Università degli Studi di Padova

MIME
Master's degree ICT Internet Multimedia Engineering

Department of Information Engineering (DEI)
Master degree on ICT for Internet and Multimedia Engineering (MIME)

Internet of Things and Smart Cities
09 – NB-IoT

Marco Giordani (marco.giordani@unipd.it)
Department of Information Engineering (DEI) – SIGNET Research Group
University of Padova – Via Gradenigo 6/B, 35131, Padova (Italy)

NB-IoT

Introduction

- <u>Idea</u>: use cellular networks for IoT.
  - Presence of ubiquitout public wireless infrastructure (good <u>reuse</u>).
  - Provides good features for IoT: localization, flexibility (5G), slicing and virtualization, …
  - Attention being paid on higher and higher bitrates, which is not compatible with IoT.
- There are two options:
  1. **Adapting** existing cellular solutions (3G, 4G, etc.) for IoT via **new user profiles**.
     - Use the cellular network “as it is” with limited investmnets.
     - Radio protocols remain inefficient (e.g., from a power consumption point of view).
  2. **Specifically-designed** cellular-based solution for IoT.
     - For example: Extended coverage GSM; LTE-M, **NB-IoT**.
     - NB-IoT can work based on both 4G-LTE and 5G-NR, and is the most promising solution.

NB-IoT

Overview

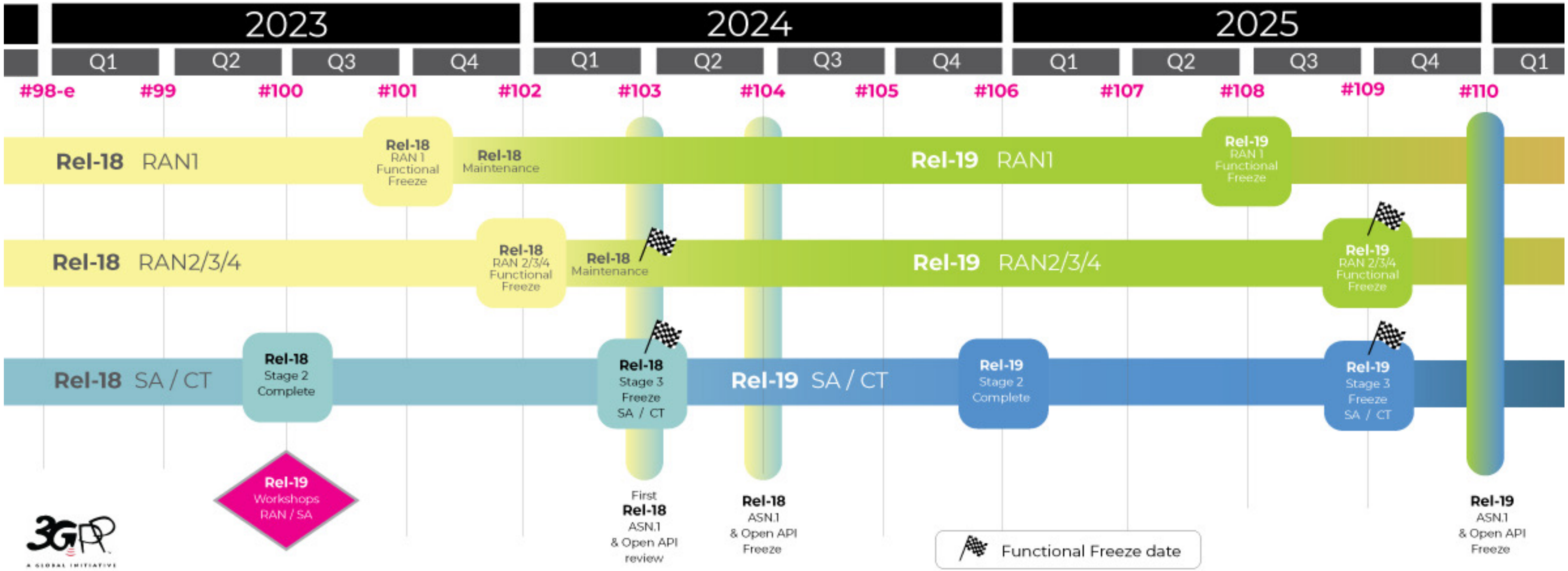
- NB-IoT → NarrowBand IoT.
- Standardized by the **3GPP** (that typically addresses cellular mobile standards).
- Target low complexity and small resource (power and spectrum) usage.
- Based on the design principles of **4G-LTE**.
  - Still, it is not compatible with LTE: an NB-IoT radio access is provided with its own control signals and radio channels.

