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FEUP FACULDADE DE ENGENHARIA
UNIVERSIDADE DO PORTO

Arquiteturas da Computação Industrial

Industrial Computing Architectures

Lecture 24 – **Long-range Vertical Solutions**

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Course Coordinator: Luís Almeida

Last lecture

- Integrated Automation Architectures

  (CIM – Computer Integrated Manufacturing)
  - Layers and protocols
  - Integrated solutions
    - » **TIA – Totally Integrated Automation (Siemens)**
    - » **CIP – Common Industrial Protocol (ODVA)**
    - » **OPC-UA – OLE for Process Control – Unified Architecture (OPC Foundation)**
    - » **Other standards**

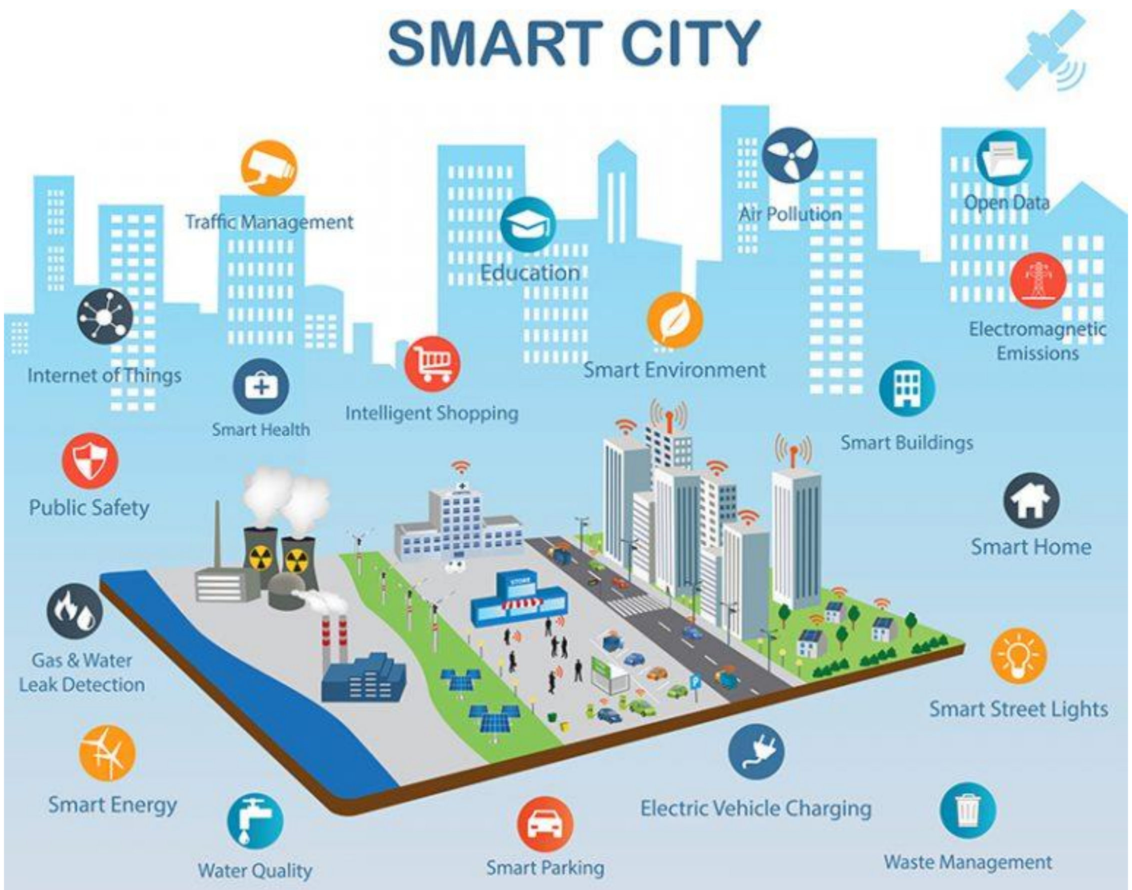
This lecture

- **Introduction to long-range vertical technologies**
  - Motivation, problems/solutions, available tecnhologies
  - 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** and **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 & infrastructure**: may be **proprietary** or **free-to-use**

Applications for Long-Range Technologies



Ref.[10]

- 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 in Portugal

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.

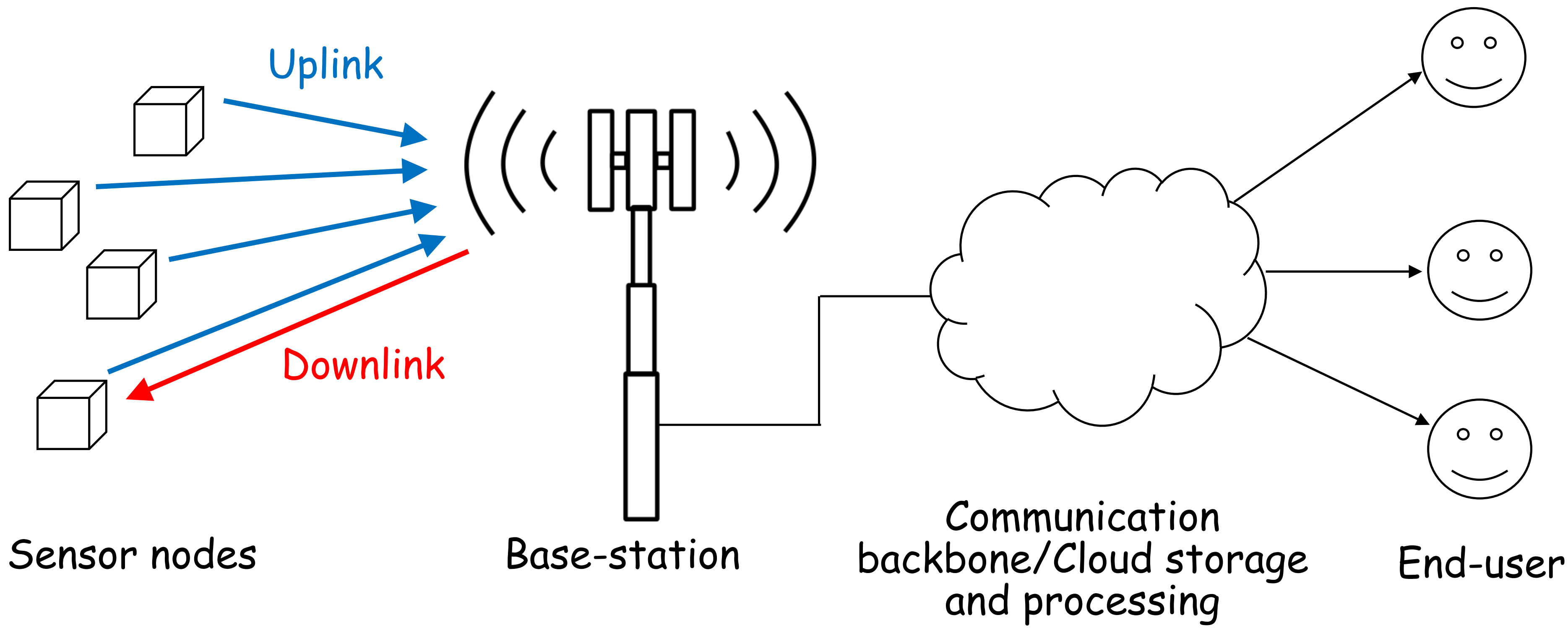
ANA BRITO · 10 de Julho de 2017, 17:52

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.

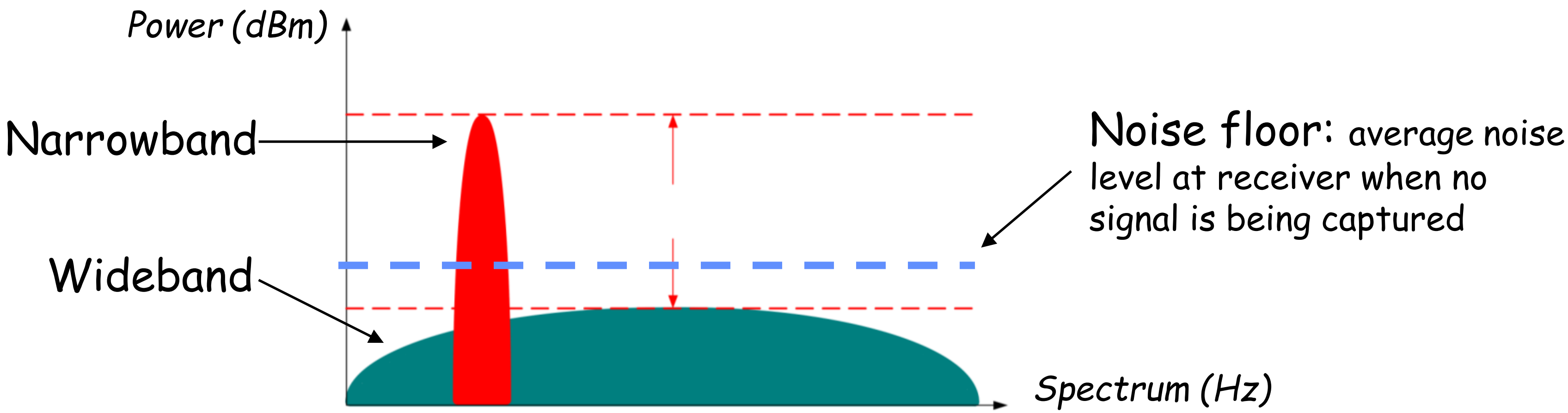
Typical Architecture

- Long-range vertical systems typically use the **Base station (BE)-User Equipment (UE)** architecture – *better for long range communication*
  - **Uplink:** UE to BS communication
  - **Downlink:** BS to EU communication
- Data from multiple base stations is collected at a centralized point (i.e., a server)



