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UNIVERSIDADE DO PORTO

Arquiteturas da Computação Industrial

Industrial Computing Architectures

Lecture 21 – **Long-range Vertical Solutions**

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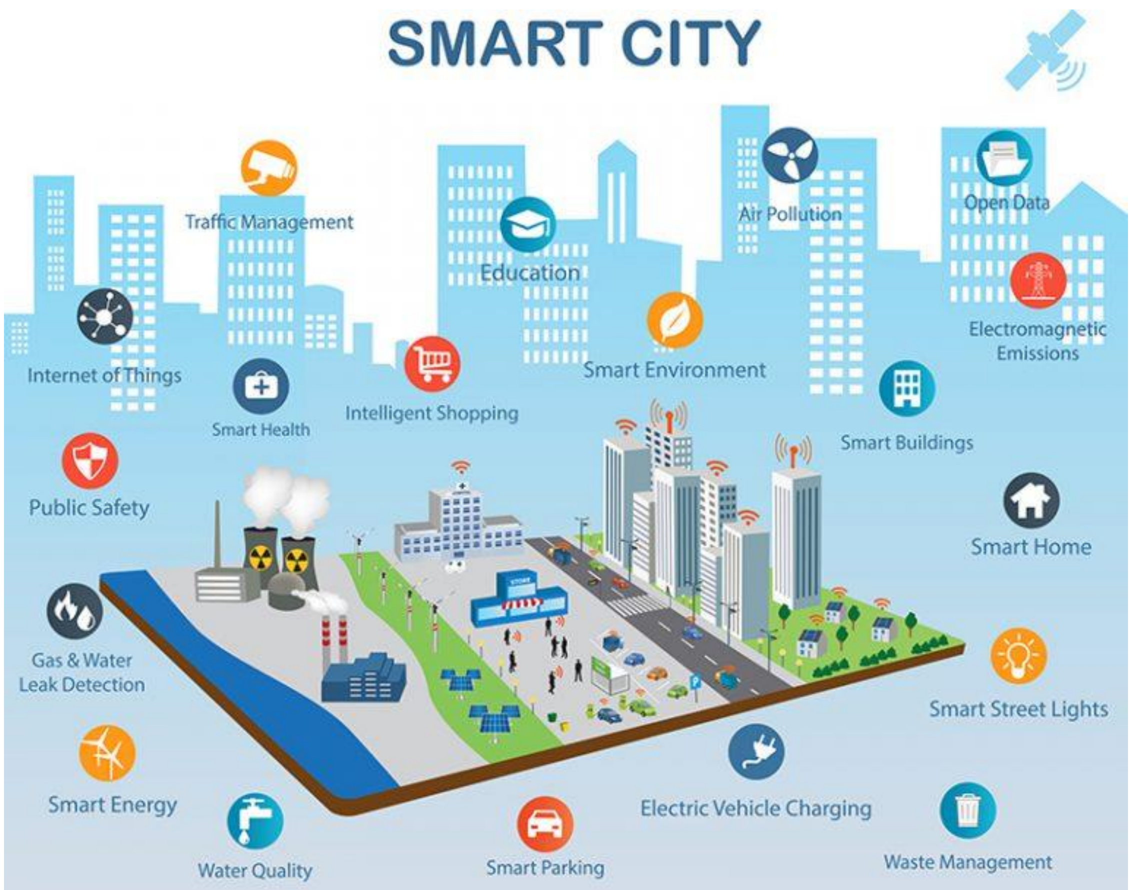
This lecture

- **Introduction to long-range vertical technologies**
  - Motivation, problems/solutions;
  - Narrowband vs. Wideband signals
- **LoRa / LoraWAN**
  - Spread spectrum modulation
- **SigFox**
  - Link budgets
- **NB-IoT**
  - Cellular Physical Layer

Long-Range Vertical Communication Solutions

- Long-range: - Designed for sensing applications over a wide area
  - Thus, implement Long-Range Wide Area Networks (LPWAN)
- Vertical: - Define the full network stack (from PHY to APPL)
  - Offer end-to-end solutions: from collection to delivery to client
- Examples: SigFox, LoRa, NB-IoT
  - Common Properties
    - » **Designed for low power, low bit rates but long range** *(how do they achieve this?)*
    - » **Security by design** *(these are new technologies)*
    - » **Designed under the Base station-User Equipment paradigm**
  - Differentiating Properties
    - » **Spectrum usage**: may use **licensed** or **unlicensed** bands
    - » **Spectrum/modulation**: **narrowband** or **wideband**
    - » **Technology & infrastrucutre**: may be **proprietary** or **free-to-use**

Applications for Long-Range Technologies



- Cities
  - » Street lighting
  - » Smart waste
  - » Smart transport
  - » Road traffic monitoring
  - » Smart parking
  - » Infrastructure sensors
- Agriculture
  - » Animal welfare monitoring
  - » Crop monitoring
  - » Animal tracking
  - » Soil monitoring
- Industry
  - » Warehouse monitoring
  - » Safety and security
  - » Wear monitoring
  - » Asset tracking

An actual use case

P2 ÍPSILON CULTO FUGAS P3 CINECARTAZ Entrar Assine já

ECONOMIA › MERCADOS EMPRESAS BANCA TRABALHO E EMPREGO CONJUNTURA FINANÇAS PÚBLICAS INTERNACIONAL EMPREENDEDORISMO

EDP

EDP e Nos juntam-se para um projecto-piloto de contadores inteligentes

A EDP Distribuição vai testar contadores inteligentes da Janz, equipados com uma nova tecnologia da Huawei, assente sobre a rede Nos.

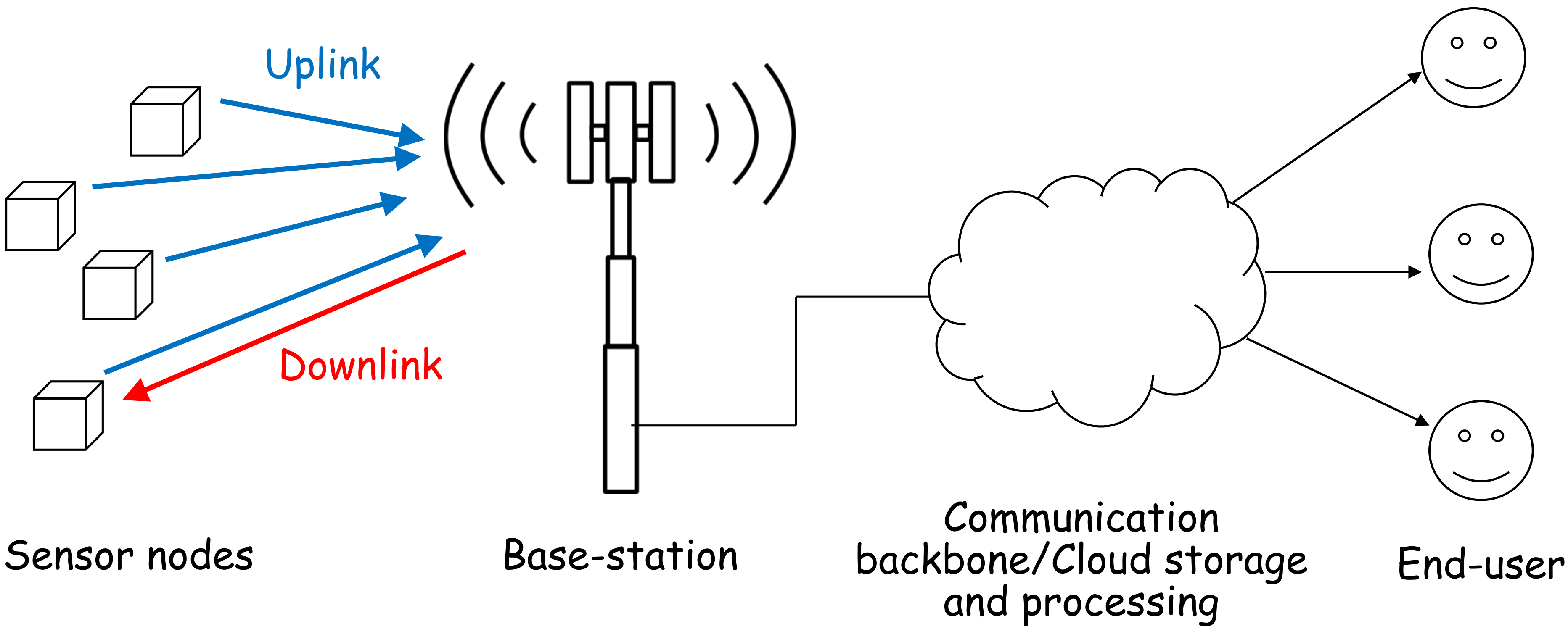
ANA BRITO · 10 de Julho de 2017, 17:52 16 PARTILHAS

O presidente da EDP Distribuição, João Torres MÁRIO PEREIRA

É na zona do Parque das Nações, em Lisboa, que a EDP Distribuição vai testar, com a colaboração de 100 consumidores de electricidade, a nova tecnologia NB – IoT (tecnologia 4,5G), desenvolvida pela Huawei e assente na infra-estrutura de rede da Nos. É sobre este tecnologia que vão operar os contadores inteligentes fabricados pela portuguesa Janz, que permitem leituras de consumos eléctricos em tempo real.

