CZECH TECHNICAL UNIVERSITY IN PRAGUE
FACULTY OF ELECTRICAL ENGINEERING
DEPARTMENT OF TELECOMMUNICATION ENGINEERING

B(E)2M32BTS - Wireless Technologies

LPWAN protocols for IoT

Long-range communication for IoT

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Outline

Overview of protocols for Internet of Things (**IoT**)

- Overview and applications, trends

LoRa (Long Range) protocol

- Overview
- Architecture and device connection
- Communication
- Data rates
- Device types

Overview of IoT protocols

Protocols designed to **specific needs** of **IoT devices**

- **Low cost and complexity**
  - Many (dozens per household) simple devices
- **Low bit-rates**
  - From bps to hundreds of kbps (few Mbps?)
- **Delay tolerant**
  - Not continuous transmission, occasional transmission
- **Low energy consumption**
  - Often powered from batteries → long battery life-time (years)

Classification of protocols

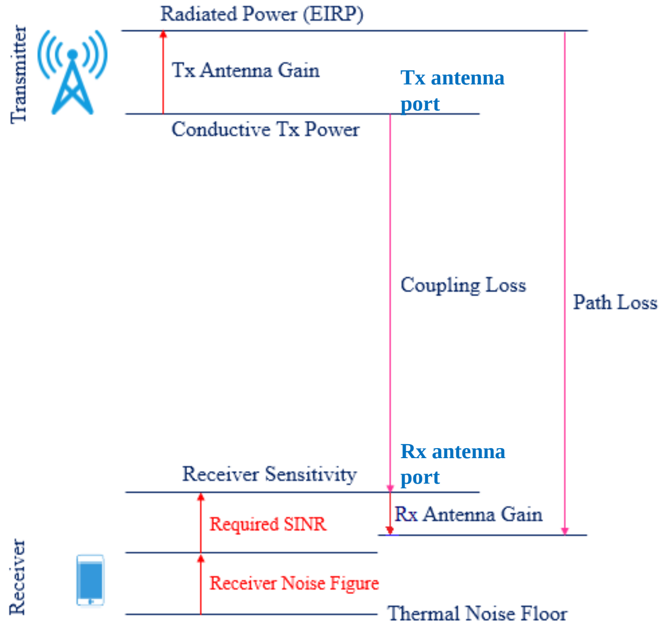
- **Short-range**
  - Coverage radius ~ in (few, dozens, hundreds) meters
  - Technologies and protocols: Bluetooth, 6LoWPAN, ZigBee,…
- **Long-range**
  - Coverage radius ~ in (few to dozen) kilometers
  - **Wide area networks** & **low power** consumption→ **Low-Power Wide Area Networks (LPWAN)**
  - Technologies and protocols: Cellular IoT, LoRa, SigFox, Weightless,…

Communication range

Communication range defined by **Maximum Coupling Loss** (MCL)

Maximum **Coupling Loss**

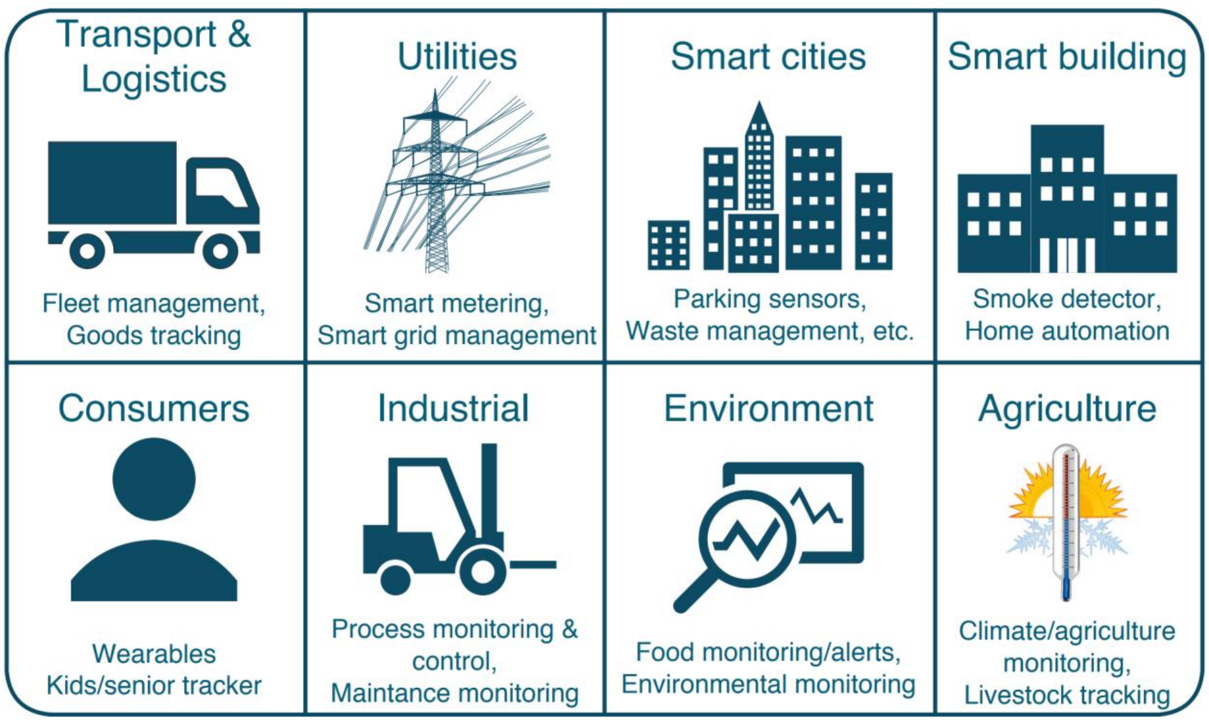
- Maximum loss in conducted power level that system can tolerate and still operate
- **Coupling Loss**
  - Difference between **conducted power levels** measured **at transmitting and receiving antenna ports**
  - Defined by a minimum acceptable received power level
  - **Antenna ports/connectors** = reference points for MCL → antennas gains not considered