Wideband vs. Narrowband

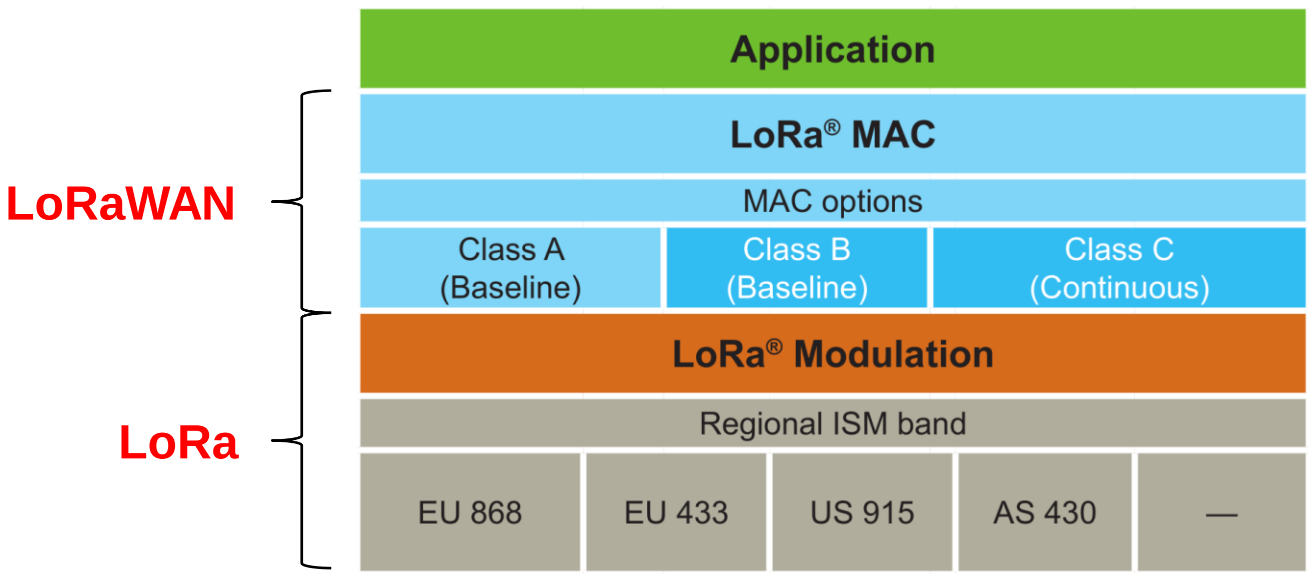
- A characterizing aspect of these LPWAN technologies is the width of EM spectrum required by the respective signals
  - Wideband: a wide band of spectrum is used; signal power spectral density may be inferior to noise floor
  - Narrowband: a very narrow band of spectrum is required, typically having 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

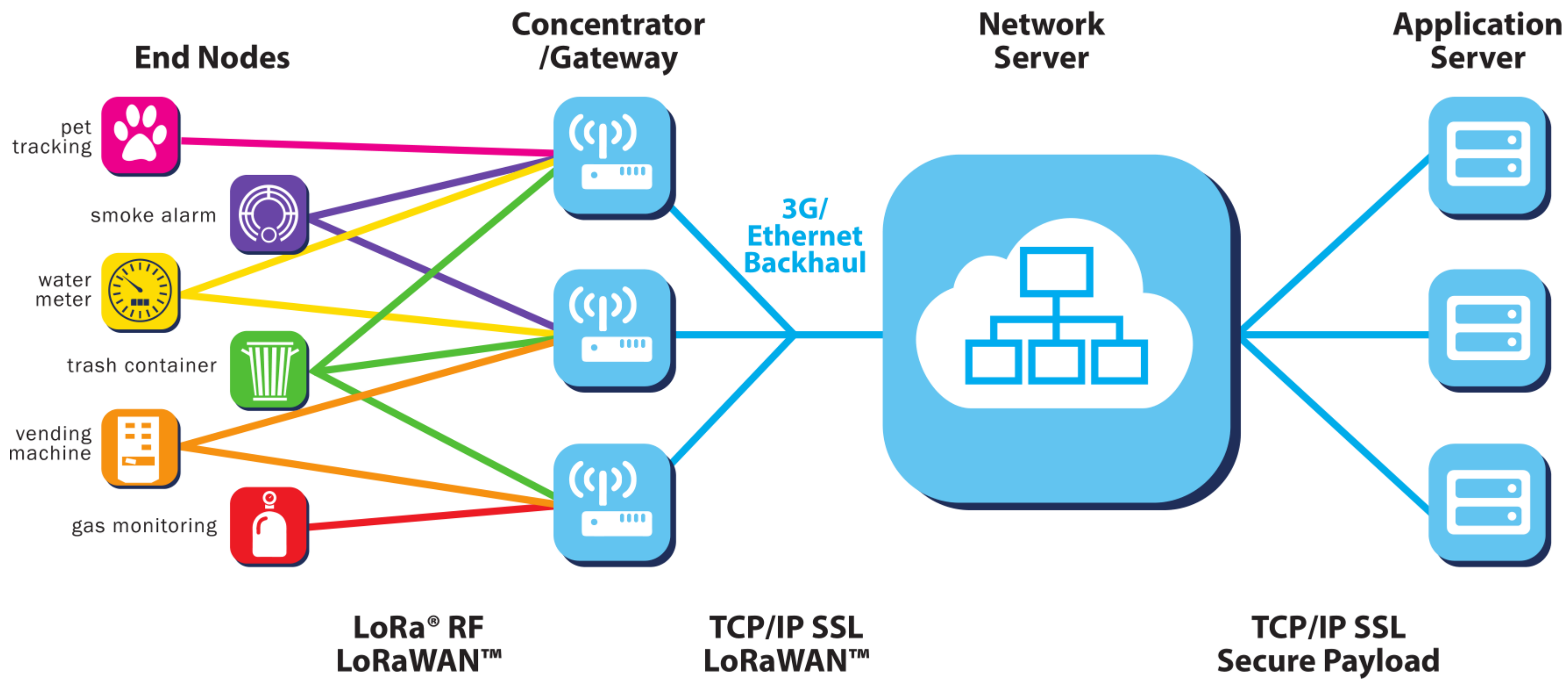
- **LoRa**: stands for **Long-Range**, proposed by French company Semtech
- Composed by two parts: **LoRa** and **LoRaWAN**
  - **LoRa:** "physical layer enables the long-range communication link"
  - **LoRaWAN:** "defines the communication protocol and system architecture for the network [that operates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



Ref.[2]

Architecture & General Specs

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

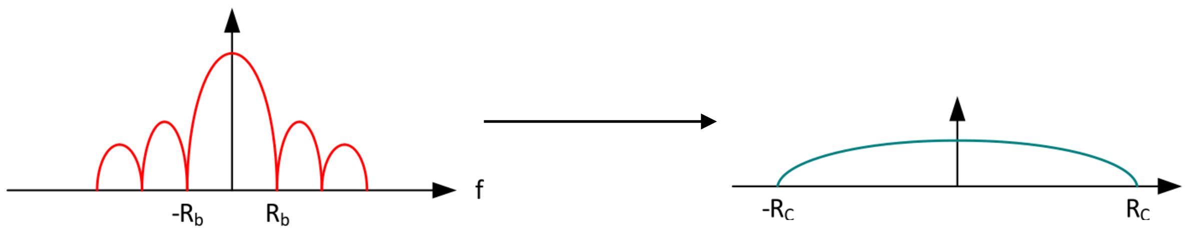


- Data rates (uplink/downlink): 0.3 kbps to 50 kbps.
- Modulation: chirp spread spectrum (CSS)

Ref.[1]

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 transmission over wireless link

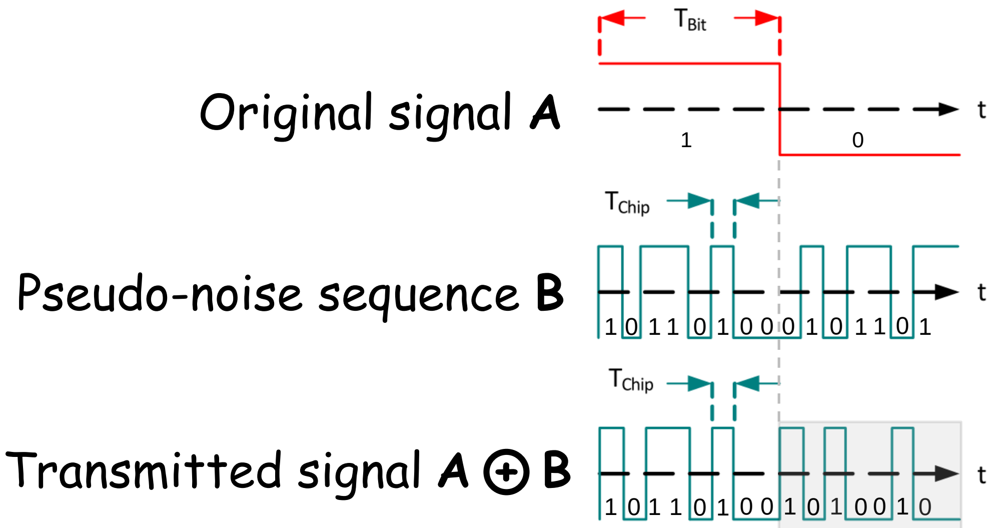


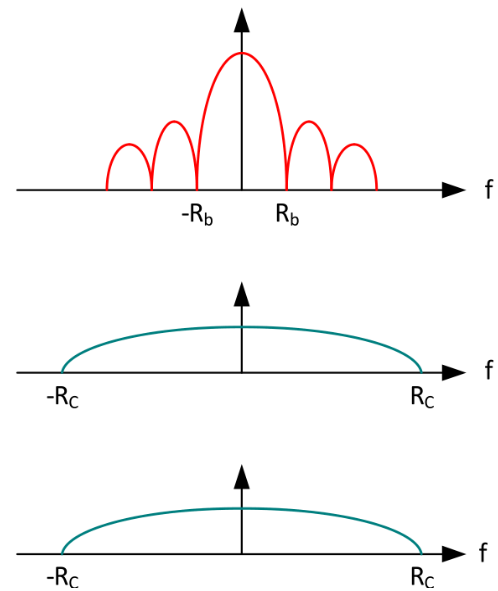
- Same power, but spread over more frequencies
- What's the point?
  - Resilient against in-band and out-of-band interference
  - May be transmitted below the noise floor (security)
  - Allows to trade-off range and rate

A Primer on Spread Spectrum (2/3)

1. Modulation/spreading (at TX):

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**.
3. Wideband signal is transmitted over the wireless link.