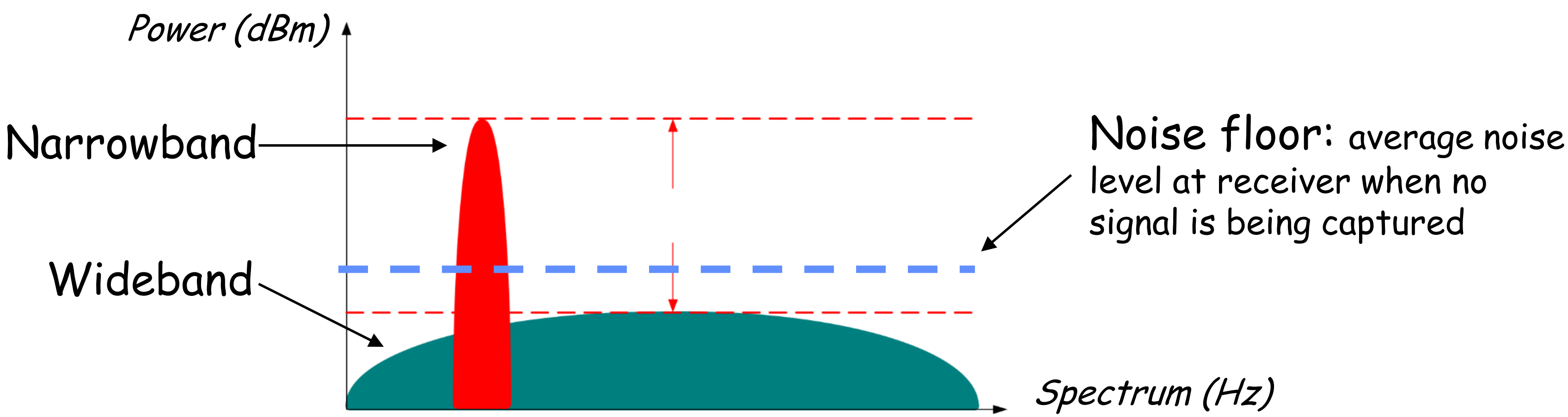
Typical Architecture

- Most long-range vertical solutions use a Base station (BE)-User Equipment (UE) architecture



Wideband vs. Narrowband

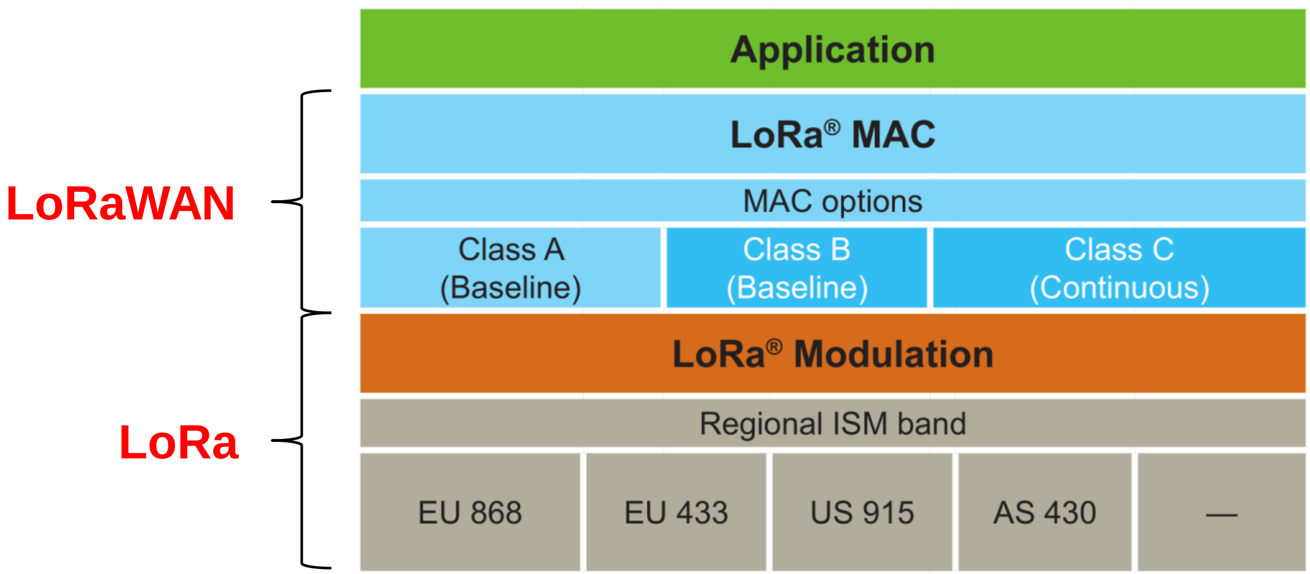
- A characterizing aspect of these LPWAN technologies is the width of EM spectrum required by the respective signals
  - Wideband: a wide band of spectrum is used; signal power spectral density may be inferior to noise floor
  - Narrowband: a very narrow band of spectrum is required, typically having high power (and possibly disrupting other communications)
- Different modulations and mechanisms required to implement each solution
- Note: total transmit power may be the same ***(usually the maximum legally allowed)***



LoRa / LoraWan

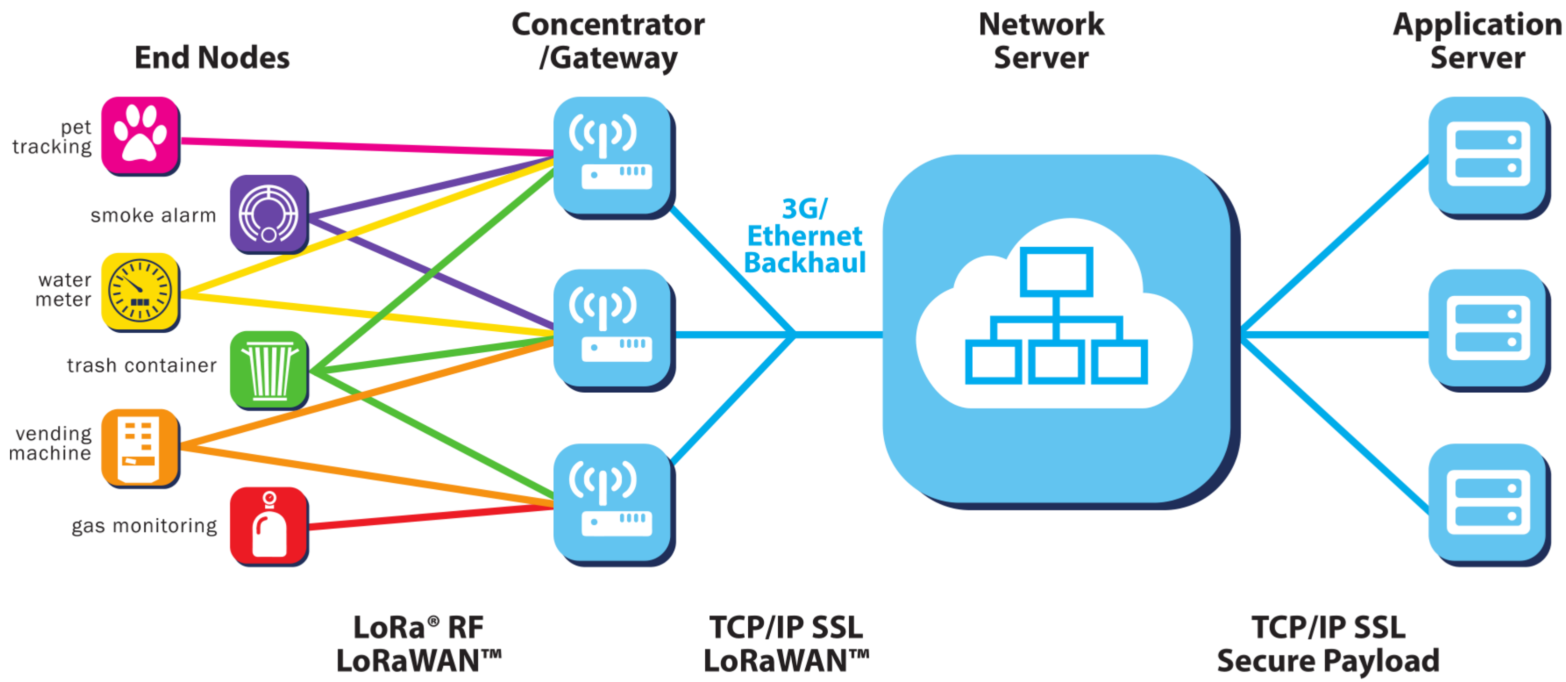
LoRa / LoraWan

- **LoRa**: stands for **Long-Range**, proposed by French company Semtech
- Composed by two parts: **LoRa** and **LoRaWAN**
  - **LoRa:** "physical layer enables the long-range communication link"
  - **LoRaWAN:** "defines the communication protocol and system architecture for the network [that operates over LoRa]"



