

	sigfox	LoRa
Coverage (BS Sensitivity)	-142 dBm	-120 to -138 dBm
Capacity (Report/BS/Day)	Very high	Low
Resilience to Interferences	Very good	Poor
BoM Modem	Current Price: $2	Estimated $5
Power Consumption	Low	Medium
Security	AES128	AES128
Downlink	Device triggered	Device triggered
Data Rate	100 bps in EMEA 600 bps in Americas, APAC	300bps to 11 Kbps
Message size	12 bytes	Up to 50 bytes
Daily Traffic per device	1.6 Kbyte	Up to 10 Kbytes

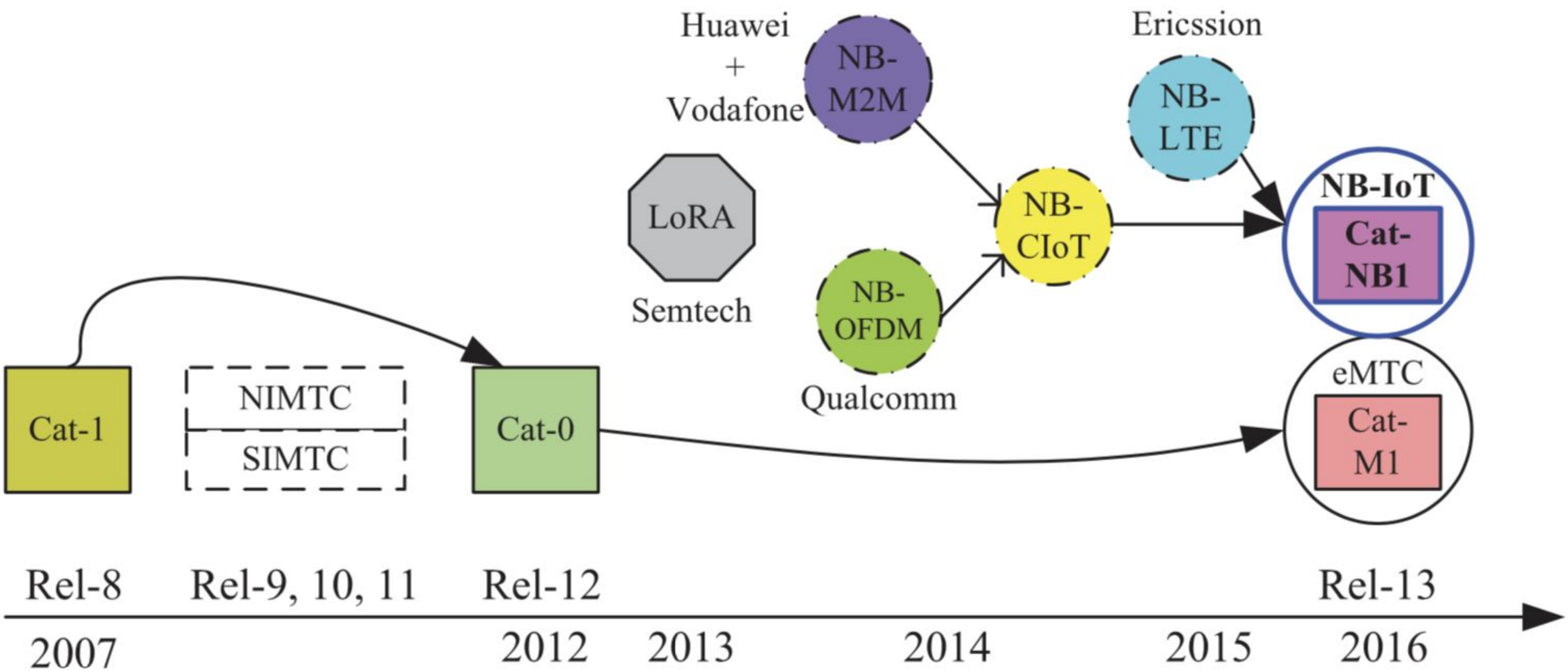
SigFox vs LoRa (data from SigFox)