Corresponding Signal Spectrums

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

Ref.[2]

A Primer on Spread Spectrum (3/3)

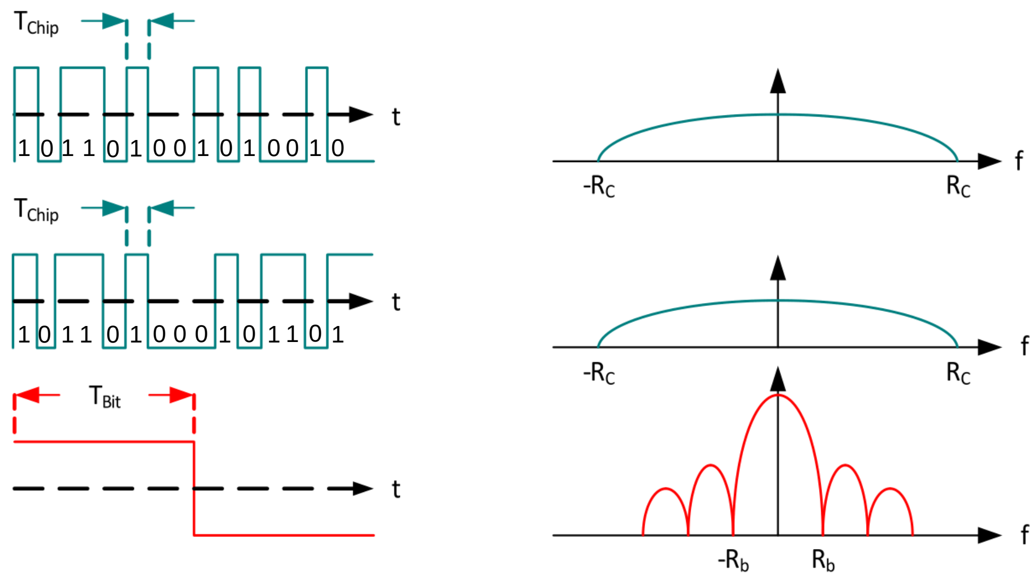
2. Demodulation/de-spreading (at RX):

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

Received signal **A ⊕ B**

Pseudo-noise sequence **B**

Original signal **A**



Corresponding Signal Spectrums

Ref.[2]

LoRa DSSS and the Spreading Factor

- LoRa extends the basic idea of DSSS → Chirp Spread Spectrum (CSS)
  - 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 higher the SF (e.g., 12), the farther the range and lower the bit rate

    (Mnemonic: SF ↑ → range ↑, rate ↓ ; SF ↓ → range ↓, rate ↑)

LoRaWAN

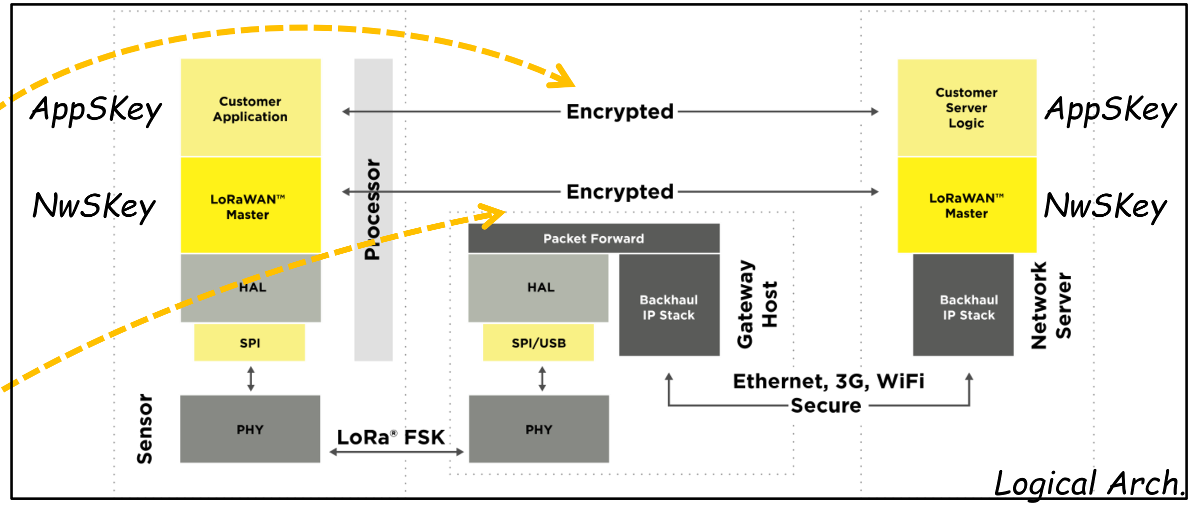
- **LoRaWAN**: the networking overlay that operates over LoRa
- Network topologies by design:
  - Star topology
  - Mesh topology
- Power conscious - three classes of devices:
  - **Class A:** Lowest power, bi-directional end-devices
  - **Class B:** Bi-directional end-devices with deterministic downlink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

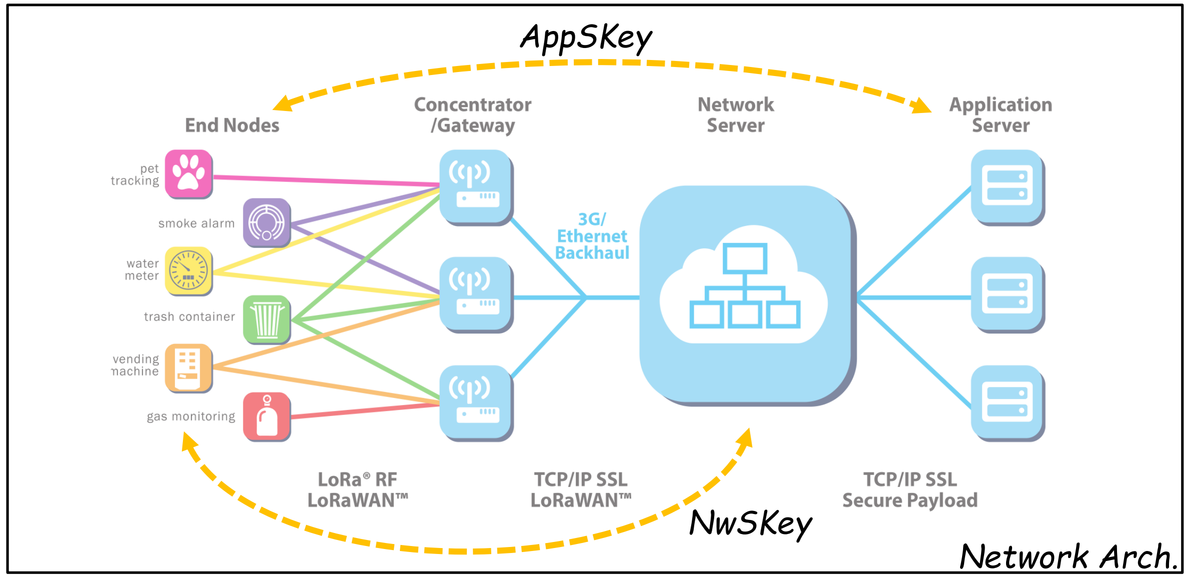
Security in LoRaWAN

Two layers of encryption that operate with different scopes:

- **End-to-end:** the end-device and the client share the <u>Application Session Key</u> (*AppSKey*), a 128-bit key

- **Network:** the end-device and the LoraWan network server share the <u>Network Session Key</u> (*NwSKey*), also a 128-bit key





Ref.[1]

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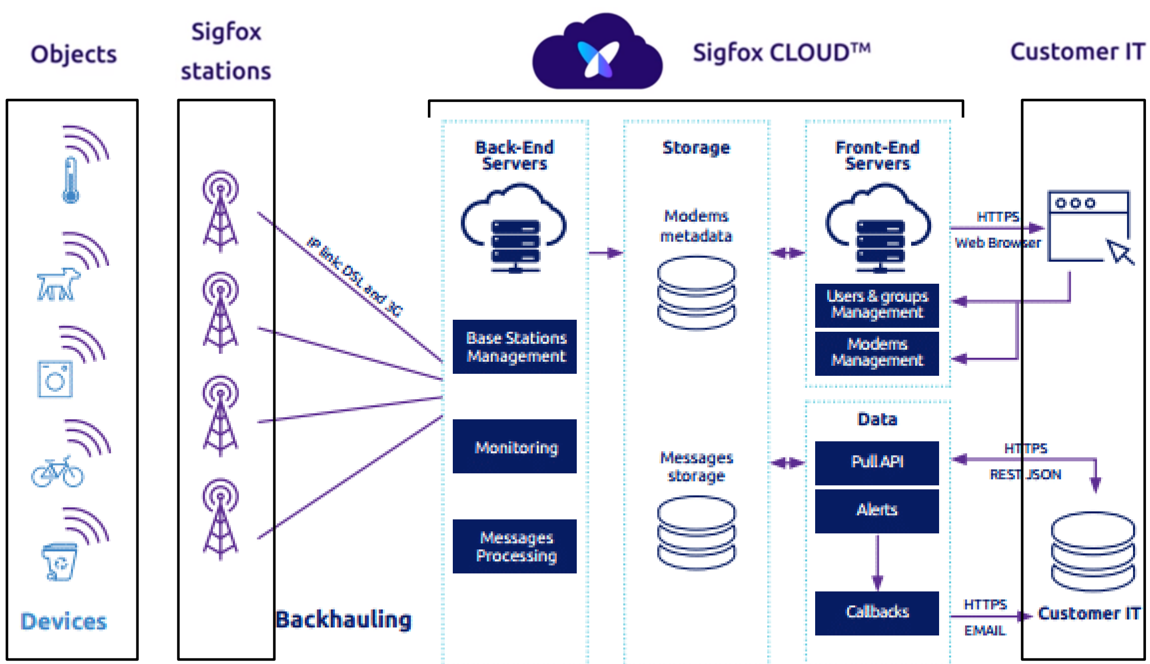
SigFox

SigFox

- **SigFox:** proprietary technology and infrastructure developed by French company SigFox
  - » **By contrast, LoRa/LoRaWAN technology can be implemented by anyone**
- Noteworthy features
  - **BS-UE 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:** message size: 0>12 bytes; 140 messages / day
  - **Downlink service:** message size: 0 - 8 bytes; 4 messages / day

SigFox Architecture

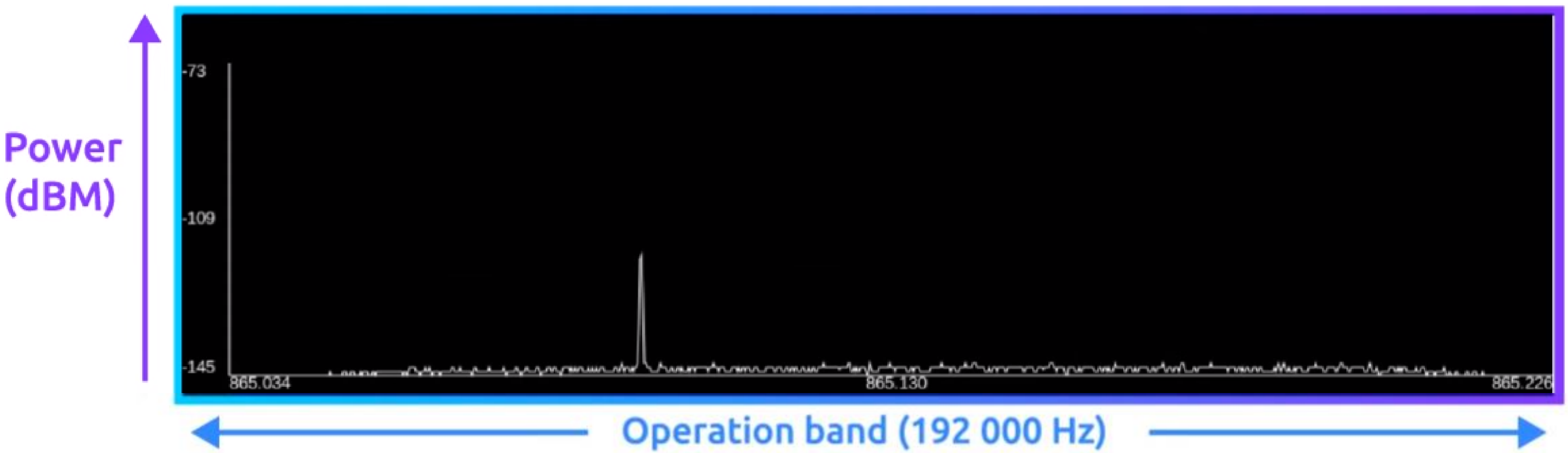
- Elements of the SigFox architecture
  - **Objects:** SigFox nodes deployed throughout area of interest
  - **SigFox base stations:** collect messages from objects and forward to the cloud
  - **SigFox Cloud:** manages the network, stores data, and provides APIs for data access
  - **Customer IT:**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