Architecture & General Specs

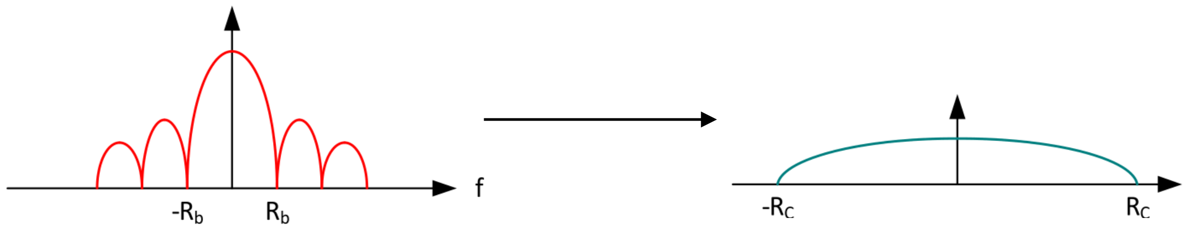
- LoraWAN implements a node/base station/cloud/user architecture



- Data rates (uplink/downlink): 0.3 kbps to 50 kbps.
- Modulation: chirp spread spectrum (CSS)

A Primer on Spread Spectrum (1/3)

- LoRa is a **wideband** technology (in terms of spectrum usage)
- This is achieved via a method called direct-sequence spread spectrum (DSSS)
- DSSS takes a signal for transmission and produces a related signal with a larger spectrum (wideband) prior to wireless transmission



- Same power, but spread over more frequencies
- What's the point?
  - Resilient against in-band and out-of-band interference
  - May be transmitted below the noise floor (security)
  - Allows to trade-off range and rate

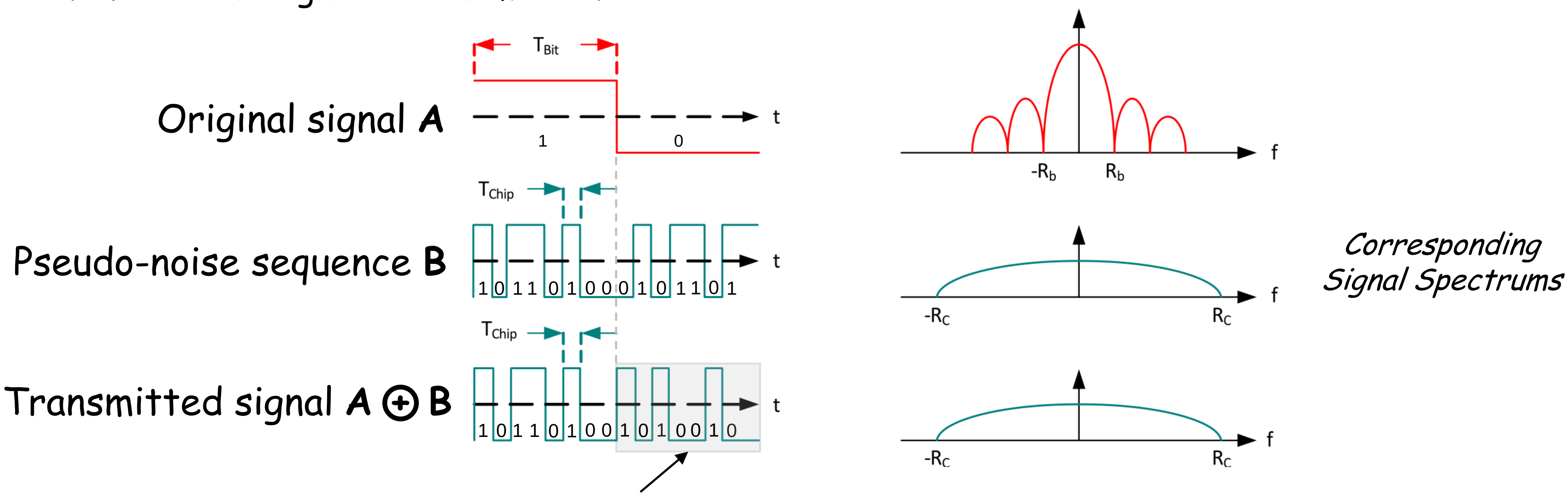
A Primer on Spread Spectrum (2/3)

1. Modulation/spreading:

1. Consider two signals: the signal to be transmitted **A**, and a higher-frequency pseudo-noise (PN) sequence **B** *(note: Bits in sequence B are called chips).*

2. Signals A and B are XORed. Resulting signal has an expanded spectrum – it is **wideband**.

1. Wide-band signal is transmitted.

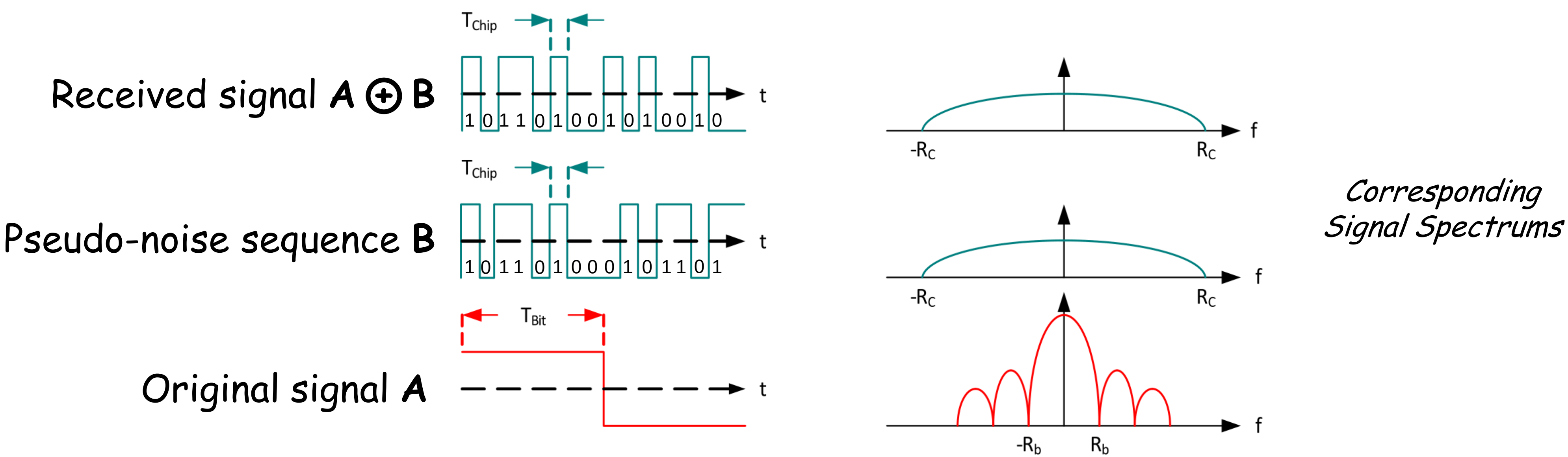


Note the inverted chips w.r.t. sequence B.