Applications and use-cases for LPWAN

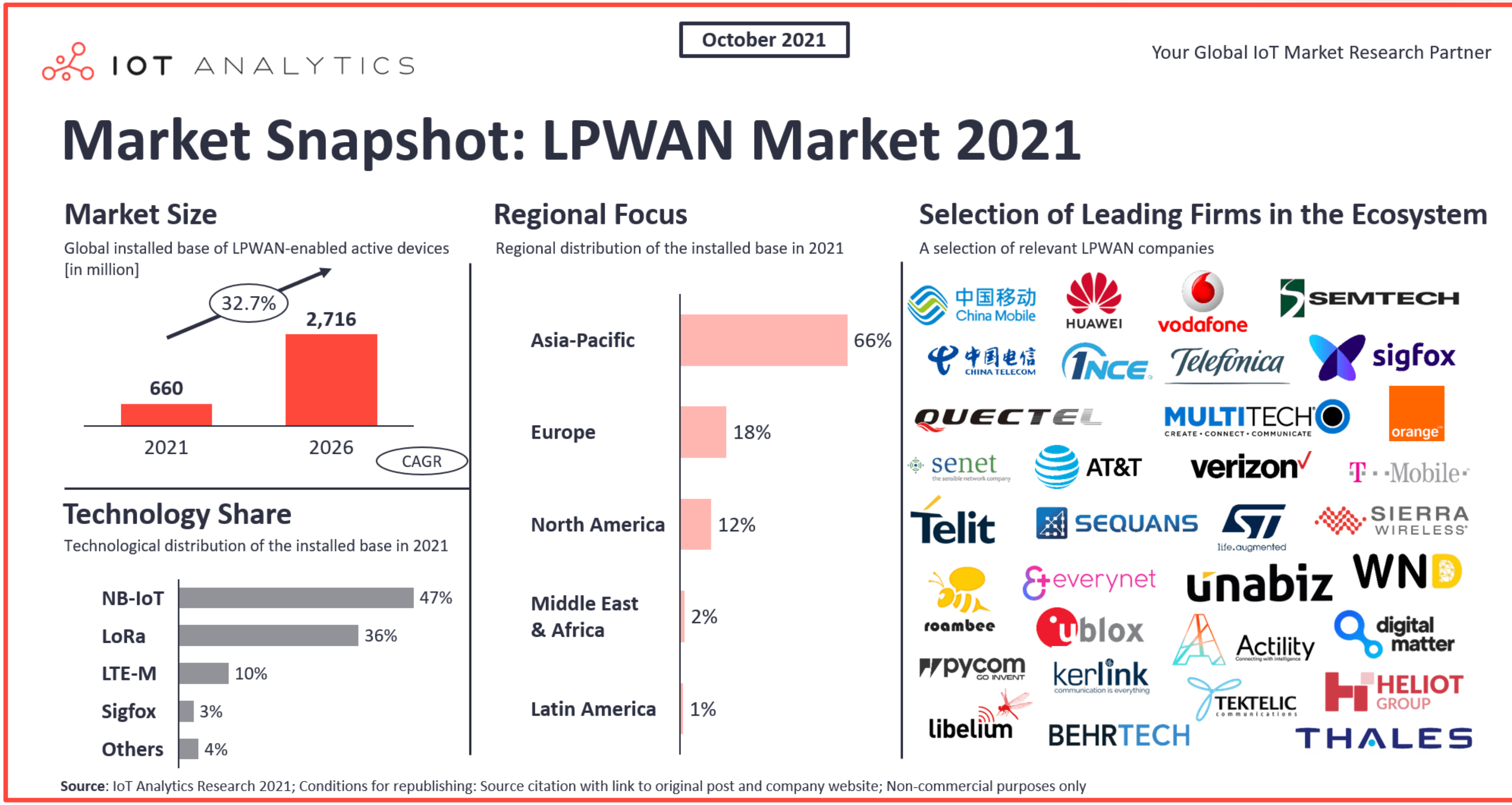
Cheap devices, **rare low bit-rate** communication, **long** battery **life-time**

- **Long operation** on single battery charge
- Often for devices with limited mobility that **lack power source** for recharging
  - Mobile devices still possible (Cellular IoT – next lecture)



A.-A. A. Boulogeorgos, et al, "Low Power Wide Area Networks (LPWANs) for Internet of Things (IoT) Applications: Research Challenges and Future, Trends," https://arxiv.org/pdf/1611.07449.pdf, November 2016.