Ref.[4]

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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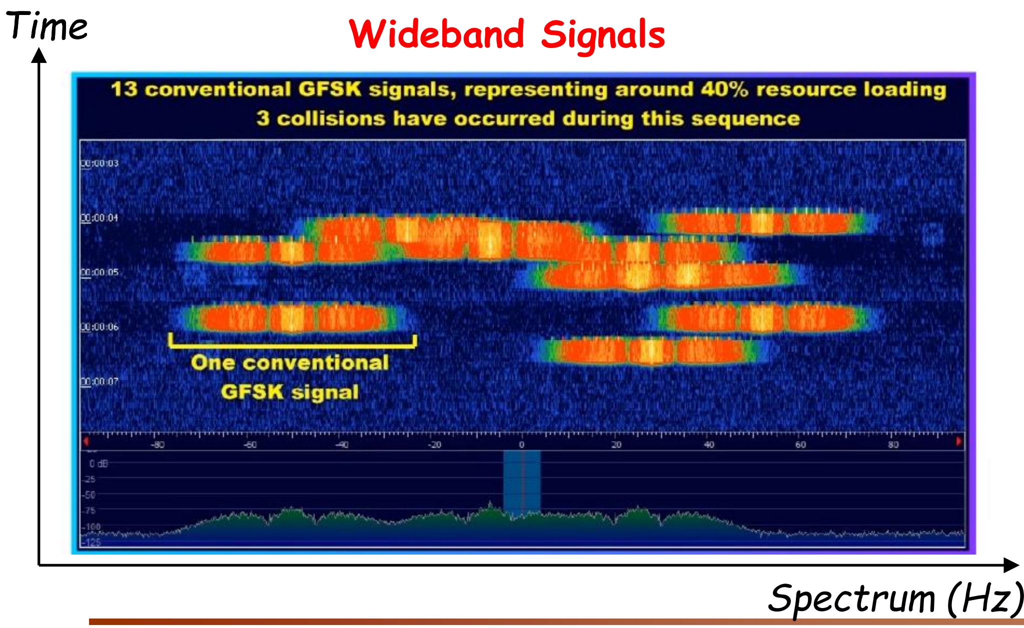
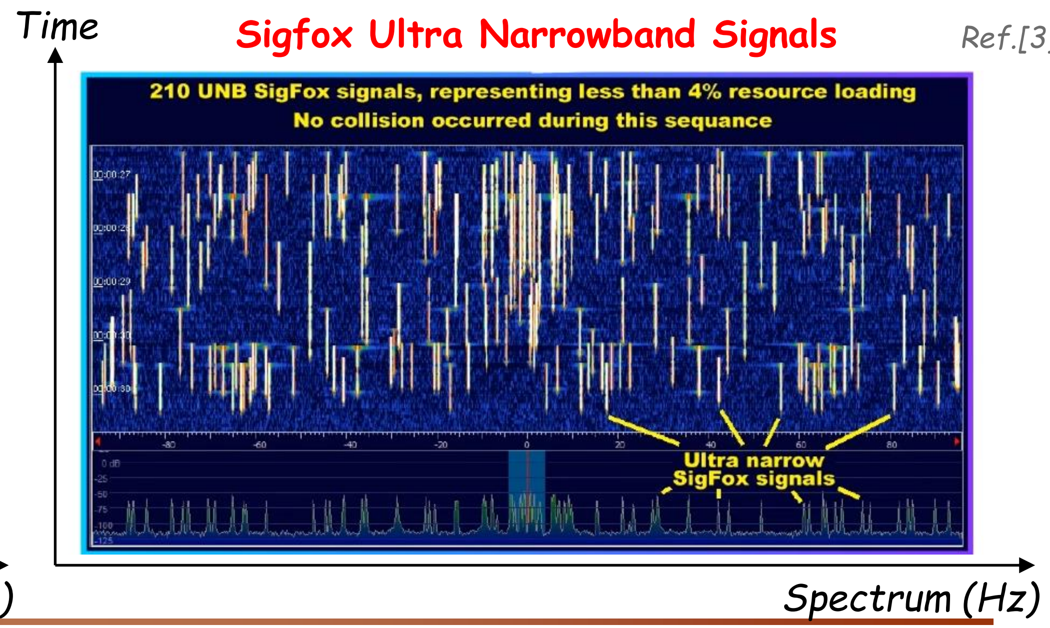
Wideband Signals



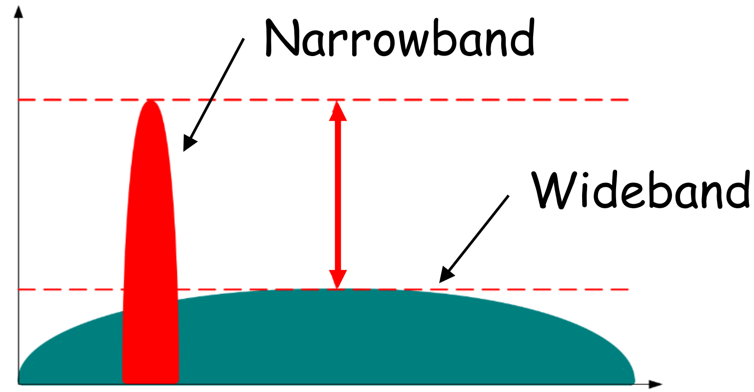
Sigfox Ultra Narrowband Signals

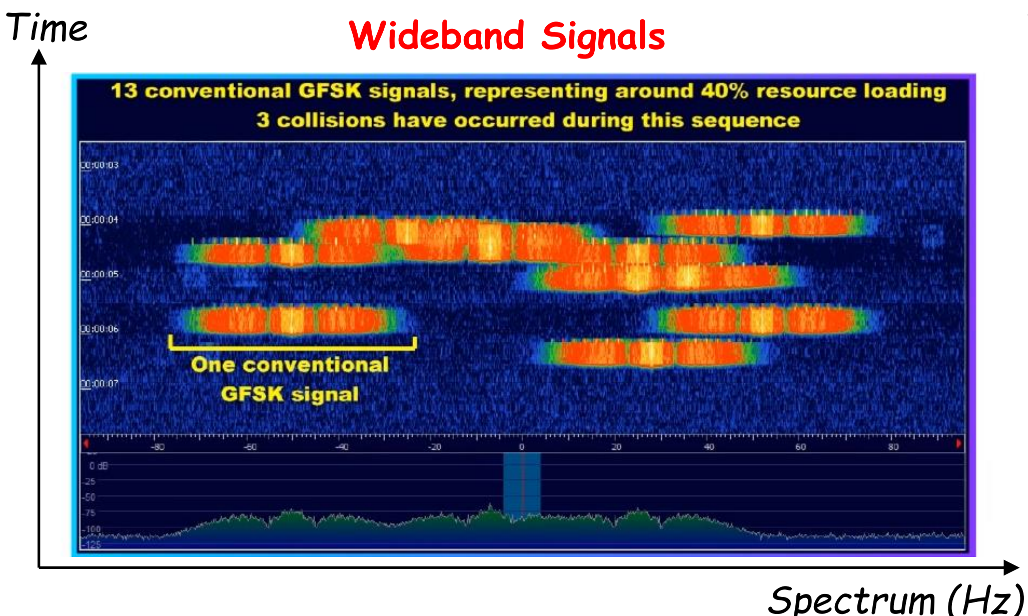
Ref.[3]

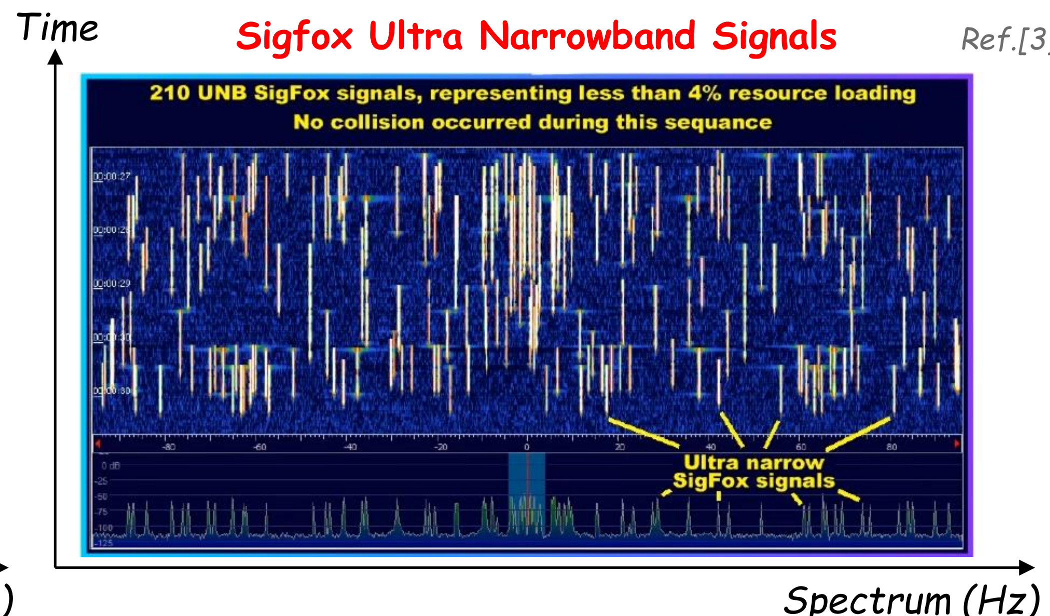


Spectrum Usage

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







Ref.[3]