A Primer on Spread Spectrum (3/3)

2. Demodulation/de-spreading:

1. Received signal A⊕B is again XORed again with PN sequence (receiver must know it)
2. This retrieves signal **A**.



LoRa DSSS and the Spreading Factor

- LoRa extends the basic idea of DSSS
  - The PN sequence code used by LoRa **varies in frequency** over time - **CHIRP**
- **Range** and **rate** can be traded off by changing the **spreading factor**
- It is achieved by changing the **spreading factor SF**

$$Rb = \mathrm{SF} * \frac{1}{\frac{2^{\mathrm{SF}}}{BW}}$$

- Rb: Modulation bit rate
- SF: Spreading factor
- BW: bandwidth

- Spreading factor SF ranges from 7 to 12
- The lower the SF, the farther the range

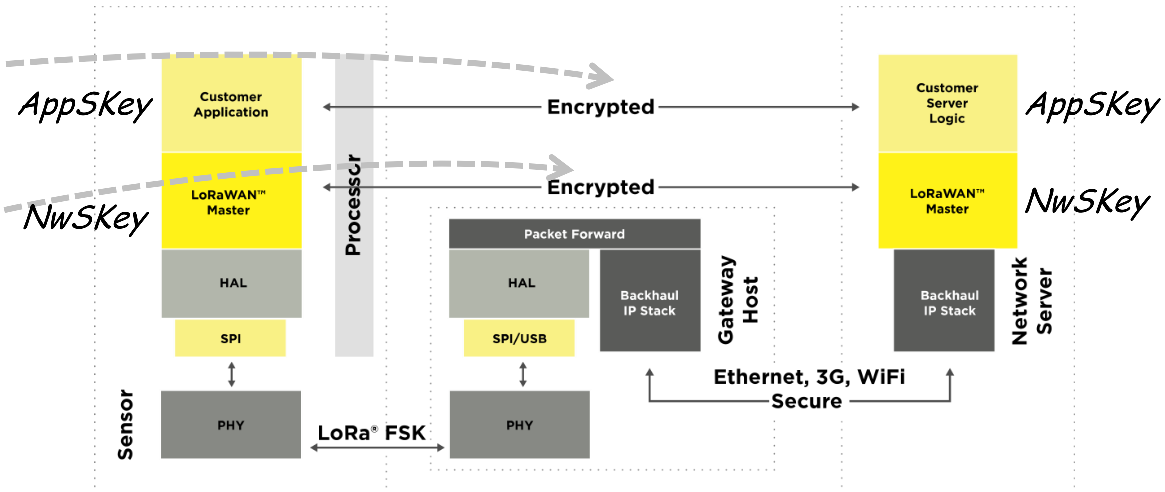
LoRaWAN

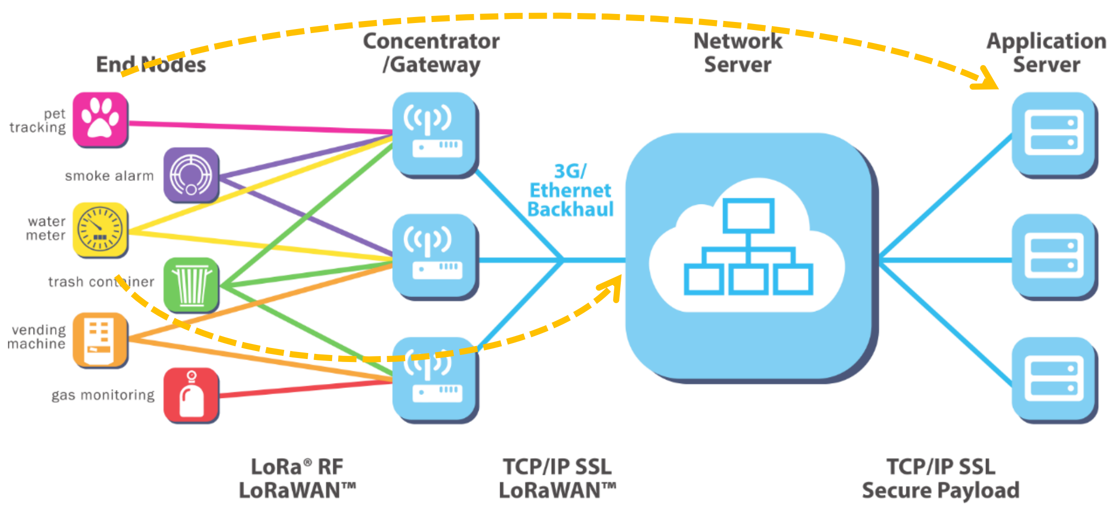
- **LoRaWAN**: the networking overlay that operates over LoRa
- Network Topologies:
  - Star Network Topology
  - Mesh Network Topology
- Power conscious: three classes of devices:
  - Class A - Lowest power, bi-directional end-devices
  - Class B - Bi-directional end-devices with deterministic downlink latency
  - Class C – Lowest latency, bi-directional end-devices

Security in LoRaWAN

- Application Session Key (AppSKey): 128-bit key shared **end-to-end** at the application level

- Network Session Key (NwSKey): 128-bit shared between the **end-device and network server**





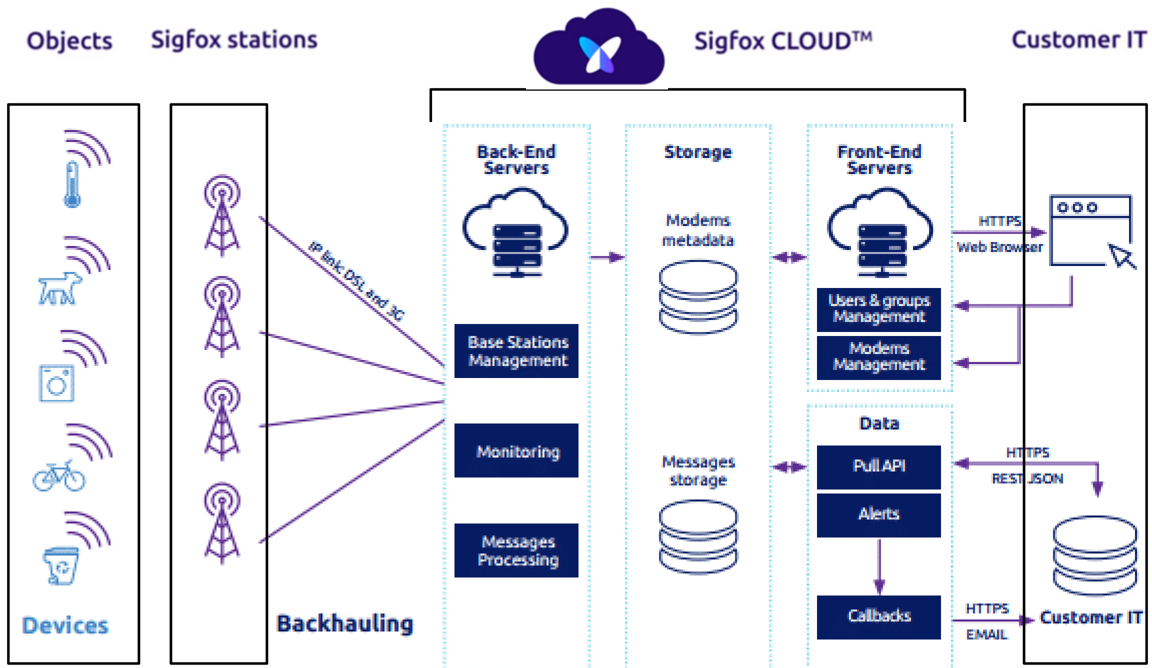
SigFox

SigFox

- **SigFox:** proprietary technology and infrastructure developed by French company SigFox
    - » **By contrast, LoRa/LoRaWAN technology can be implemented by anyone**
- Noteworthy features
    - **Cellular paradigm** with base stations and backend infrastructure
    - Infrastructure is licensed to national companies (in PT, *Narrownet*)
    - Operates in ISM bands
        - » **Like LoRaWAN (non-proprietary infrastructure) but unlike NB-IoT**
    - Data flow from sensing devices to end-consumer is controlled by SigFox
- Offered Service:
    - **Uplink service:** messages size: 0>12 bytes; 140 messages / day
    - **Downlink service:** messages: 0 - 8 bytes; 4 messages / day

SigFox Architecture

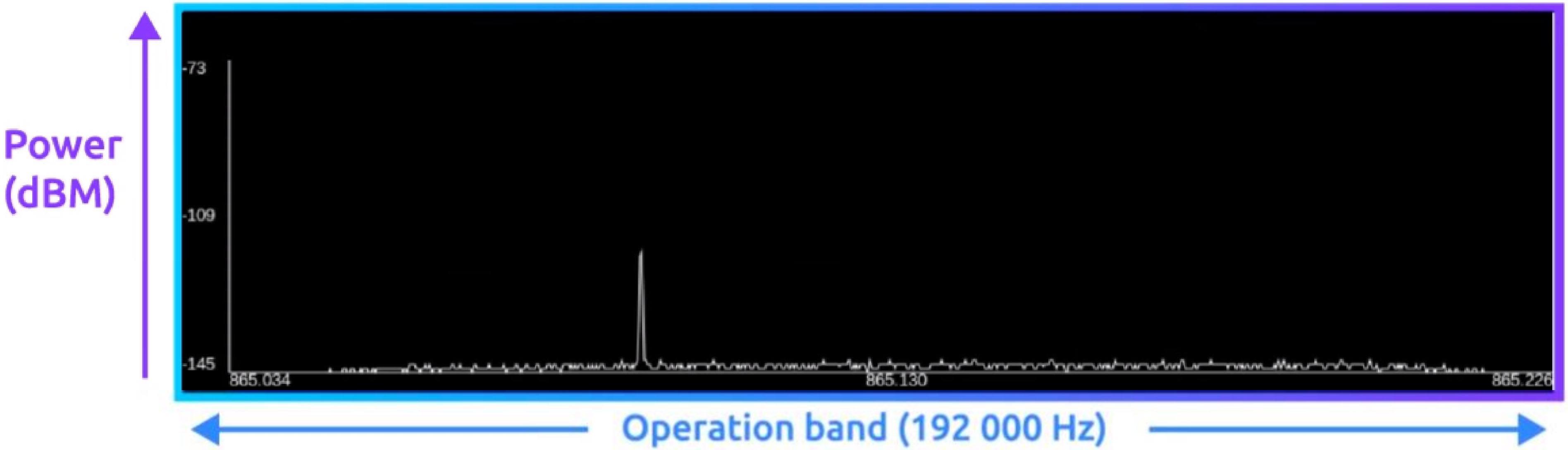
- Elements of the SigFox architecture
  - **Objects:** SigFox nodes deployed throughout area of interest
  - **SigFox base stations:** collect messages from objects and forward to the
  - **SigFox Cloud:** manages the network, stores data, and provides APIs for data access
  - **Customer IT:** infrastructure through which costumer accesses data