	sigfox	LoRa
Key Attributes	- Very low Cost - Global Network - Low Power & predictability power consumption - Anti-jamming - Out of the box connectivity - Service Level Agreement	- Low cost - Larger payload - High data rate in short range - Possibility to purchase own Base station
Example of applications	**Nationwide network types** **Agriculture** **Water / gas meters** **Supply chain & logistics**	**Private network types** **Smart city** **Smart Building** **Utilities**

3GPP standards

- The *3rd Generation Partnership Project* is the group of associations for standards in telecommunications
- They were formed to create the 3G standard and the evolution of GSM
- They have designed and maintained
  - GSM 2G and 2.5G (GPRS and EDGE)
  - UMTS, 3G standard and HSPA
  - LTE and 4G standards
  - Future generations (5G)
- They publish periodic *releases*
  - When LoRa was born, Huawei and Vodafone pressed the 3GPP to develop a NarrowBand standard for IoT
  - In their Releases 13 (Q1 2016) and 14 (Q2 2017) they included specifications for IoT

3GPP standarization process



Xu, J., Yao, J., Wang, L., Ming, Z., Wu, K., & Chen, L. (2017). Narrowband Internet of Things: Evolutions, Technologies and Open Issues. *IEEE Internet of Things Journal*

NB-IoT

	Cat-1	Cat-0	Cat-M1 (eMTC)	Cat-NB1 (NB-IoT)
Deployment	In-band LTE	In-band LTE	In-band LTE	Guard-band/ In-band LTE Stand-alone
Downlink	OFDMA [15 kHz]	OFDMA [15 kHz]	OFDMA [15 kHz]	OFDMA [15 kHz]
Uplink	SC-FDMA [15 kHz]	SC-FDMA [15 kHz]	SC-FDMA [15 kHz]	SC-FDMA [3.75/15 kHz]
Peak Rate	DL:10 Mbps UL:5 Mbps	DL:1Mbps UL:1Mbps	DL: 1 Mbps UL: 1 Mbps	DL: 20 kbps UL: 250 kbps
Bandwidth	20 MHz	20 MHz	1.4 MHz	200 kHz
Duplex	Full-Duplex	Half-Duplex	Half-Duplex	Half-Duplex
Trans. Power	23 dBm	23 dBm	23 or 20 dBm	23 dBm
Power Saving Tech.	PSM, eDRX	PSM, eDRX	PSM, eDRX	PSM, eDRX