A Primer on Link Budgets (1/3)

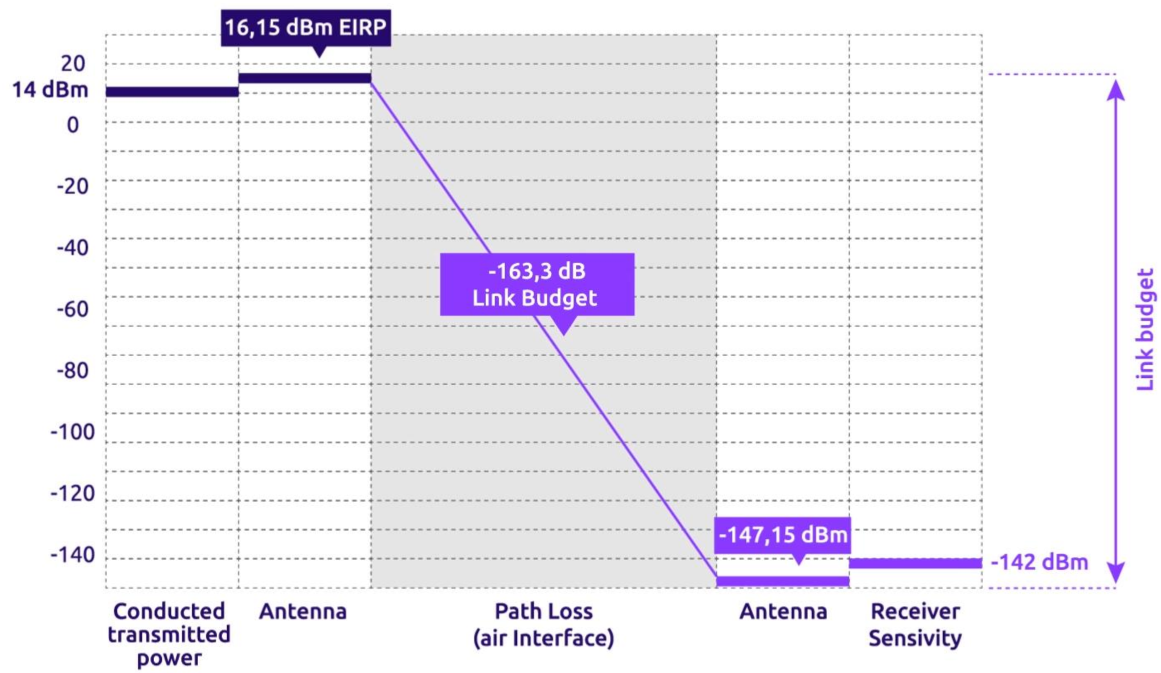
- **Link Budget:** how much attenuation can our **uplink** signal endure?
  - **Link loss** is how much the signal attenuates between transmitter and receiver
    - **Depends on distance and obstacles**
  - **Link budget** is how much attenuation your system can support and still receive the signal

- 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 (2/3)

- A particular example
  - **RX:** Base station sensitivity = -142dBm @100bps | -134dBm @600bps
    - *(Compare with WiFi module: -90dBm)*

  - **TX:** For an TX power of 16,15 dBm *(EIRP - Effective Isotropically Radiated Power)*
  - Link budget: -163,3 dB

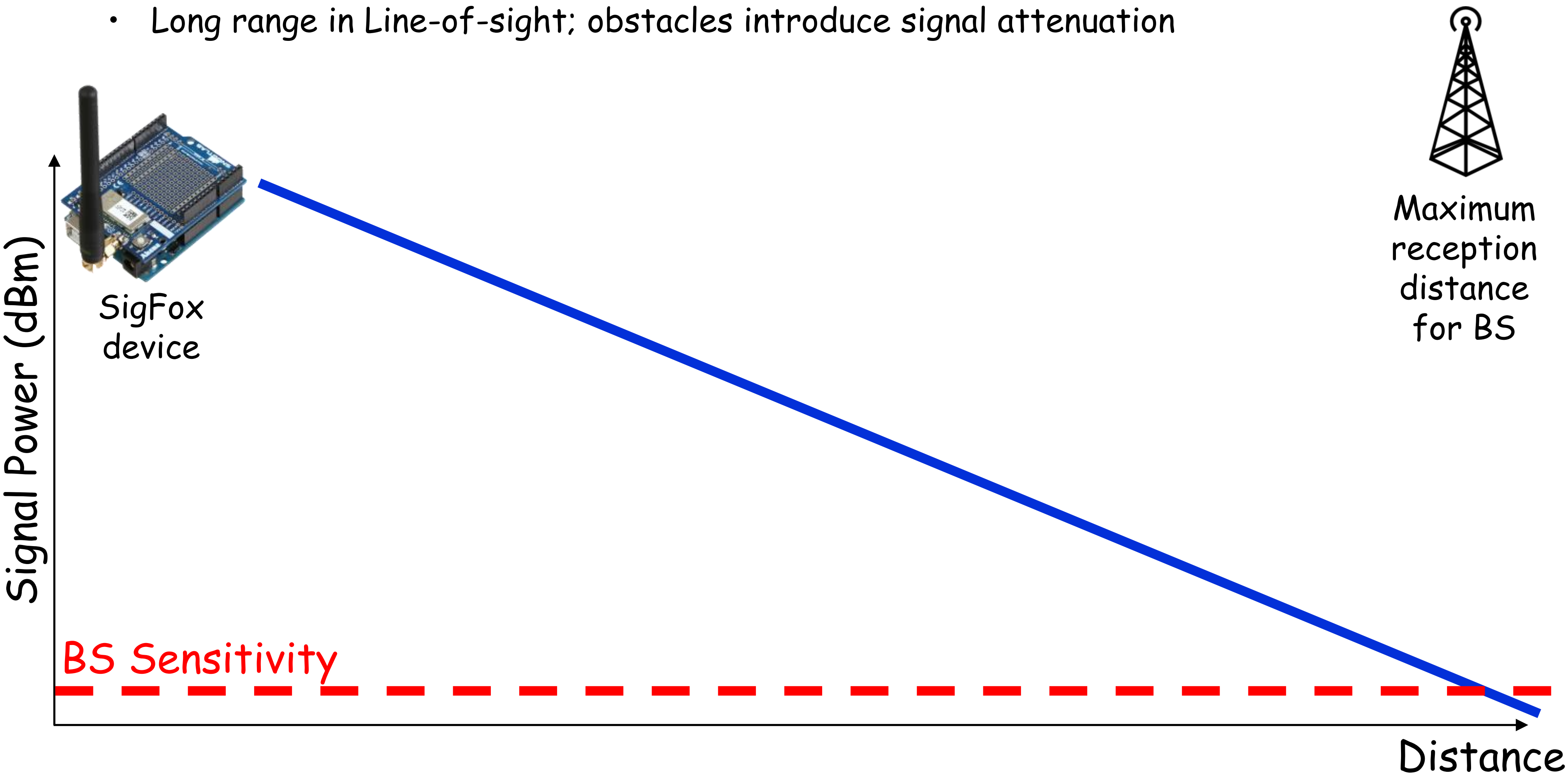


Link budget example for SigFox.
Similar math can be done for the other technologies (LoRa, NB-IoT).

Ref.[3]

A Primer on Link Budgets (3/3)

- An example with **link budget: -163,3 dB**
- Long range in Line-of-sight; obstacles introduce signal attenuation



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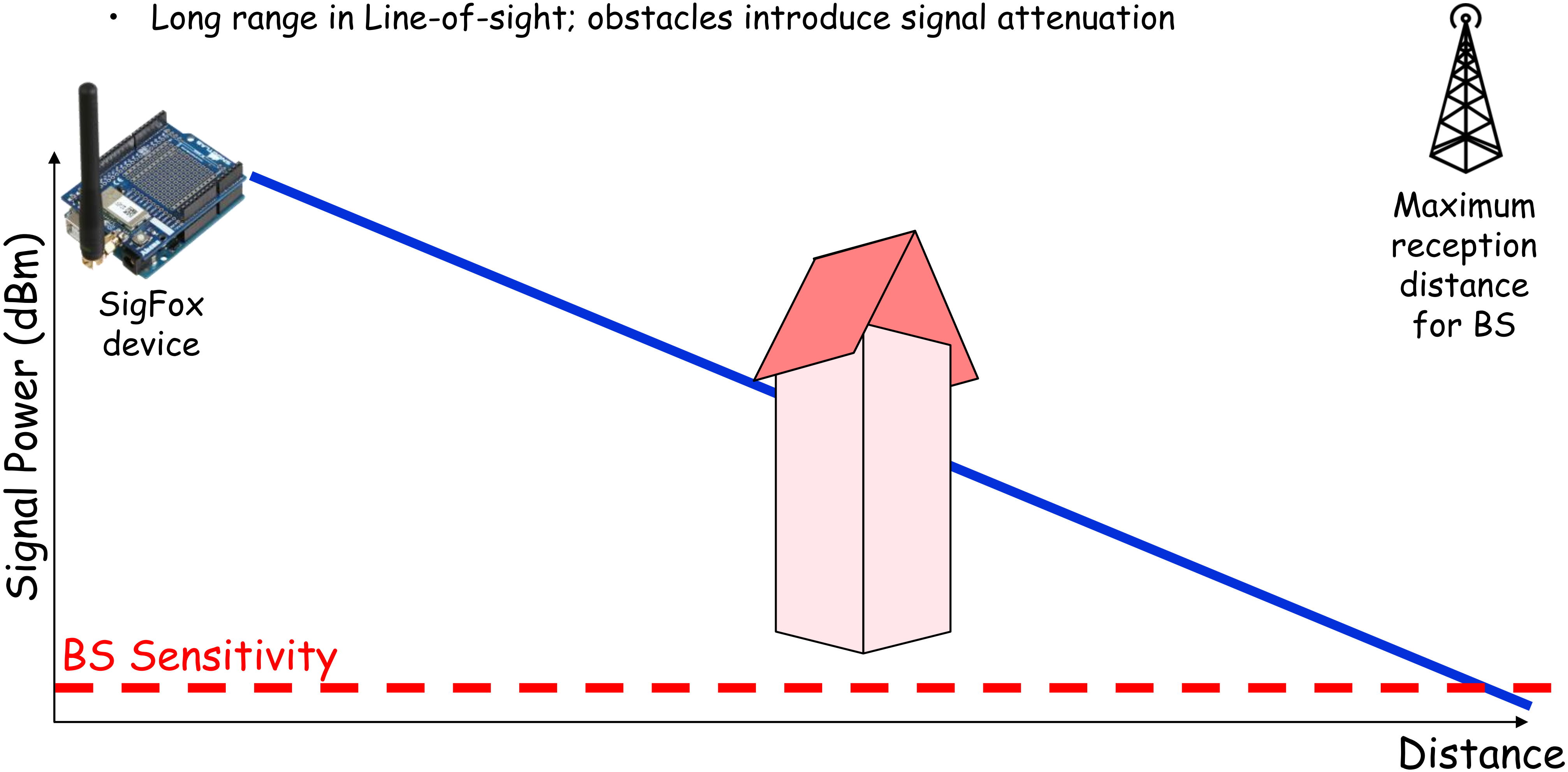