Network Management   Data storage   APIs for costumer data access and network management

Spectrum Usage

- **Ultra-narrowband:**
  - **Spectrum used by a single signal**: 1Hz to transmit 1 bit/s
    - » E.g.: 100 bps = 100Hz of used spectrum
  - Bit rate/used spectrum depends on region: 100[bps|Hz] @EU; 600[bps|Hz] @US
  - **Operation spectral band** of SigFox: 192 000Hz (~200KHz) @EU (2MHz @US)
  - A device can transmit anywhere in the operation band
    - » No synchronization between BS and device



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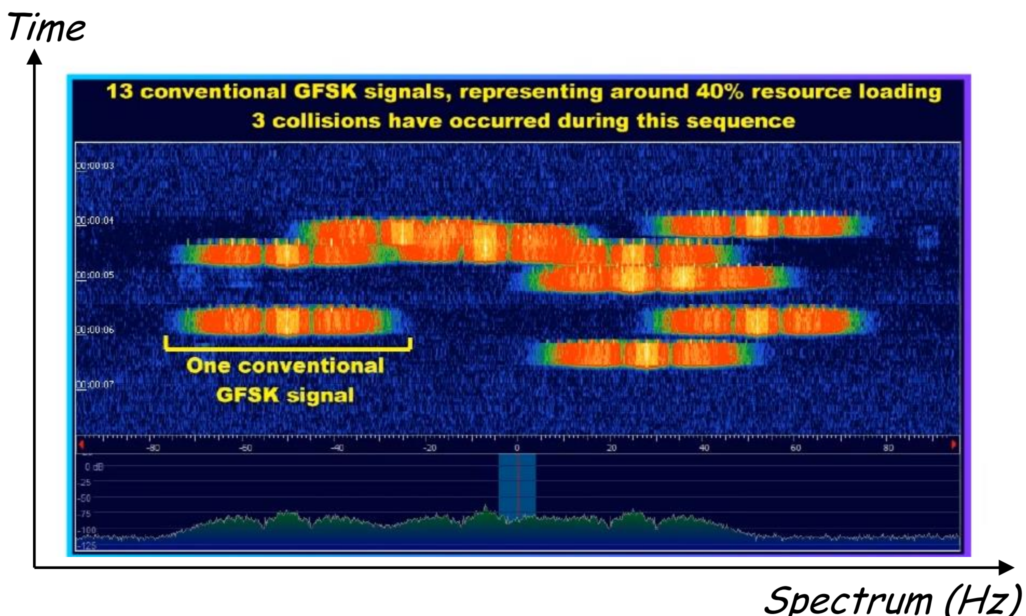
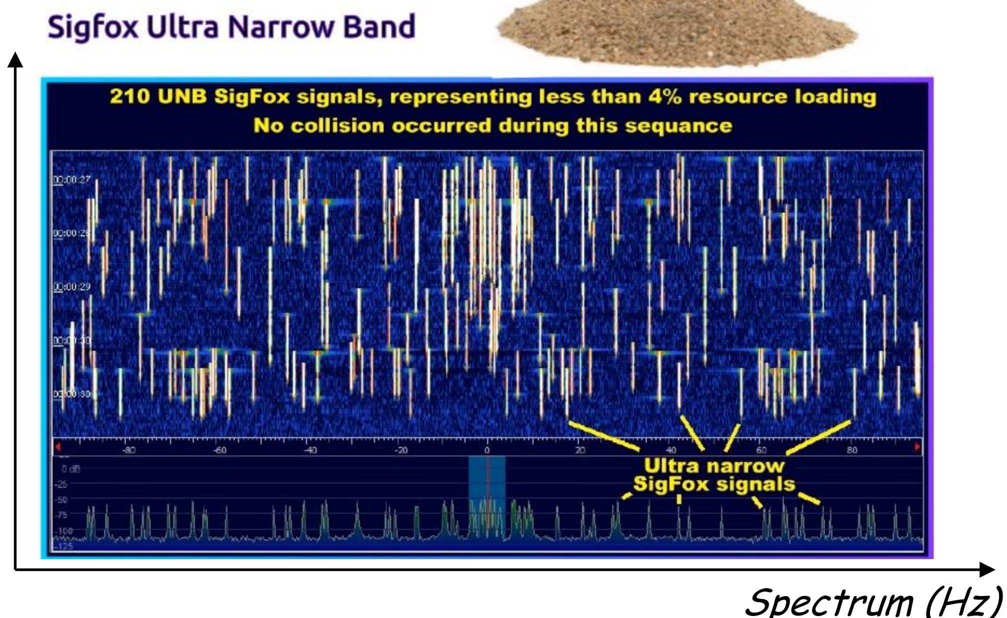
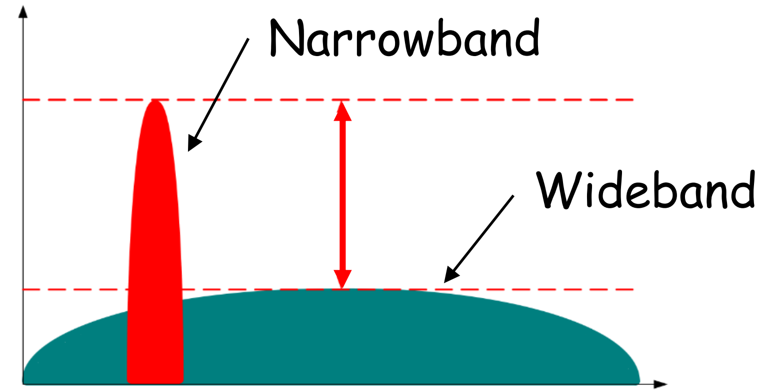
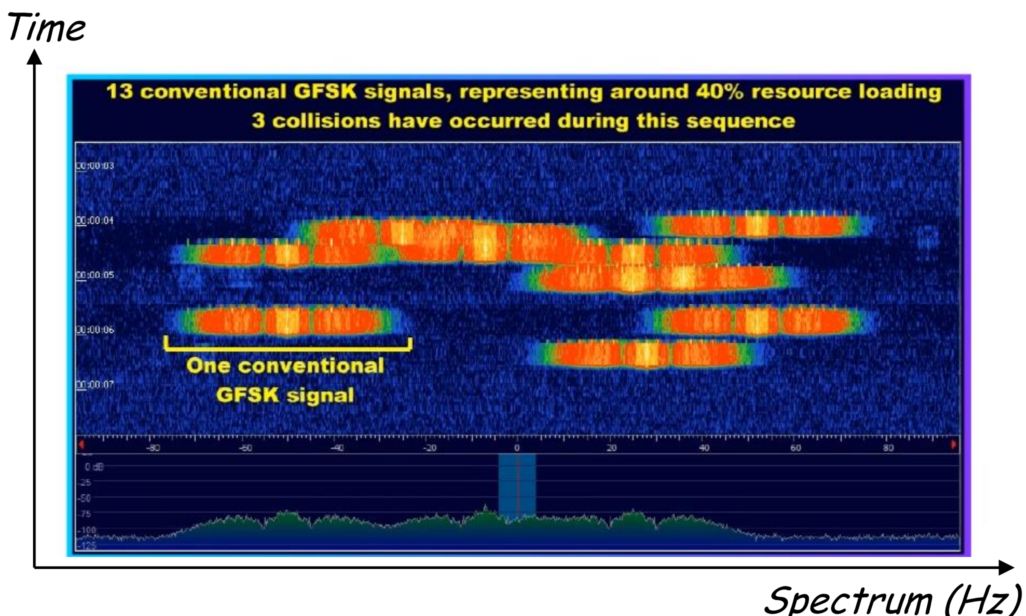