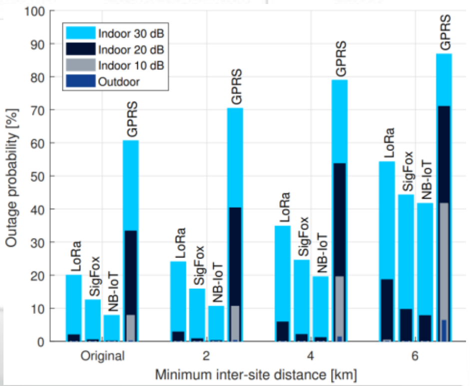
Technologies and market



Long-Range technologies: Overview

Celluar IoT (next lecture)

	Sigfox	LoRa	EC-GSM	Cat-1	Cat-0	eMTC	NB-IoT
Standardization	Private	Open	3GPP	3GPP	3GPP	3GPP	3GPP
Spectrum	Unlicensed	Unlicensed	Licensed	Licensed	Licensed	Licensed	Licensed
Channel BW	100Hz	7.8~500kHz	200kHz	1.4~20MHz	1.4~20MHz	1.4MHz	180KHz
System BW	100KHz	125kHz	1.4MHz	1.4~20MHz	1.4~20MHz	1.4MHz	180KHz
Peak Data Rate	UL:100bps DL:600bps	up to 21.9 kbps	DL: 74kbps UL:74kbps	DL:10Mbps UL:5Mbps	DL:2Mbps UL:1Mbps	DL:800kbps UL:1Mbps	DL:234.7kbps UL:204.8kbps
Max. number of Message per day	140(Device) 50000(BTS)	unlimited	unlimited	unlimited	unlimited	unlimited	unlimited
Device Peak Tx Power	14dBm	16 dBm	33dBm	23dBm	23dBm	23dBm	23dBm
MCL(Maximum Coupling Loss)	UL:156dB DL: 147dB	157/165 dB	164dB	144dB	144dB	156dB	164dB
Device Power Consumption	Low	Low-Medium	Low	Medium	Medium	Low-Medium	Low



M. Debbah, “5G: a revolution or an evolution for IoT,” Huawei, Dec. 2016.
ABI research, LoRa Aliance, "LoRaWAN and NB-IoT: Competitors or complementary?," 2019.
M. Lauridsen et al, "Coverage comparison of GPRS, NB-IoT, LoRa, and SigFox in a 7800 km2 area," VTC- Spring 2017.

LoRa/LoRaWAN technology

History

- 2009 – development by Cycleo (start-up)
- 2012 – Cycleo acquired by Semtech Corporation
- **2015** – **First specification** released (v1.0)
  - 150+ public network operators worldwide in 2020
  - Release v1.0.4 in October 2020

LoRa Alliance

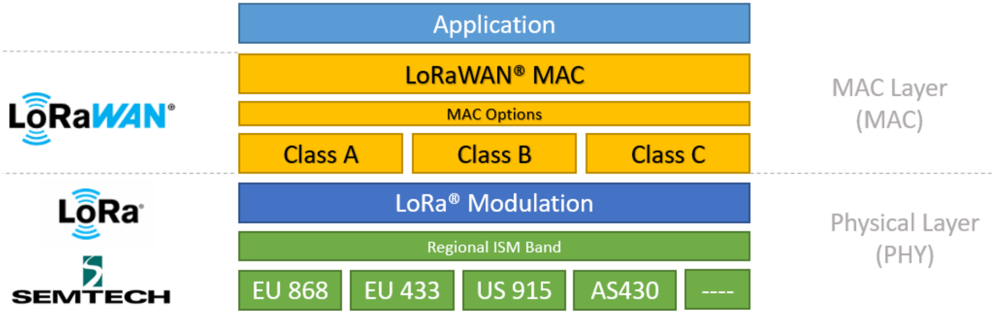
- Founded in 2015
- Develops and promote LoRaWAN® technology
- IBM, Cisco, HP, Foxconn, Semtech, Sagemcom, Schneider, Bosch,…