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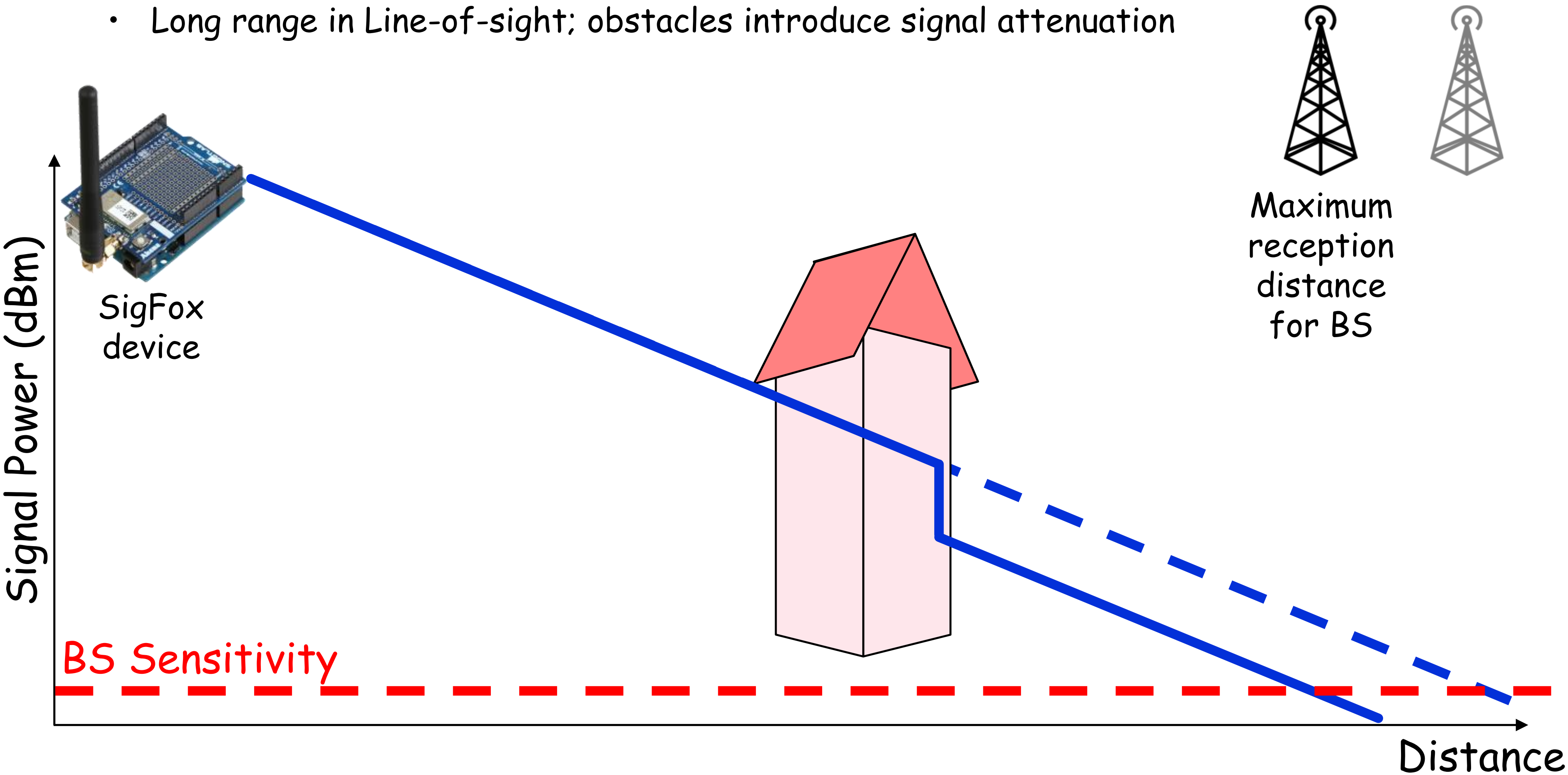

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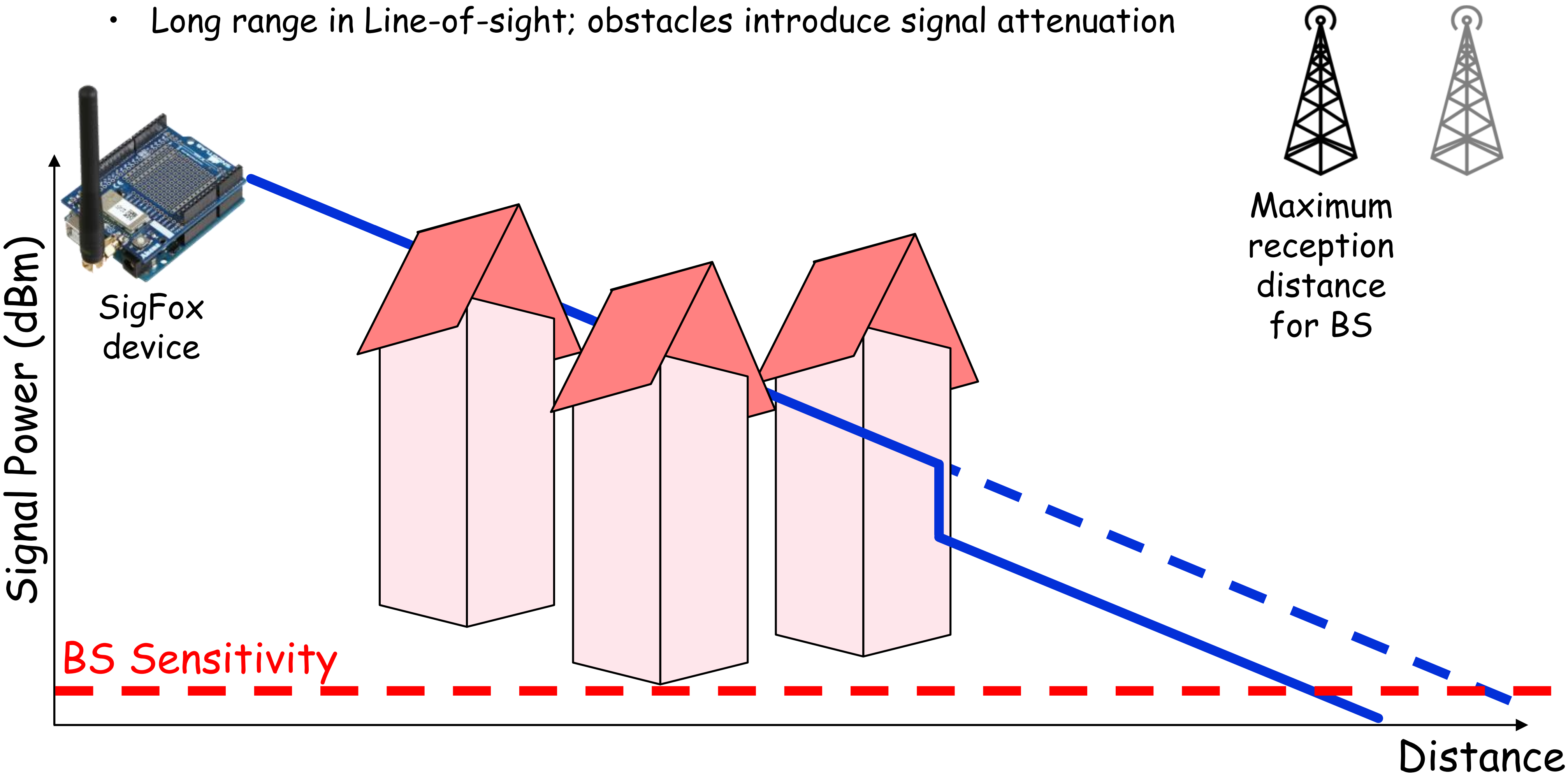

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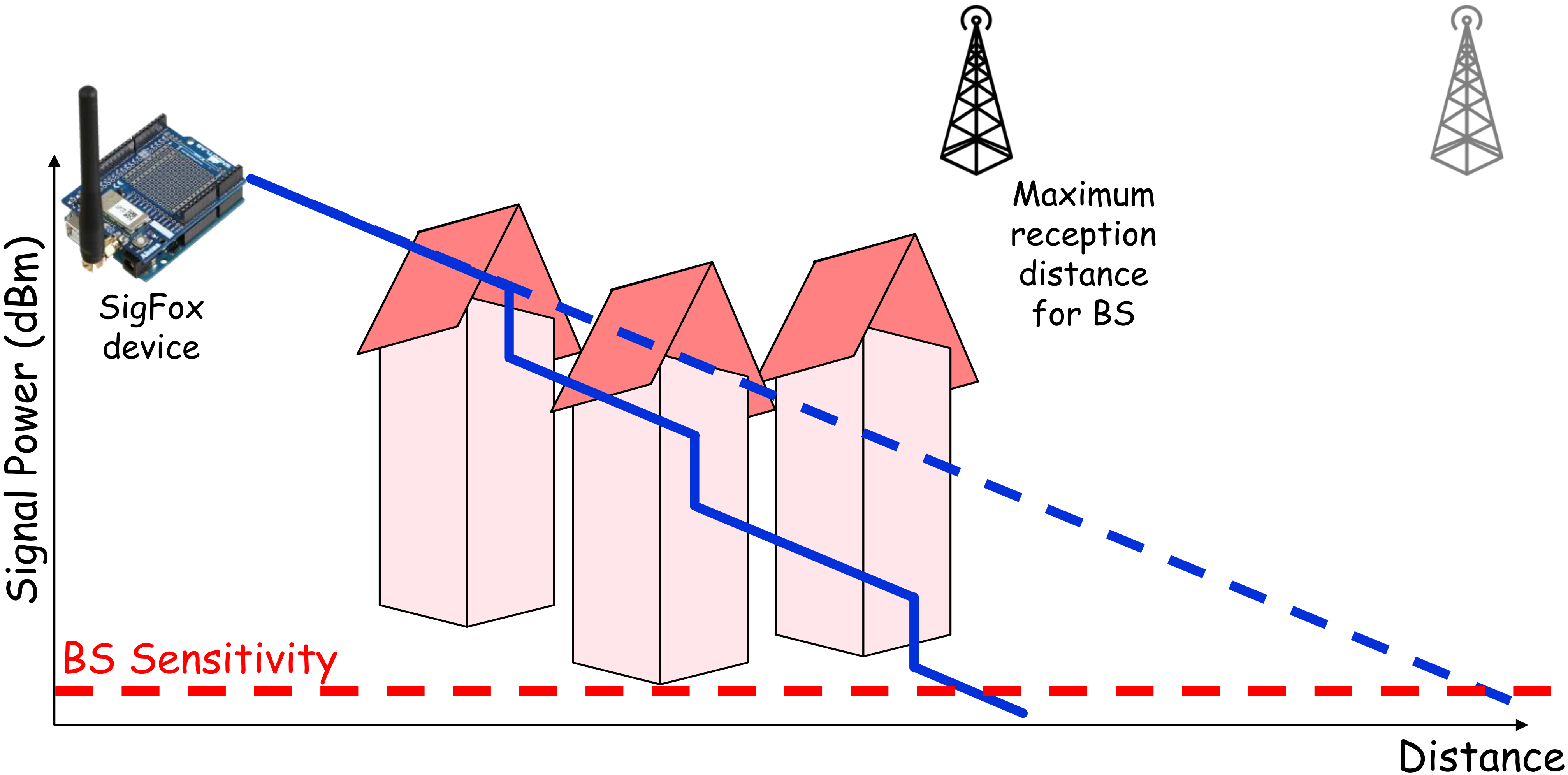