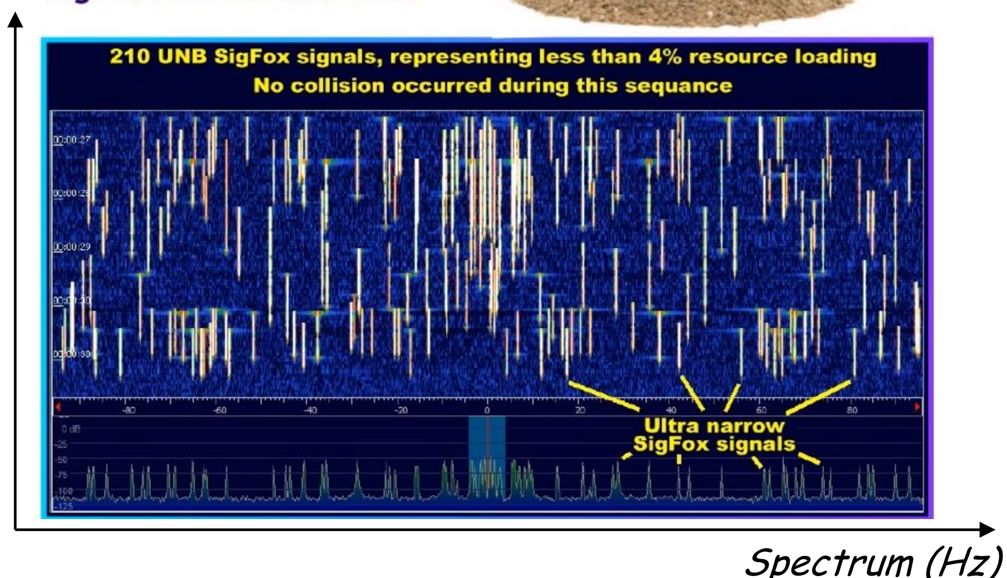
Spectrum Usage

- Upside:
  - Resilient against interference: power is concentrated in very narrowband
  - Supports more devices
- Downside:
  - Not good for high throughput transmissions (narrow bandwidth = less information)





Sigfox Ultra Narrow Band



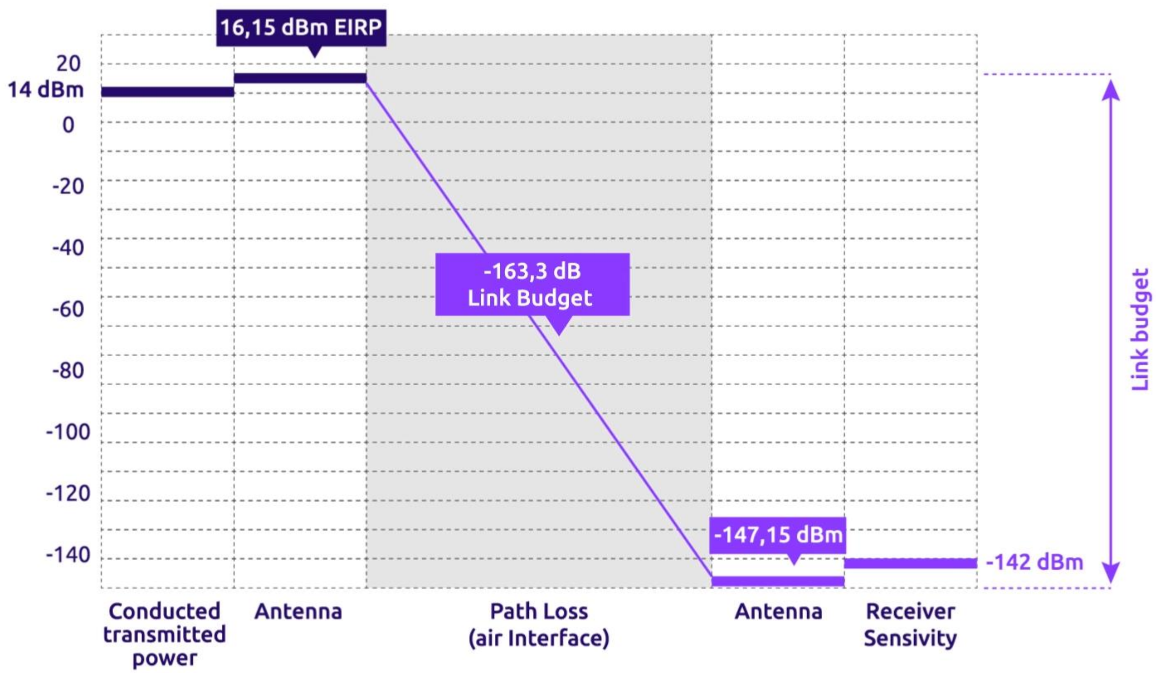
A Primer on Link Budgets (1/2)

- **Link Budget:** how much attenuation can our signal endure?
  - **Link loss** is how much the signal attenuates between transmitter and receiver
    - **Depends on distance and obstacles**
  - **Link budget** is how much attenuation your system can support and still receive the signal

- Link budgets in LPWAN technologies
  - **Large link budgets** is how low-power devices manage to transmit over long ranges
  - Base-station is typically an expensive equipment with high receiving sensitivity
  - Simpler modulations also help to achieve higher sensitivity *(cf. WiFi, a high throughput tech)*

A Primer on Link Budgets (2/2)

- A particular example
  - **RX:** Base station sensitivity = -142dBm @100bps | -134dBm @600bps
    - *(Compare with WiFi module: -90dBm)*
  - **TX:** For a 16,15 dBm EIRP (*Effective Isotropically Radiated Power*)
  - Link budget of -163,3 dB



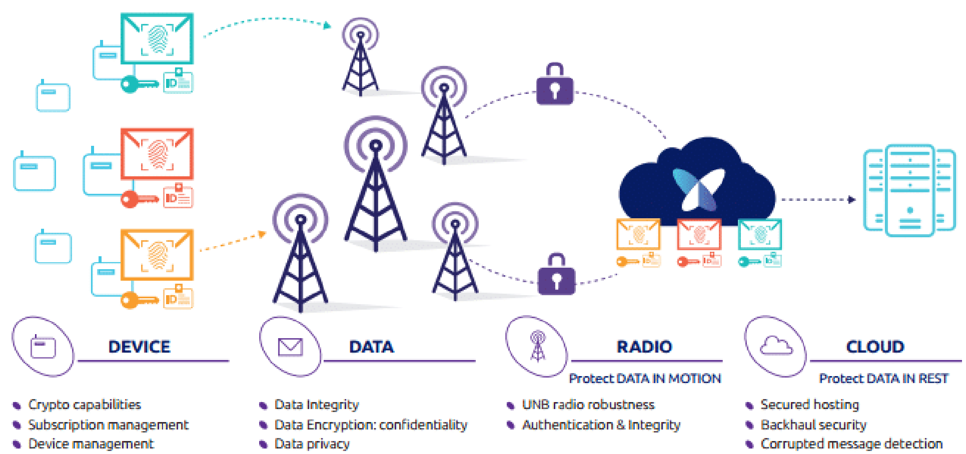
Link budget example for SigFox.
Similar math can be done for the other technologies (LoRa, NB-IoT).

Medium Access, Messaging and Security

- Medium Access
  - A message transmitted by an object can be received by many BS
  - An object can transmit a message at any time → no synchronization needed between BS and node
  - The same message is transmitted by the object **3 times, in different instants and frequencies**

- Lightweight Messaging Protocol
  - To transmit a 12 byte payload, SigFox uses 26 bytes at maximum (cf.
  - No signaling messages (as no synchronization is required between node and BS)

- Security
  - End-to-end authentication with shared key
  - At objects: shared key stored in ROM memory



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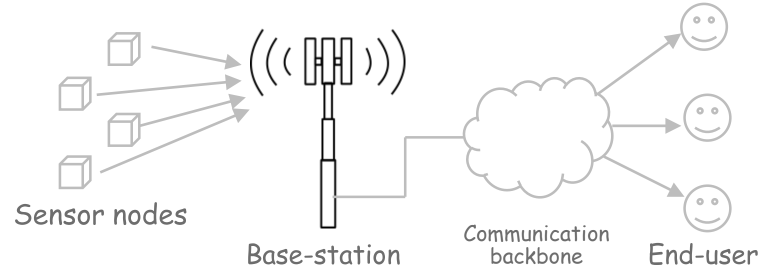
NB-IoT

NB-IoT



- **NB-IoT**: NB stands for **'Narrow-band'**
  - Developed by 3GPP, the cellular standardization body
  - Based on the cellular architecture (base station and user equipment)
  - Similar technology to LTE, but adapted for low-data rate low-power devices