LoRa (<u>Lo</u>ng-<u>Ra</u>nge) radiofrequency modulation technology for LPWAN

- **Physical layer**

LoRaWAN protocol

- Medium Access Control (MAC) **layer**



LoRAWAN overview

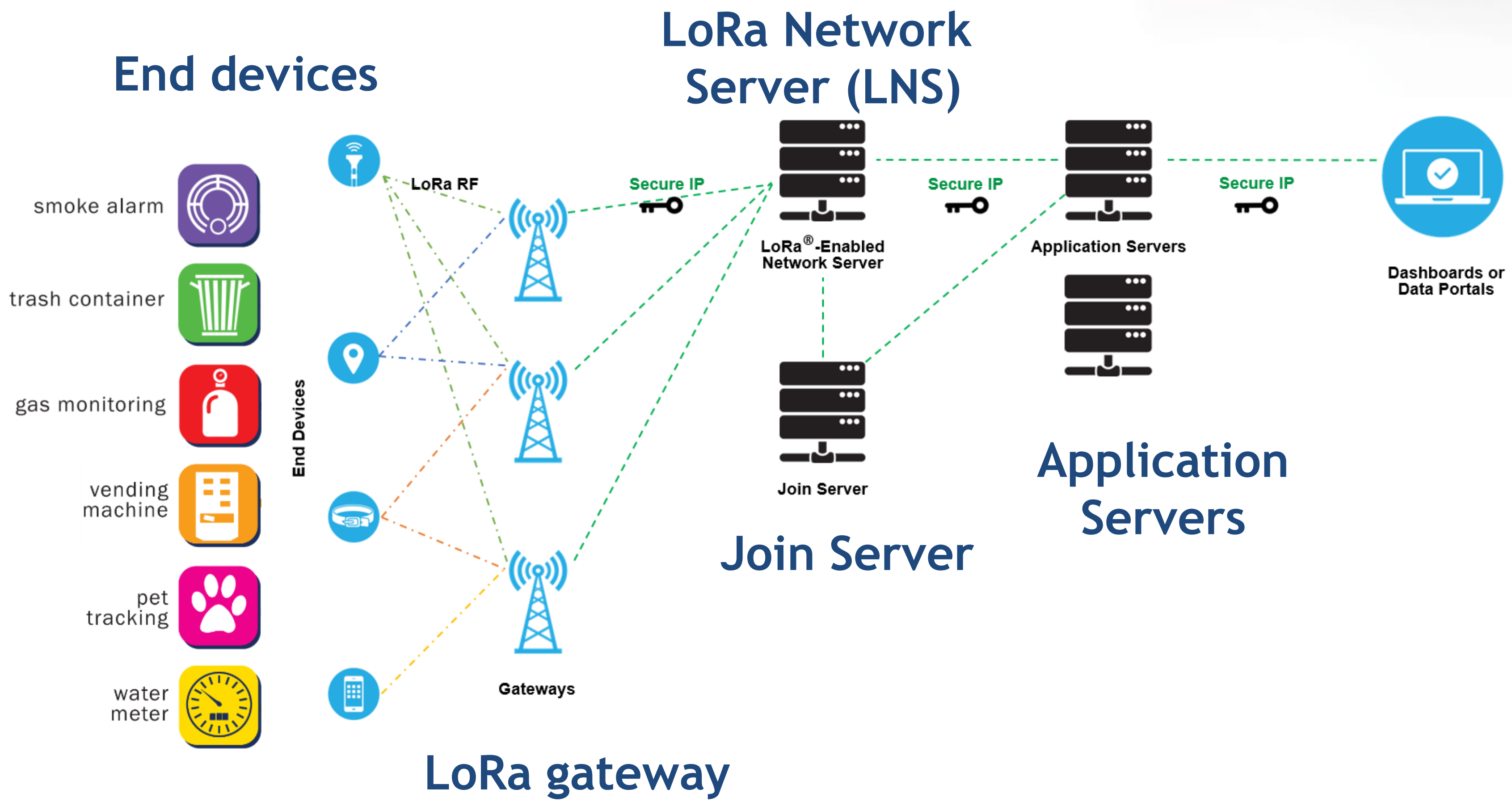
Objectives

- **~ years long operation** (consumption in micro/milliwatts)
- **Low device cost** (even gateways rather cheap)
- **Extended coverage** (157/165 dB max coupling loss)
- **Low bit rates**
  - ~hundreds of to several thousands bps (depends on physical layer, spreading factor and bandwidth)

Main features

- **Public and private networks**
- **Narrowband channels** (typically 125 kHz)
- **Chirp Spread Spectrum** (CSS)
  - Adaptive spreading factor → data rate vs coverage
- **Open** standard (except physical layer)

Network architecture



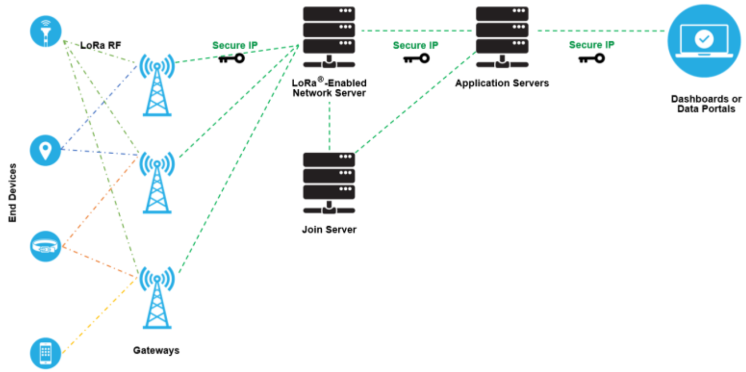
Network architecture

LoRaWAN gateway

- Receives messages from devices and forwards to LNS and vice versa
  - IP protocol (any technology, e.g., Wi-Fi, Ethernet, mobile networks,…)
- Operate at physical layer
  - Only message + metadata (received RSSI and an optional timestamp) forwarded

End devices

- **Sensor** or **actuator** wirelessly connected to LoRaWAN network
  - Connection only via LoRaWAN gateway
  - Autonomous
  - Typically battery-operated



https://lora-developers.semtech.com/documentation/tech-papers-and-guides/lora-and-lorawan/

LoRa Alliance, "LoRaWAN – What is it?"

Networks architecture

LoRa Network server (LNS)

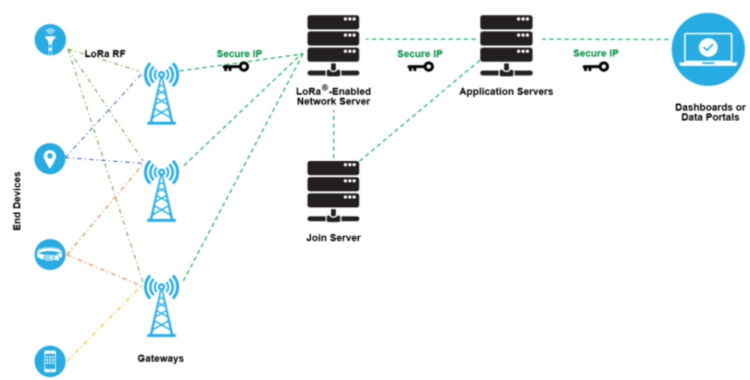
- Network management & control of network parameters
  - Ack of messages, frame counting, adapting data rate, handle MAC requests from devices
- Establishes secure 128-bit AES connections
- Ensures authenticity of End devices and integrity of message
  - Do not see or access application data