https://www.3gpp.org

A GLOBAL INITIATIVE

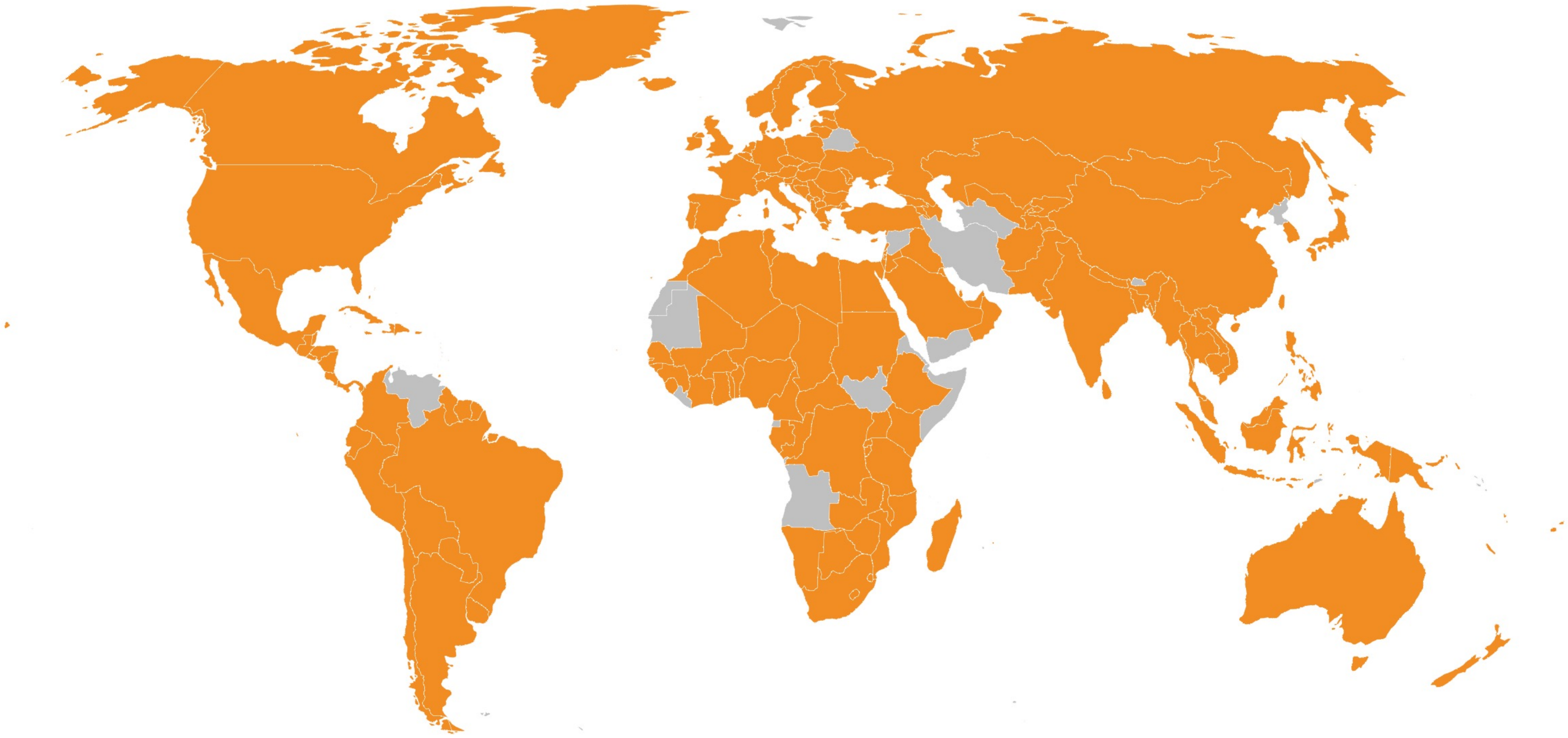
NB-IoT

Overview (5G standardization)



NB-IoT