- Where does NB-IoT fit in cellular communications
  - Cellular technology has had several evolutions – GSM (2G); UMTS (3G), LTE (4G)
  - They all co-exist, requiring independent infrastructure
    - » **Some of the older ones (e.g., 2G) are being phased out.**
  - Over time, several IoT solutions for cellular have been designed rolled-out:
    - » **GSM EC-GSM-IoT** - enhanced technology to support low power wide area needs
    - » **LTE-M** (formally known as eMTC) LTE evolution for IoT communications enabling a wide range of services
    - » **NB-IoT – New LTE solution to support ultra-low bitrate applications**

Spectrum Assignment in LTE

- Spectrum usage in LTE
  - LTE carriers can be [1.4, 3, 5, 10, 15, 20] MHz wide (defined in the standard)
  - **Physical Resource Blocks** (PRBs) are 180kHz sub-divisions that correspond to smallest chunk of data
  - For 10MHz carrier, we get 50 PRBs

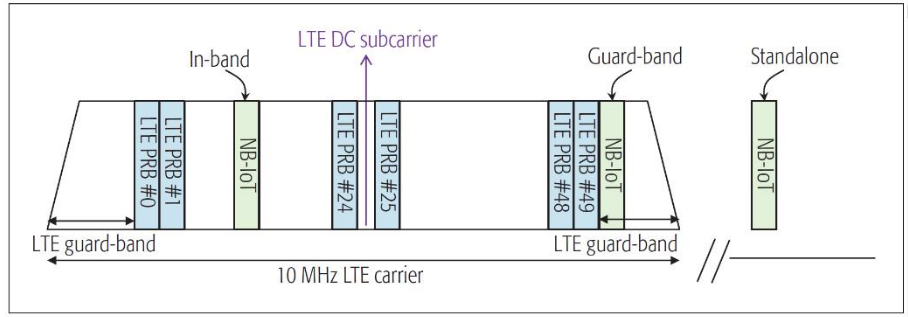


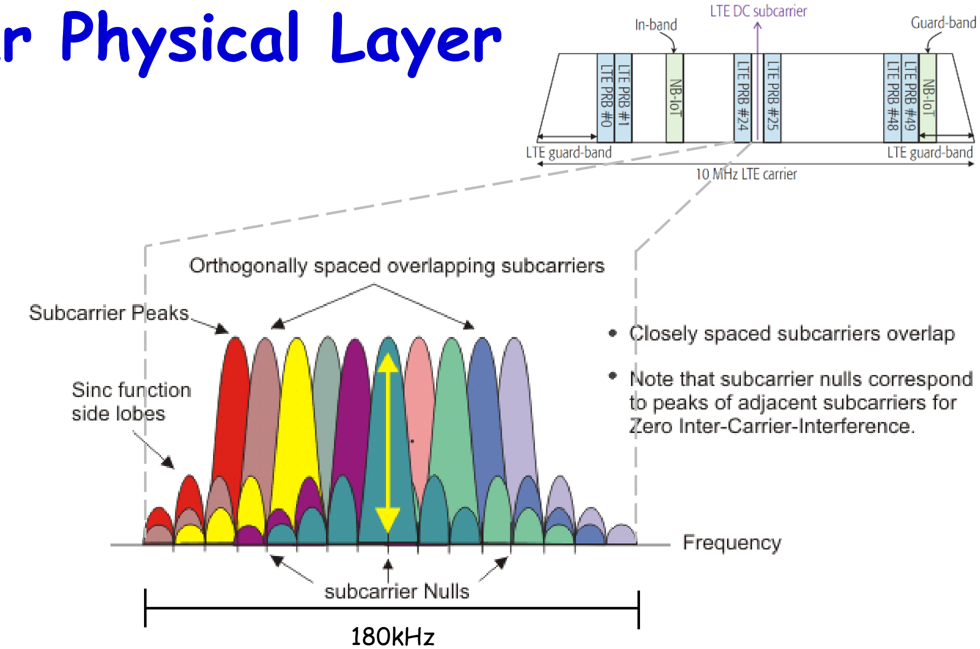
Figure 1. Examples of NB-IoT stand-alone deployment and LTE in-band and guard-band deployments.

- NB-IoT was designed to be compatible with GSM and LTE
  - NB-IoT requires a bandwidth of 180 kHz for downlink and uplink
  - In GSM: Replace one GSM carrier (200 kHz) with NB-IoT
  - In LTE: Allocate one PRB of 180 kHz to NB-IoT
    - » **In-band:** using one of the regular PRBs
    - » **Guard-band:** using unused space that borders the PRBs of that carrier

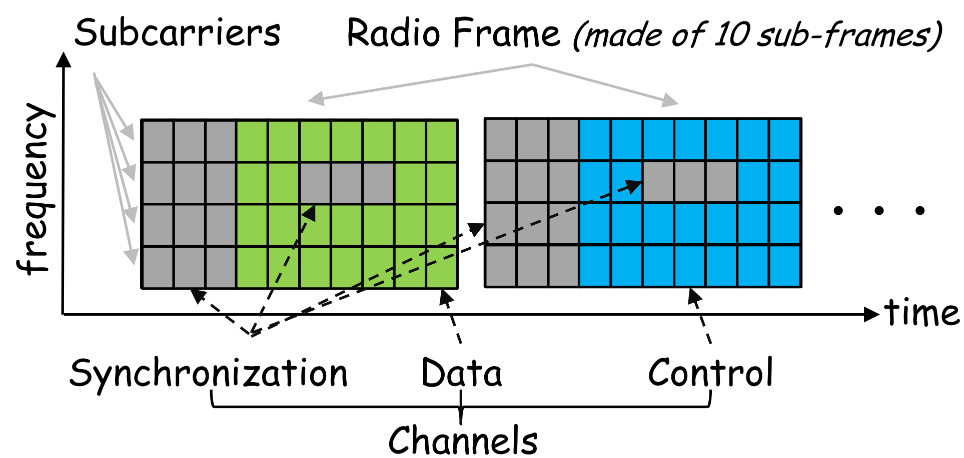
A Primer on Cellular Physical Layer

Inside a PRB

- Modulation: **OFDM**
  - *Orthogonal Frequency Division Multiple Access*
  - Number of subcarriers can vary, e.g., 12, 48, 64
  - Different modulations are possible, e.g., QPSK, 16QAM, 64QAM
- Time: **Frame**
  - Frames are composed of 10 sub-frames

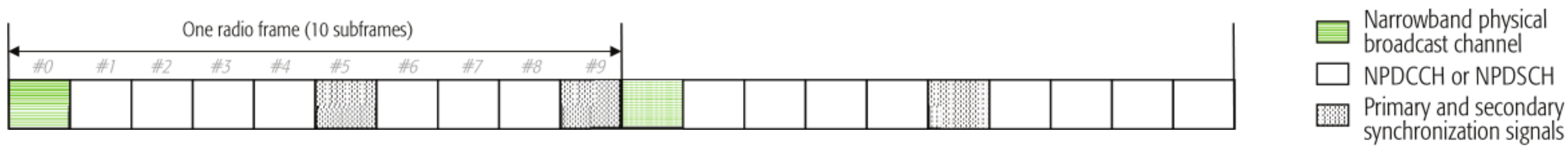


- **Channels:**
  - For <u>synchronization</u>, <u>control</u>, and <u>data</u>
  - Channels are **<u>logical</u>**, i.e.: their implementation is mapped into well defined physical resources (frequencies and sub-frames)
  - Synchronism between UE and BE is a key aspect of cellular operation.



NB-IoT Physical Layer – Downlink (BS to UE)

- Modulation: Orthogonal Frequency-Division Multiple Access (OFDMA)
- Two consecutive DL frames have the following structure:

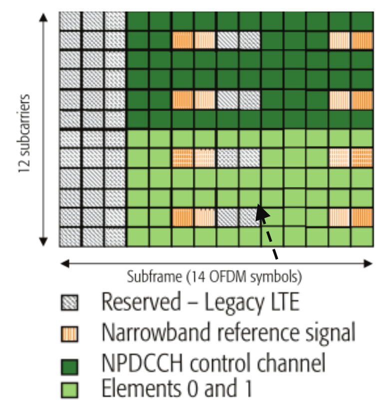


- Three channels:
  - **Synchronization** (NPSS/NSSS – *NB primary/ secondary sync. signals*)

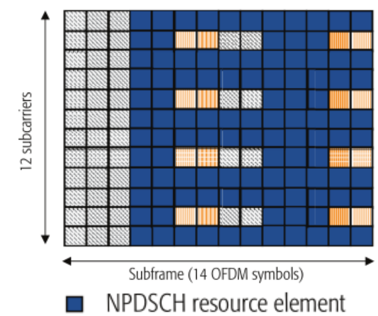
(The following can be transmitted at any white sub-frame.)