Application Servers

- Securely handling, managing and interpreting sensor application data
- Generate application-layer downlink payloads for devices

Join Server

- Manages activation of end devices
  - Adding devices to network – *Join procedure*
- Security handling
  - Contains/manages security-related information
    - Keys, service profiles of End devices,..
- Matches Application servers to end devices
  - via LNS

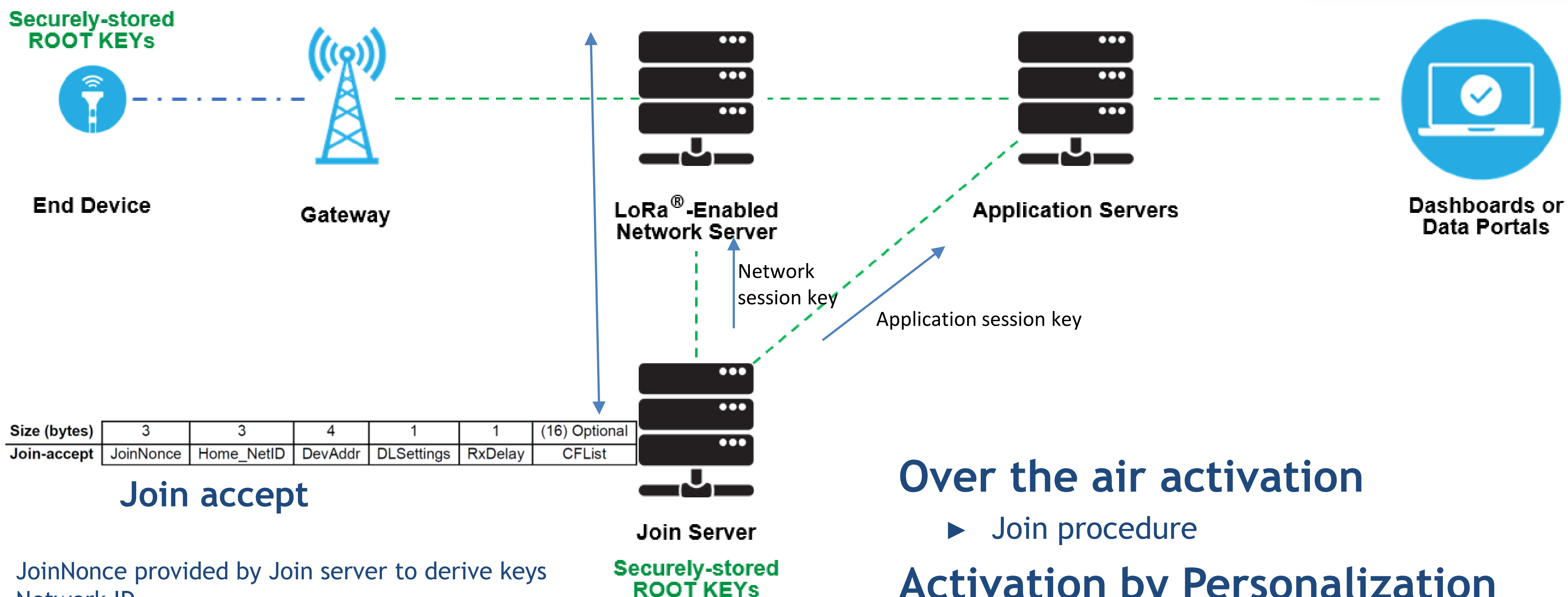


Join procedure

Join request

Size (bytes)	8	8	2
Join-request	JoinEUI	DevEUI	DevNonce

Join server ID (EUI64)
End device ID (EUI64)
DevNonce is Counter of requests (incremented with every new request)



Size (bytes)	3	3	4	1	1	(16) Optional
Join-accept	JoinNonce	Home_NetID	DevAddr	DLSettings	RxDelay	CFList

Join accept

JoinNonce provided by Join server to derive keys
Network ID
End device address (32-bits address in network)
Downlink configuration (offset between DL and UL rates, DL data rate)
Delay between transmission and reception
Channel frequency list (optional, region dependent)

Over the air activation

- Join procedure

Activation by Personalization

- End device directly coupled to specific Network
  - Device address and security keys stored in device → same keys all the time → **less secure**

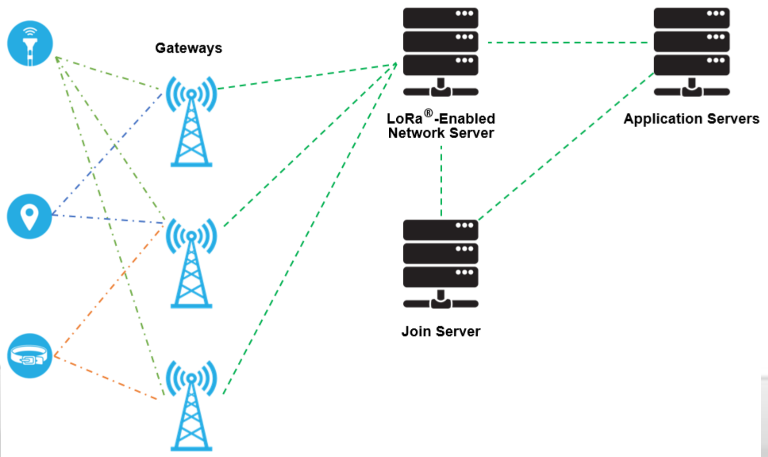
Message transmission

Uplink

- **Message broadcasted** to and received by **gateways** within reach
  - Reduces packet error rate and battery consumption and enables localization
- Gateway forwards message to LNS
- LNS performs **data de-duplication** and deletes all copies
  - Select **message** with **highest RSSI**
- LNS forwards message to targeted Application server