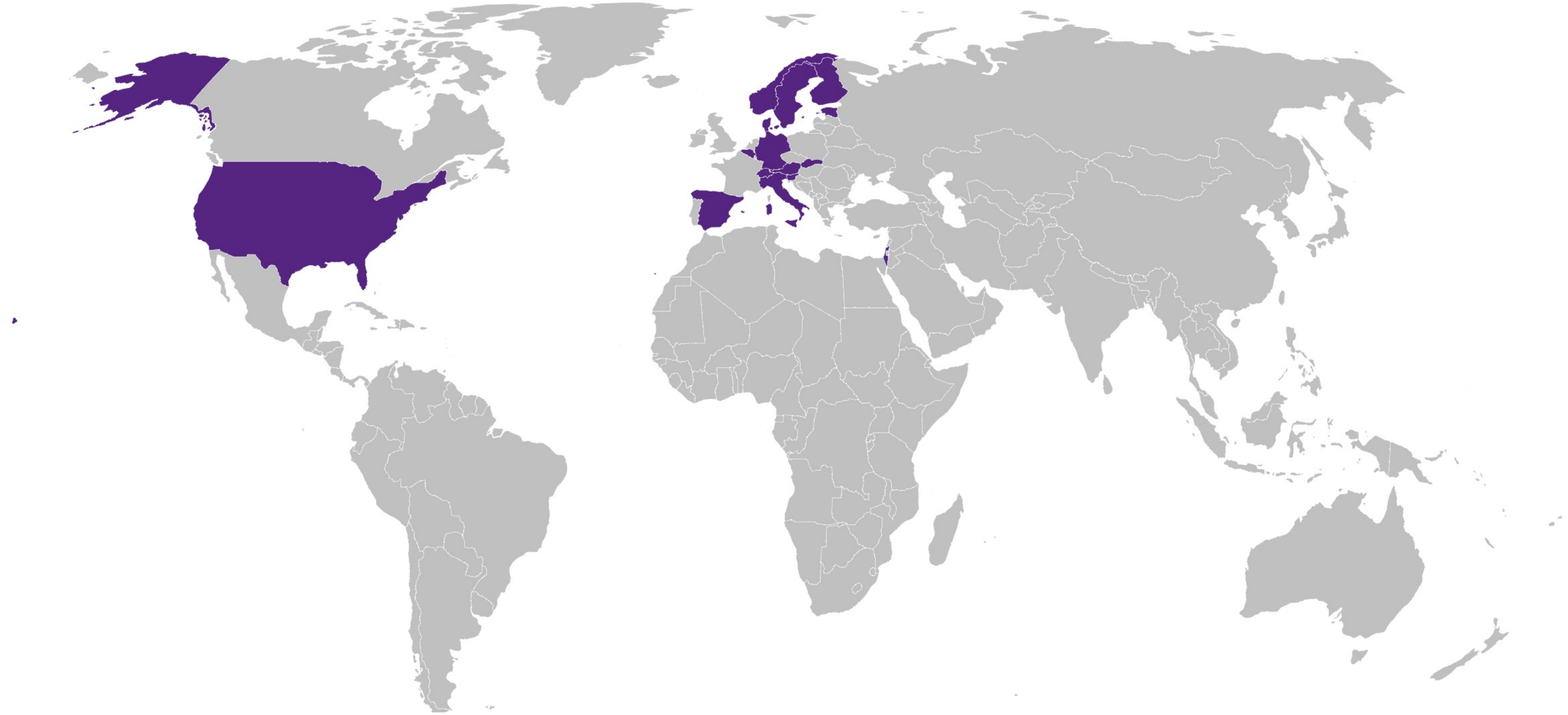
Coverage (4G)



https://velosiot.com/interactive-ultimate-global-iot-coverage/

NB-IoT

Coverage (NB-IoT)