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Business model

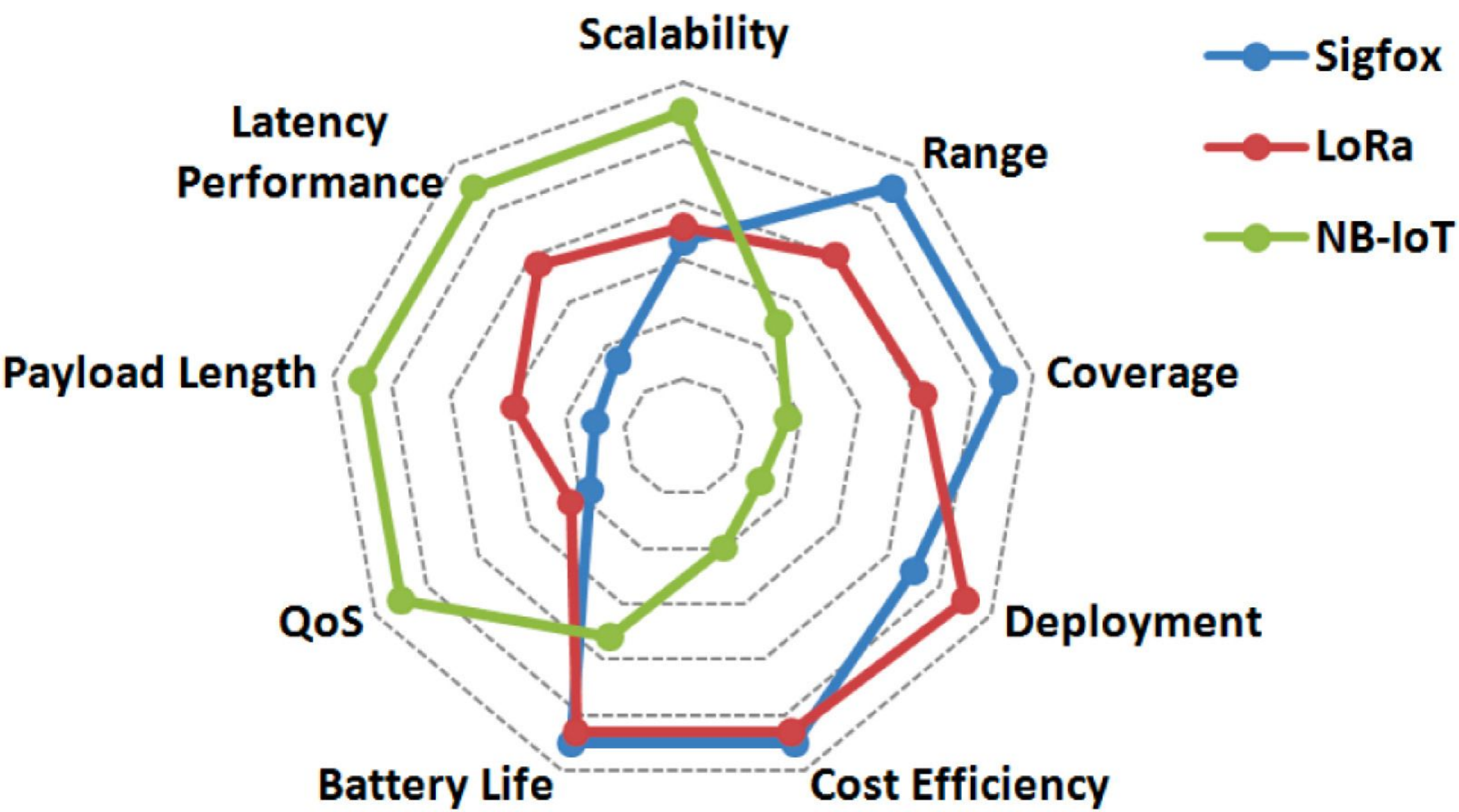
- Similar to Sigfox: operator based
  - Nodes require a SIM card
  - Subscription, monthly payment
- The big telecoms rule the network using their LTE infrastructures
  - In the case of eMTC (Cat-M1) no adaptation required
    - USA has already some deployments
  - In the case of NB-IoT, some adaptation required
- Vodafone has some coverage in spain
  - Cities with more than 25.000 inhabitants

UNIVERSIDAD COMPLUTENSE MADRID

NB-IoT vs SigFox vs LoRa

	Sigfox	LoRa	NB-IoT
Coverage	160dB	157dB	164dB
Technology	Proprietary	Proprietary	Open LTE
Spectrum	Unlicensed	Unlicensed	Licensed (LTE/any)
Duty Cycle restrictions	Yes	Yes	No
Output power restrictions	Yes (14dBm = 25mW)	Yes (14dBm = 25mW)	No (23dBm = 200mW)
Downlink data rate	0.1kbps	0.3 – 50kbps	0.5 – 200kbps
Uplink data rate	0.1kbps	0.3 – 50kbps	0.3 – 180kbps
Battery life (200b/day)	10+ years	10+ years	15+ years
Module cost	<$10 (2016)	<$10 (2016)	$7 (2017) to <$2 (2020)
Security	Low	Low	Very high

LPWA comparatives



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