Downlink

- Application server sends message to LNS
- **LSN selects Gateway** that should send message to End device
  - **Gateway** selected by LNS based on **maximum RSSI** of **messages received in uplink**



Physical (PHY) layer overview

ISM bands

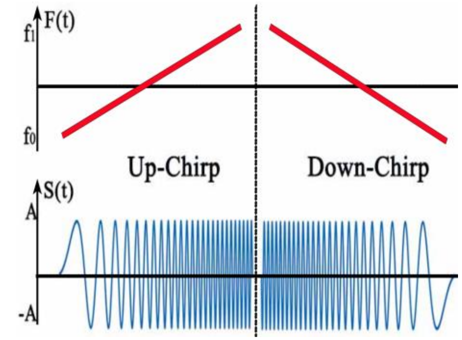
- EU: 433, **868** MHz, US: 902-928 MHz
- Unlincesed

Chanel Bandwidth of 125 kHz (250, 500,... kHz)

- Regional parameters at https://lora-alliance.org/resource_hub/rp2-1-0-3-lorawan-regional-parameters/
- EU: channels @ 868 MHz typically for 125 kHz bandwidth

Proprietary spread-spectrum modulation

- Based on **Chirp Spread Spectrum** (CSS)
  - Resilience to interference, multipath, (and doppler effect)
  - Low power
  - **Signal spread in frequency domain**
  - Orthogonal spreading factors
  - **Chirp** – sweep tone/signal
    - Frequency increases/decreases in time (up-chirp/down-chirp)



G. Huang,, et al, "COOK: Chirp-OOK Communication with Self-reliant Bitrate Adaptation in Backscatter Networks", https://arxiv.org/pdf/1911.11417.pdf, November 2019.

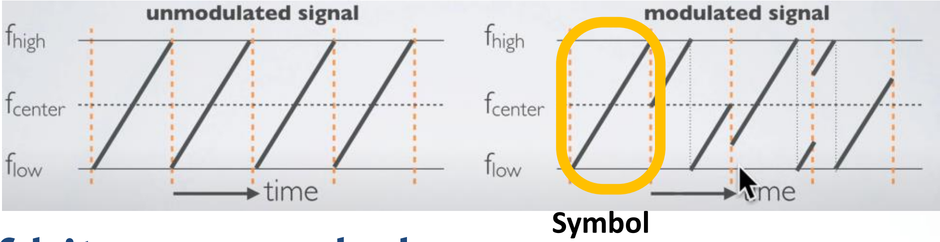
Frequency hopping (Uplink, different PHY – 3.9 kHz hopping channels, bandwidth of 137 kHz, very low bit rates of 162 – 325 bps)

- Robustness to interference

Spreading factor and Data rate

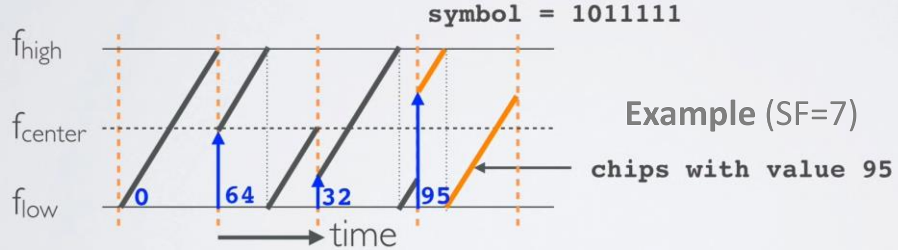
Modulation

- Data encoded via frequency changes at the beginning of symbol
  - Starting frequency of chirp
  - $\boldsymbol{Bandwidth = f_{high} - f_{low}}$



Spreading Factor (SF) = Number of bits per symbol

- 2^{SF} values (steps, chips) per symbol



Robert Lie,"LoRa/LoRaWAN tutorial 13: Symbol, Spreading Factor and Chip," https://www.youtube.com/watch?v=0FCrN-u-Vpw

Symbol duration: $T_s = \frac{2^{SF}}{BW}$

- SF increases → Symbol duration increases
- Bandwidth increases → Symbol duration decreases

Symbol rate: $R_s = \frac{1}{T_s} = \frac{BW}{2^{SF}}$

Data rate: $R_d = SF \times \frac{BW}{2^{SF}} \times CR$

- Number of bits/symbol *times* Symbol rate *times* code rate (CR)
  - Code rate 4/5, 4/6, 4/7, 4/8 (Code rate index 1, 2, 3, 4, resp)

Examples

BW=125 kHz, **SF=7**, CR=4/5 → $\boldsymbol{R_d}$ **= 5460 bps,** $\boldsymbol{T_s}$ **= 1.02 ms**

BW=125 kHz, **SF=12**, CR=4/5 → $\boldsymbol{R_d}$ **= 290 bps ,** $\boldsymbol{T_s}$ **= 33.77 ms**