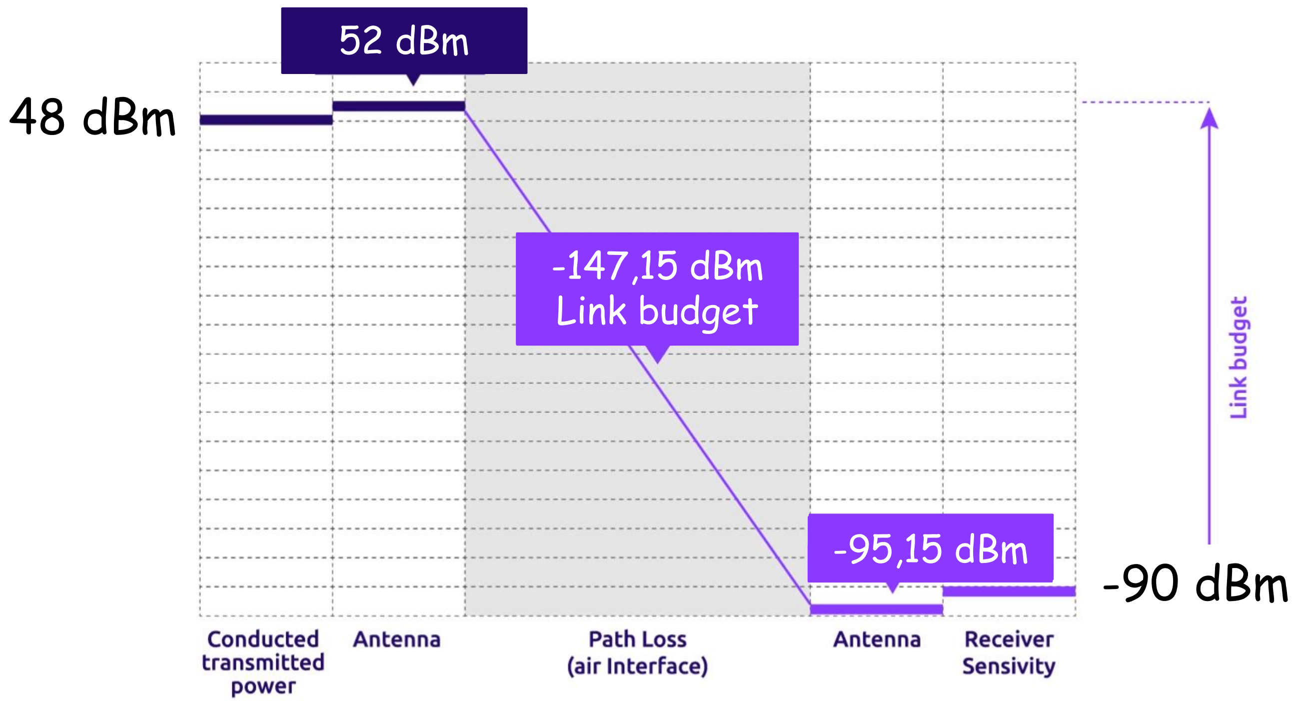
What about the downlink?

- So far we have been discussing **uplink** (device to base-station)
- The downlink also has a large link budget, but for different reasons.

But!

- **RX:** device sensitivity is much inferior! Similar to WiFi module: **-90dBm**

- **TX:** base station transmit power is much higher! → **43–48 dBm**
- Link budget also large: -147,15 dBm or more



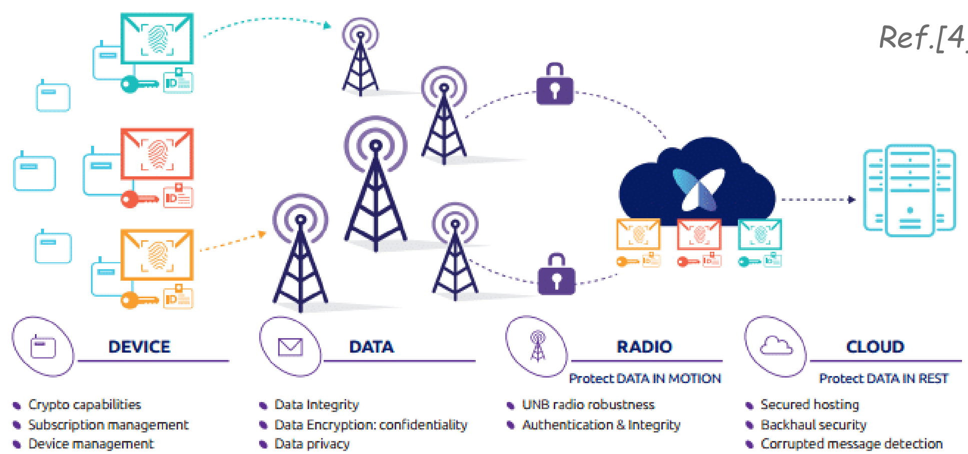
Medium Access, Messaging and Security

- 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. TCP/IP)*
  - No signaling messages (as no synchronization is required between node and BS)

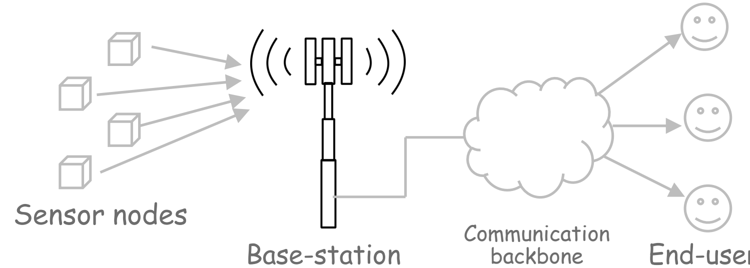
- Security
  - End-to-end authentication with shared key
  - At objects: shared key stored in ROM memory

Ref.[4]



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
    - » **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

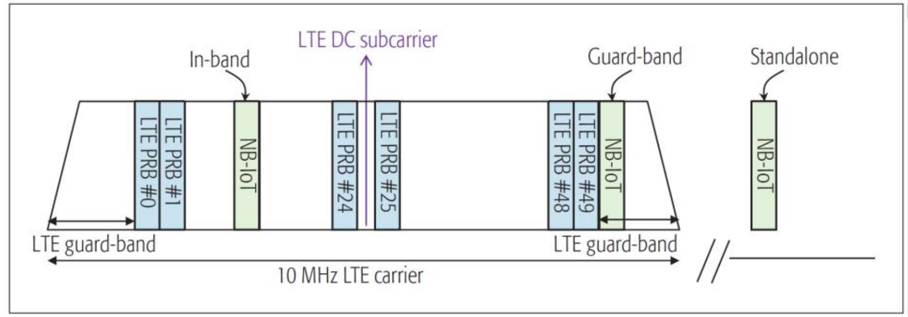


Figure 1. Examples of NB-IoT stand-alone deployment and LTE in-band and guard-band deployments.

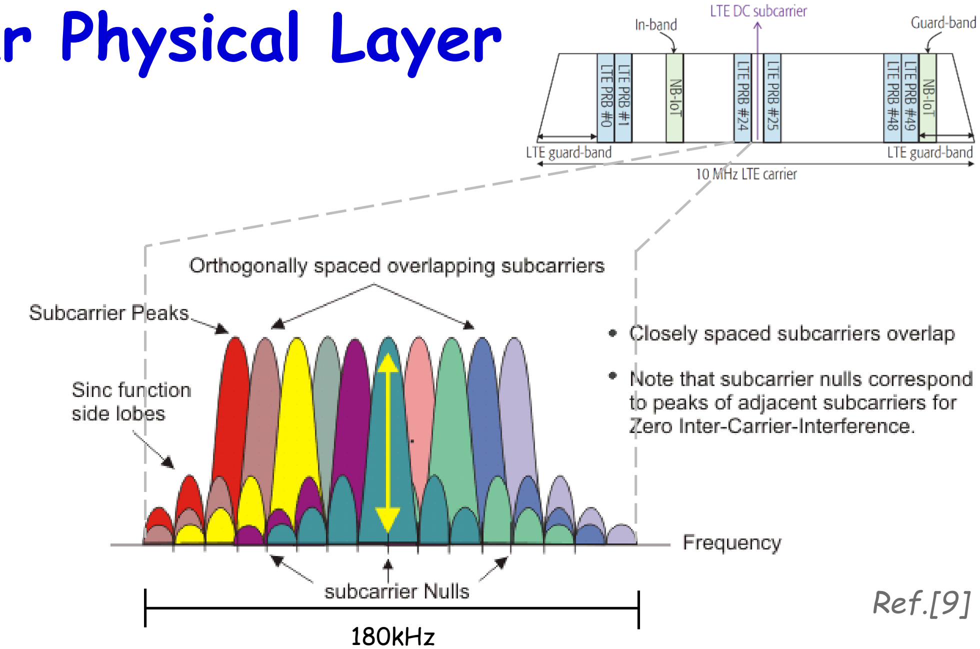
Ref.[5]

- NB-IoT was designed to be compatible with GSM and LTE
  - NB-IoT requires a bandwidth of 180 kHz for downlink and uplink
  - <u>In GSM:</u> Replace one GSM carrier (200 kHz) with NB-IoT
  - <u>In LTE:</u> 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