  - **Control frame** (NPDCCH - *NB physical downlink control channel*)
  - **Data frame** (NPDSCH - *NB physical downlink shared channel*)

Control frame (NPSCCH)

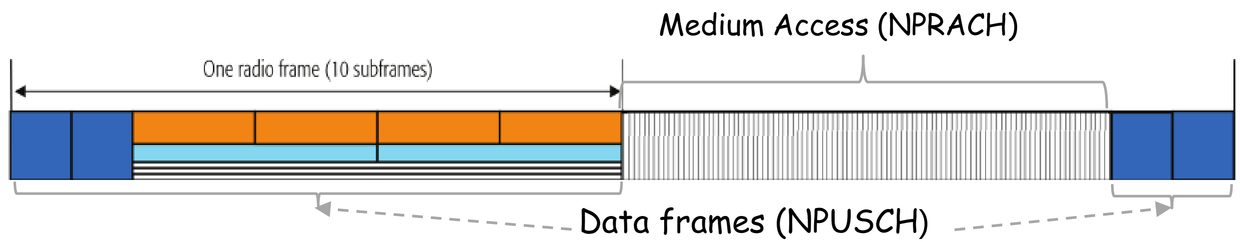


Data Frame (NPDSCH)



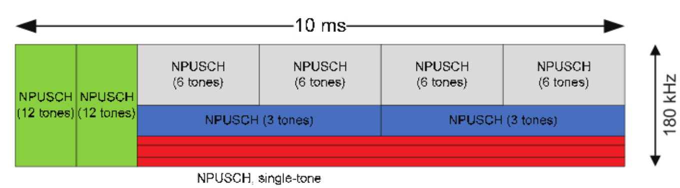
NB-IoT Physical Layer – Uplink (UE to BS)

- Modulation: single-carrier frequency-division multiple access (SC-FDMA)
- Two consecutive UL frames have the following structure:

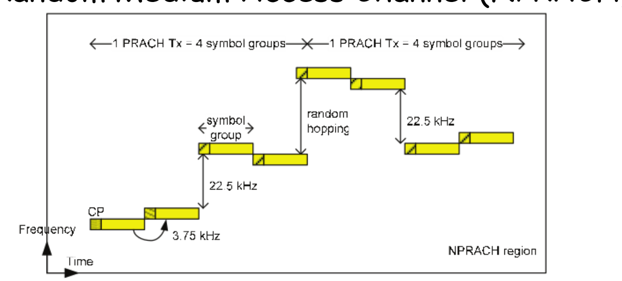


- Two channels:
  - **Data frames** (NPUSCH - *NB physical uplink shared channel*)
    - » A data package can be split per multiple sub-carriers and/or subframes
  - **Random Medium Access** (NPRACH - *NB physical random access channel*)
    - » Allows UE to request a uplink to BS by sending a random tone sequence
    - » If correctly received, BS schedules transmissions for that UE

Data Frame (NPUSCH)



Random Medium Access Channel (NPRACH)



Technical Specifications

- Noteworthy operational aspects
  - **Peak data rates:** around 226.7 kb/s peak data rate.
  - **Reliability:** retransmissions via an hybrid automatic repeat request (HARQ)
  - **Device complexity:** inferior to devices that implement LTE
  - **Latency and Battery Time:** a 10-year battery life if UE transmits 200 bytes/day
  - **Capacity:** single PRB can support uplinks and downlinks, thus increasing network capacity
  - **Coverage:** plus more 20 dB of link budget than LTE

	NB-IoT
3GPP Release	13
Uplink rate	250 kbit/s
Downlink rate	10 Mbit/s
Latency	1.6s-10s
# antenas	1
Duplex	Half Duplex
Dev. Recv. Bandwidth	180 kHz
Receiver chains	1 (SISO)
Dev. Tx power	20/23 dBm

- Overview of NB-IoT:
  - NB-IoT can be seen as a 'simplified' version of LTE for low-rate applications
    - » **NB-IoT resources were designed to be mapped into LTE resources**
  - In release 14, NB-IoT will provide localization services

Comparison

Comparative Performance

- Collisions (from node to BS)
  - Sigfox: almost no collisions
    - » **Due to narrowband signals with high power**
  - LoRa is more exposed to interference
    - » **But retransmissions improve a lot**
  - Cellular technologies fit somewhere in-between

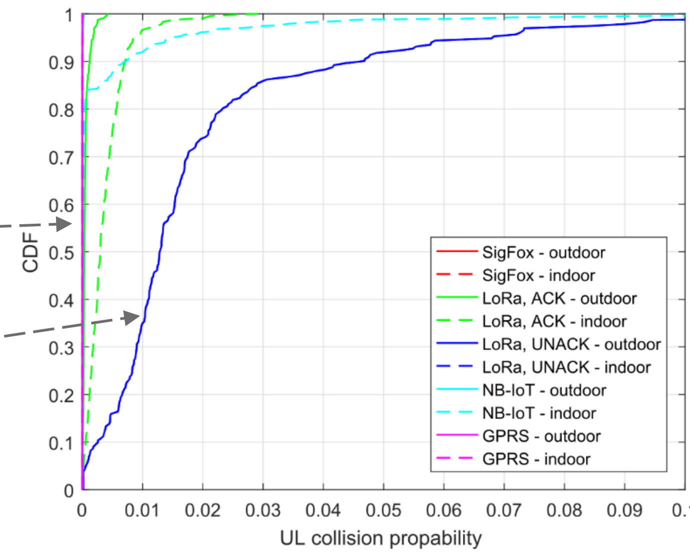


Fig. 5. CDF of the uplink collision probability due to random access failure.

- Data rate vs. Link Loss
  - Link loss is defined by distance and/or obstacles
  - NB-IoT offers the largest data rates
  - LoRa is still able to transmit at large link losses, albeit at lower data rates
  - SigFox offers always the same bit rate

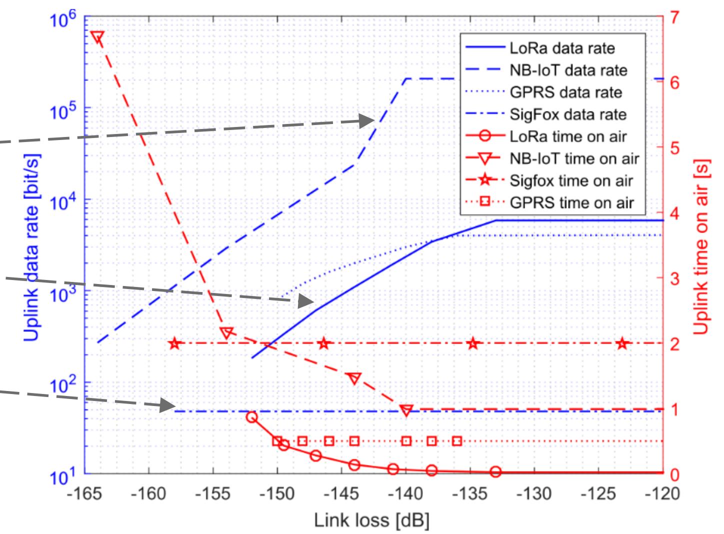


Fig. 3. Mapping curves for uplink data rate and uplink time on air as a function of link loss.

Vejlgaard, Benny; Lauridsen, Mads; Nguyen, Huan Cong; Kovács, István; Mogensen, Preben Elgaard; Sørensen, Mads: **Coverage and Capacity Analysis of Sigfox, LoRa, GPRS, and NB-IoT**. Published in: 2017 IEEE 85th Vehicular Technology Conference (VTC Spring)

Comparison of LPWAN technologies

- All are designed for long-range low-data rates low-power devices:
  - '**Long range**' should actually be '**large link budgets**'
    - » You get long range in line-of-sight; in urban areas, not so much due to obstacle-induced attenuation
  - **Base station-user equipment paradigm** → large link budgets
    - » **BS has higher sensitivity (i.e., can receive weaker signals) and higher transmit power than regular devices**
  - **Simple modulations** → low data rates and power consumption; also help with large link budgets
    - » **Hard for more complex modulations to have similar link budgets**

		LoRa/LoRaWAN	SigFox	NB-IoT
Data rates	*Downlink rate*		12byte/pkt; 140pkt/day	10Mbit/s
	Uplink rate		8byte/pkt; 4pkt/day	250kbit/s
Spectrum utilization	*Signal spectrum*	Wide-band/spread spectrum	Narrow-band	Narrow-band
	Trade-offs	Range vs. rate	None	Range vs. rate
Business model	*Technology*	Proprietary	Proprietary	Proprietary
	Infrastructure	Open	Licensed	Proprietary
	Spectrum band	Unlicensed	Unlicensed	Licensed

Bibliography

- **LoRa/LoRaWAN:** https://lora-alliance.org/
- **SigFox:** https://www.sigfox.com/en
- **NB-IoT:**
  - Huawei White paper on IoT: https://www.huawei.com/minisite/iot/img/nb_iot_whitepaper_en.pdf
  - Vodafone https://www.vodafone.com/business/iot/managed-iot-connectivity/nb-iot