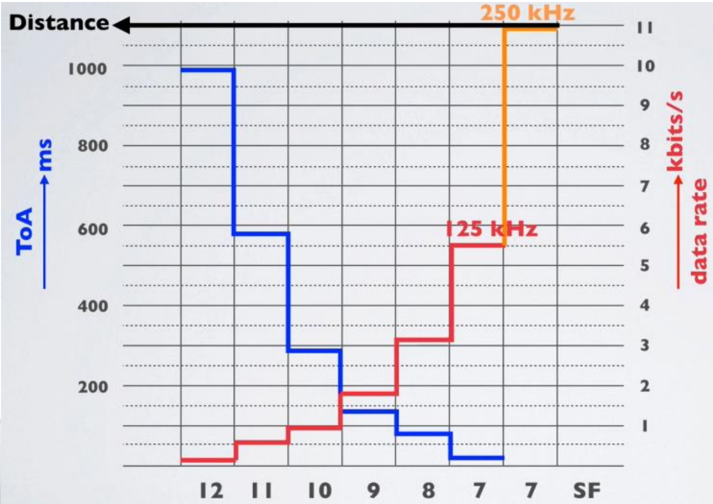
Impact of Spreading Factor

Spreading Factor	SNR limit (dB)
7	-7.5
8	-10
9	-12.5
10	-15
11	-17.5
12	-20

Increasing SF

- ▶ **Symbol duration increases**
  - ➢ Time on Air (ToA) increases (longer time of transmission) → increase energy consumption
    - ▪ **Symbol duration doubles** if **SF increased by 1**
    - ▪ [*loratools.nl/#/airtime*](loratools.nl/#/airtime)
- ▶ **Extending coverage**
  - ➢ End device **further** from Gateway → **Longer** transmission time
  - ➢ SNR required for decoding is lowered
    - ▪ -2.5 dB for SF increased by 1
- ▶ **Data rate is decreased**
  - ➢ **Bit rate** reduced by a **half if SF increased by 1**

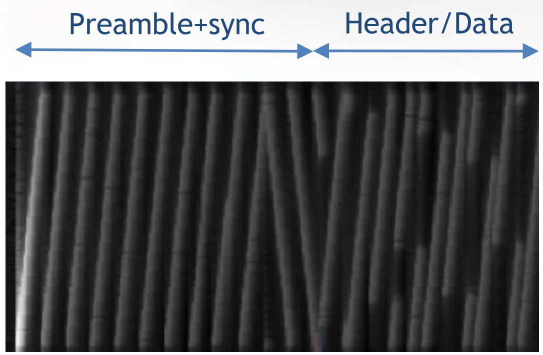
BW=125 kHz
CR=4/5
Payload 10 bytes



Packets

Explicit header mode

- **Preamble** + **Sync word** (EU: 8 + 4.25 symbols)
- Physical layer **Header** (PHDR) + **CRC** (PHDR_CRC)
  - Payload length in bytes
  - Forward error correction rate (CR)
  - Presence of CRC for payload
- Physical layer **Payload** (data + headers of upper layers)
- **Payload CRC** (optional)



Message starts with number of up-chirps followed by 2.25 down-chirps, then data/header

Implicit header mode

- **No header**
- Used for beacon transmission (Device B, see later)

Size	8 Symbols	4.25 Symbols	8 Symbols		*L* bytes (from PHDR)	2 Bytes
Packet Structure	Preamble	Synchronization Word	PHDR	PHDR_CRC	PHYPayload	CRC (uplink only)

1	7..*M*	4
MHDR	MACPayload	MIC

MIC… Message Integrity Check
MHDR… MAC (Medium Access Control layer) header

Adaptive data rate

Uplink transmission parameters control (**SF, bandwidth, Tx power**)

- Controlled by LNS
  - Only for not (or slow) moving nodes
- Controlled by End device
  - Mobile device

Default setting

- Tx power – **maximum allowed Tx power**
  - Regional limits, EU868 band: max 16 dBm, 2dBm step
- Data rate – **minimum allowed rate for device**
  - Device specific and regional limits, EU868 band: 250 bps (SF12, 125 kHz bandwidth)

Data rate adaptation

- Measured $\boldsymbol{SNR_{meas}}$ **above** $\boldsymbol{SNR_{limit}}$ (minimum SNR for demodulation) → LNS recommends to **reduce SF** and, if required, also **Tx power**
  - $margin = SNR_{meas} - SNR_{limit}$

Example

BW=125 kHz, **SF=12**, SNR_{meas}=7dB, $\boldsymbol{SNR_{limit}}$**=-20dB** → margin = 27 dB

Change of SF to **SF=7** → $\boldsymbol{SNR_{limit}}$**=-7.5dB** → **margin = 14.5 dB** → reduce Tx power

- Some margin (several dB) is usually kept to compensate changes in channel

Spreading Factor	SNR limit (dB)
7	-7.5
8	-10
9	-12.5
10	-15
11	-17.5
12	-20

Robert Lie,"LoRa/LoRaWAN tutorial 17: LoRa Packet Format, Time on Air and Adaptive Data Rate" https://www.youtube.com/watch?v=C_Rh5GSENA4

LoRaWAN Device classes

Classes define devices' communication and management

- Class can be switched

Class A – All end-device

- **Mandatory** for all devices all the time
- **Energy efficient** bi-directional communication
- Access to medium based on ALOHA
- **Device reachable only after transmission**

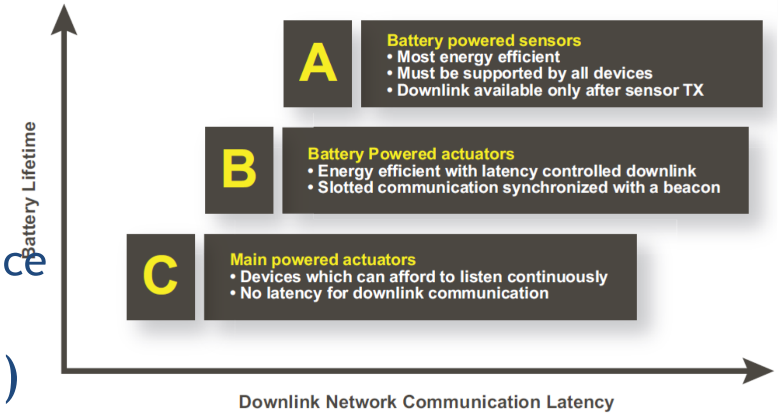
Class B – Beacon

- Optional
- **Periodic scheduled opportunity** to reach device
  - Scheduling based on beacons from gateways