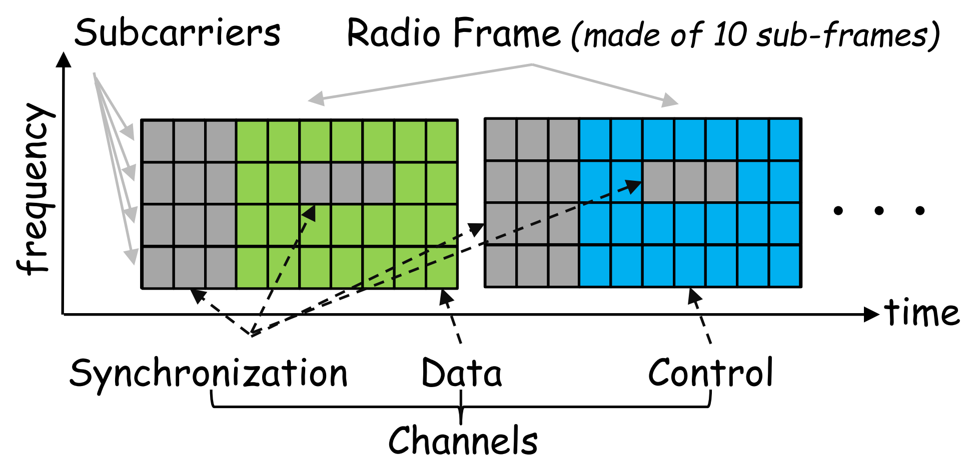
A Primer on Cellular Physical Layer

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 synchronization, control, and data
  - Channels are **logical**, 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 (unlike SigFox)

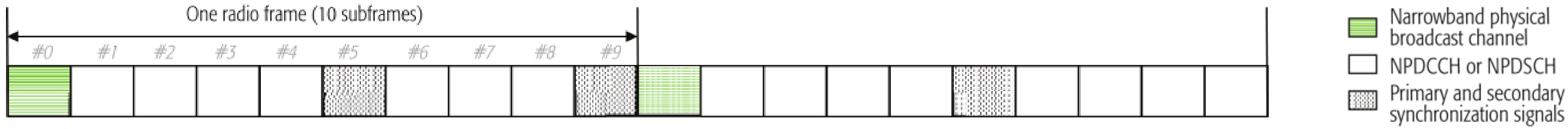


Ref.[9]



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

- Modulation: orthogonal frequency-division multiple access (OFDMA)
- Two consecutive DL frames have the following structure:

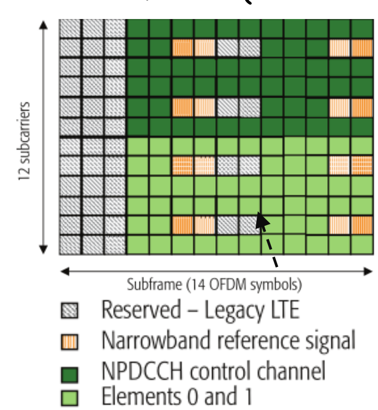


- Three channels:
  - **Synchronization** (NPSS/NSSS – *NB primary/ secondary sync. signals*)

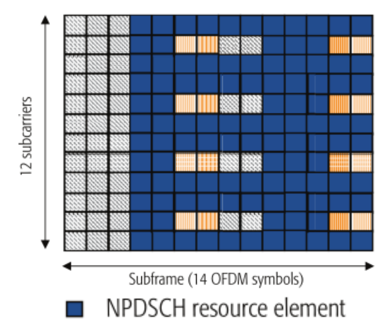
(*The following can be transmitted at any white sub-frame.*)

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

Control frame (NPSCCH)



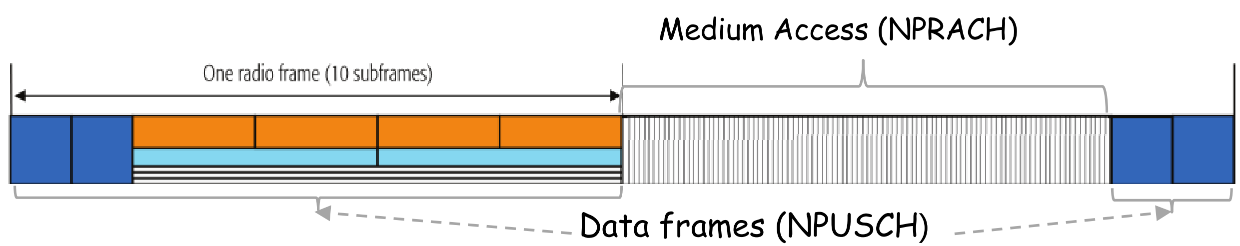
Data Frame (NPDSCH)



Ref.[6]

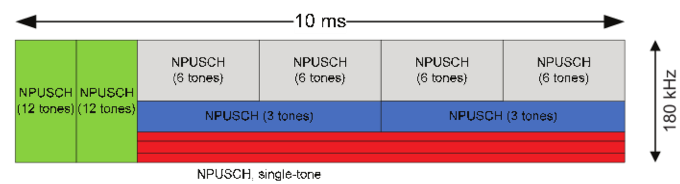
NB-IoT Physical Layer – Uplink (UE to BS)

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

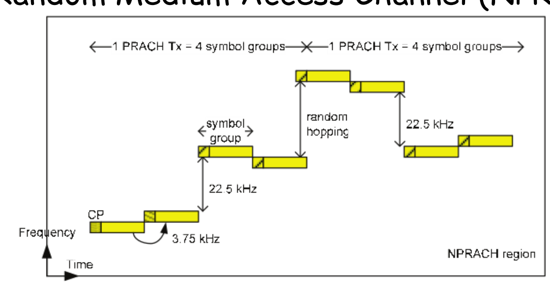


- Two channels:
  - **Data frames** (NPUSCH - *NB physical uplink shared channel*)
    - » A data package can be split per multiple sub-carriers and/or subframes
  - **Random Medium Access** (NPRACH - *NB physical random access channel*)
    - » Allows UE to request a uplink to BS by sending a random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

Data Frame (NPUSCH)



Random Medium Access Channel (NPRACH)



Ref.[6]

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

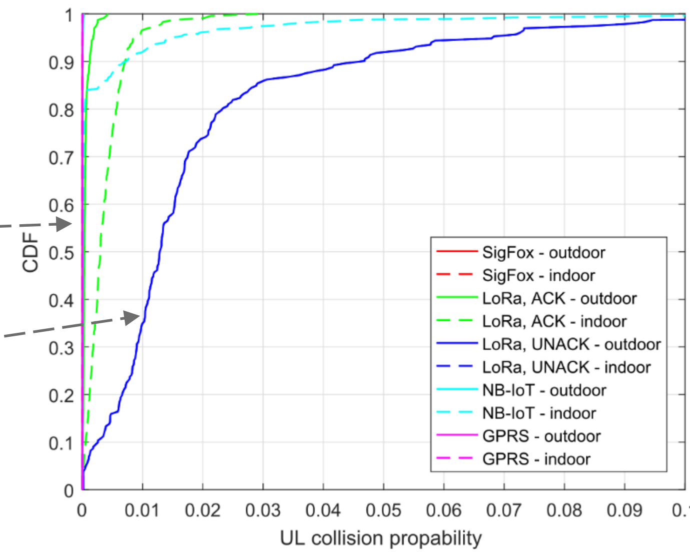


Fig. 5. CDF of the uplink collision probability due to random access failure.

- 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

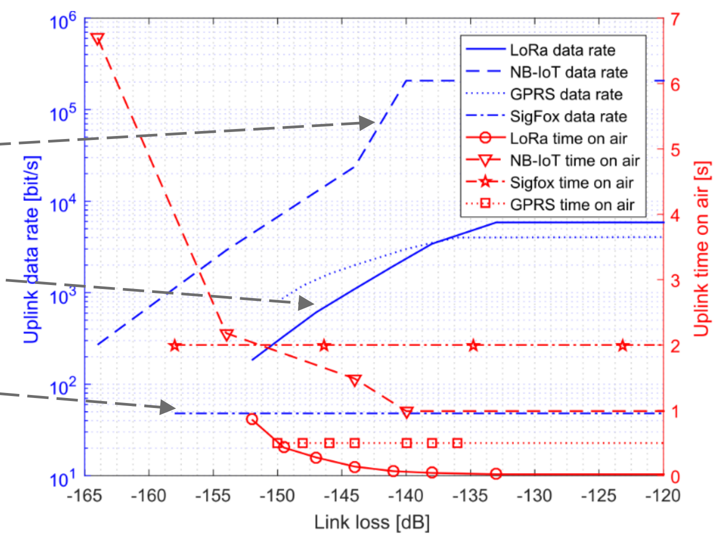


Fig. 3. Mapping curves for uplink data rate and uplink time on air as a function of link loss.

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*	0.3 to 50 kbps	12byte/pkt; 140pkt/day	10Mbit/s
	Uplink rate	0.3 to 50 kbps	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*	**Open**	**Proprietary**	**Proprietary**
	Network Service	**Open** (anyone can set up a LoRa network)	**Licensed** to national companies	**Proprietary**
	Spectrum band	**Unlicensed**	**Unlicensed**	**Licensed**

Bibliography

- **LoRa/LoRaWAN:**
  - [1] https://lora-alliance.org/
  - [2] Semtech corporation: *Application Note: AN1200.22 LoRa™ Modulation Basics*. Rev 2, May 2015.
- **SigFox:**
  - [3] https://www.sigfox.com/en
  - [4] https://www.embarcados.com.br/uma-visao-tecnica-da-rede-sigfox/
- **NB-IoT:**
  - [5] Y.-P. Eric Wang, Xingqin Lin, Ansuman Adhikary, Asbjörn Grövlen, Yutao Sui, Yufei Blankenship, Johan Bergman, and Hazhir S. Razaghi: *A Primer on 3GPP Narrowband Internet of Things*. IEEE Communications Magazine, March 2017.
  - [6] Rapeepat Ratasuk, Nitin Mangalvedhe, Yanji Zhang, Michel Robert, Jussi-Pekka Koskinen: *Overview of Narrowband IoT in LTE Rel-13*. IEEE Conference on Standards for Communications and Networking (CSCN), 2016.
  - [7] Huawei White paper on IoT: https://www.huawei.com/minisite/iot/img/nb_iot_whitepaper_en.pdf
  - [8] Vodafone: https://www.vodafone.com/business/iot/managed-iot-connectivity/nb-iot
- Other
  - [9] OFDM: http://rfmw.em.keysight.com/wireless/helpfiles/89600b/webhelp/subsystems/wlan-ofdm/content/ofdm_basicprinciplesoverview.htm
  - [10] SmartCity] https://www.itchronicles.com/news/connected-city-north-america/