Class C – Continuously listening (end-device)

- (Almost) **continuously reachable end device**
  - Not reachable during own transmission
- **High energy consumption** with respect to Classes A and B
- **Low latency**

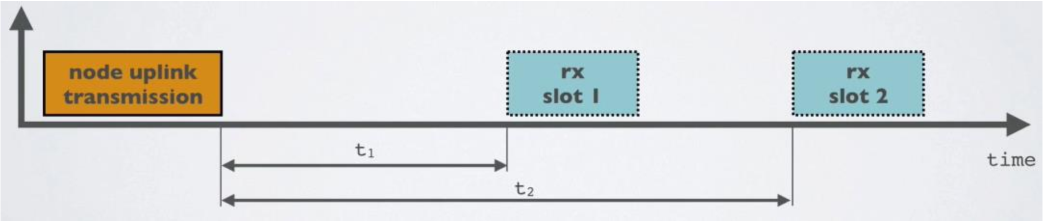
Classes B and C not concurrently, but Class A is always available



Device Class A

Bi-directional transmission

- ▶ **Uplink**
  - ➢ End devices transmits at **arbitrary time** (ALOHA)
    - ▪ Retransmission after random backoff
  - ➢ Next uplink transmission not before downlink transmission windows/slots expire
- ▶ **Downlink**
  - ➢ End device reachable **only after** its own **transmission**
    - ▪ **Opens** one or two **receive windows** (RX1 and RX2) **after each own transmission**
    - ▪ If no packet received by End device in RX1, End device opens RX2, otherwise RX2 not open
    - ▪ **Receive windows timing** defined using end of transmission as a reference
      - RX1 starts 1-15 seconds after end of transmission (1 second step) (*RXTimingSetupReq/Ans msgs*)
      - RX2 always 1 second after RX1
      - Default delays between end of transmission on RX1 and RX2: 1 and 2 seconds, respectively



Robert Lie,"LoRa/LoRaWAN tutorial 4: LoRaWAN Device Classes," https://www.youtube.com/watch?v=ShJ5RERof5I

Device Class B

Encompasses Class A communication, **but…**

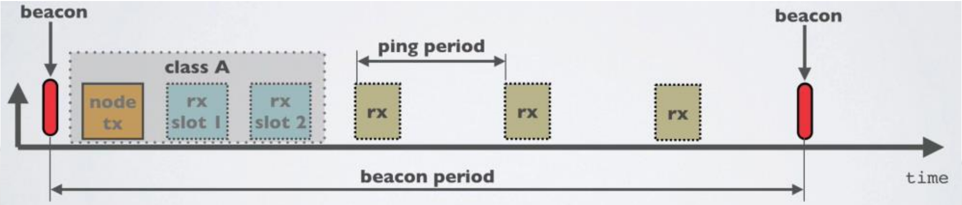
Gateway regularly (but optionally) transmits Beacons

Beacon

- Unmodulated 10 symbols + Beacon payload (dozens of bytes, gateway ID, GPS,…)
- **Period** of 128 sec between beacons
  - Starting on January 6, 1980, 00:00:00 UTC (GPS epoch start)
- **Ping slots for data reception**
  - **Beacon** period divided into $2^{12} = 4096$ **ping slots** (30 ms each)
  - Regular duration, but **starting randomly** after beacon to avoid collisions
  - End device opens periodically ping slots when it is reachable
- If beacon not received at expected time, **reception window enlarged**
  - Beaconless operation max 120 minutes with progressively **expanding beacon reception window**

Network should be informed about **device's position**

- End device sends **regular uplinks** to inform about best way to reach End device



Robert Lie,"LoRa/LoRaWAN tutorial 4: LoRaWAN Device Classes," https://www.youtube.com/watch?v=ShJ5RERof5I

Device Class C

Encompasses Class A communication, **but…**

End-device listens on continuous RX window (RXC) except:

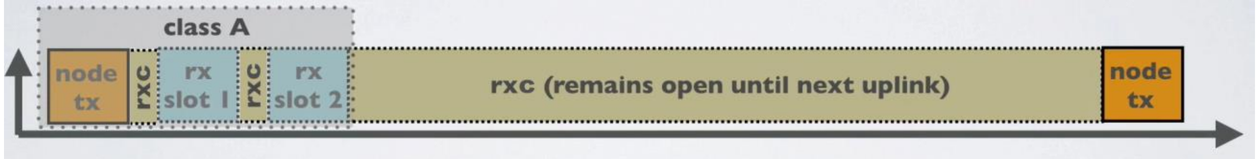
- Own transmission or
- Receiving data on RX1 or
- Receiving data on RX2.

End device opens RXC:

- between **end of uplink** transmission and **beginning of RX1** reception window, and
- between **end of RX1** window and **beginning of RX2** window, and
- as soon as **RX2** reception window is **closed**
  - Keeps open until End-device sends another packet

Network should be informed about **device's position**

- End device sends **regular uplinks** to inform about best way to reach End device



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Questions?

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