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NB-IoT

Applications

- **Smart agriculture**
  - Soil and environmental data collection: https://shorturl.at/NzoJZ
- **Healthcare monitoring**
  - Remote monitoring devices to transmit vital health data in real-time:
- **Retail**
  - Manage inventory, enhance customer experiences, and ensure asset security.
- **Public safety**
- **Supply chain and logistics**
- **Energy management**
  - Smart meters to obtain real-time data on electricity consumption, enhancing efficiency and reducing waste: https://shorturl.at/Olwyr

NB-IoT

LTE frequency bands
https://en.wikipedia.org/wiki/LTE_frequency_bands

Frequency range

- 3GPP has defined a set of frequency bands for which NB-IoT can be used.
- Use the same frequency bands as in LTE, **with a subset defined for NB-IoT**.
  - Generally in the **lower range** of existing LTE bands, to increase the range.
- **Licensed** bands (vs. unlicensed in LoRa).

Region	LTE bands
EU	3, 8, 20
Commonwealth of Independent States	3, 8, 20
North America	2, 4, 5, 12, 66, 71, 26
Asia Pacific	1, 3, 5, 8, 18, 20, 26, 28
Sub-Saharan Africa	3, 8
Middle East and North America	8, 20
Latin America	2, 3, 5, 28

NB-IoT

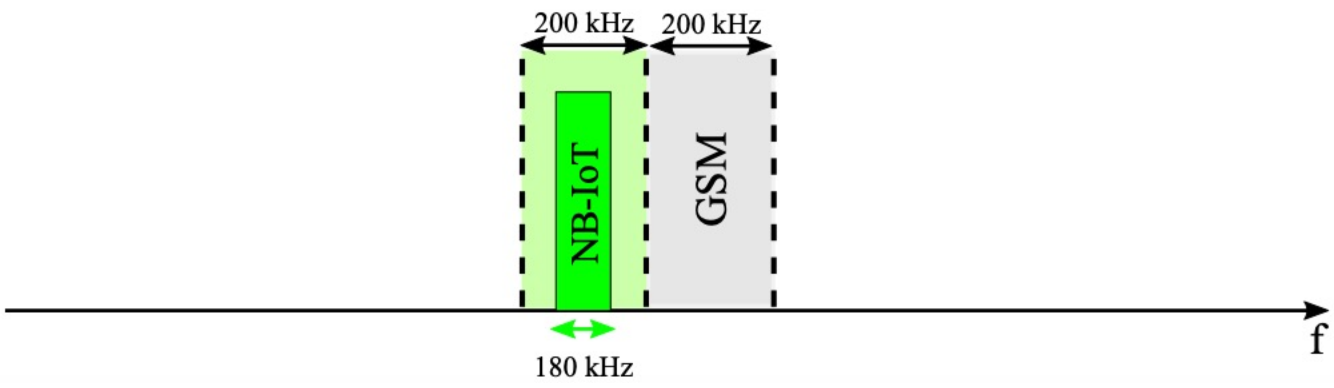
Frequency range (Europe)

NB-IoT band	Uplink band	Downlink band	Bandwidth	Duplex mode
3	1710 - 1785 MHz	1805 - 1880 MHz	75 MHz	HD-FDD
8	880 - 915 MHz	925 - 960 MHz	25 MHz	HD-FDD
20	832 - 862 MHz	791 - 821 MHz	30 MHz	HD-FDD

NB-IoT

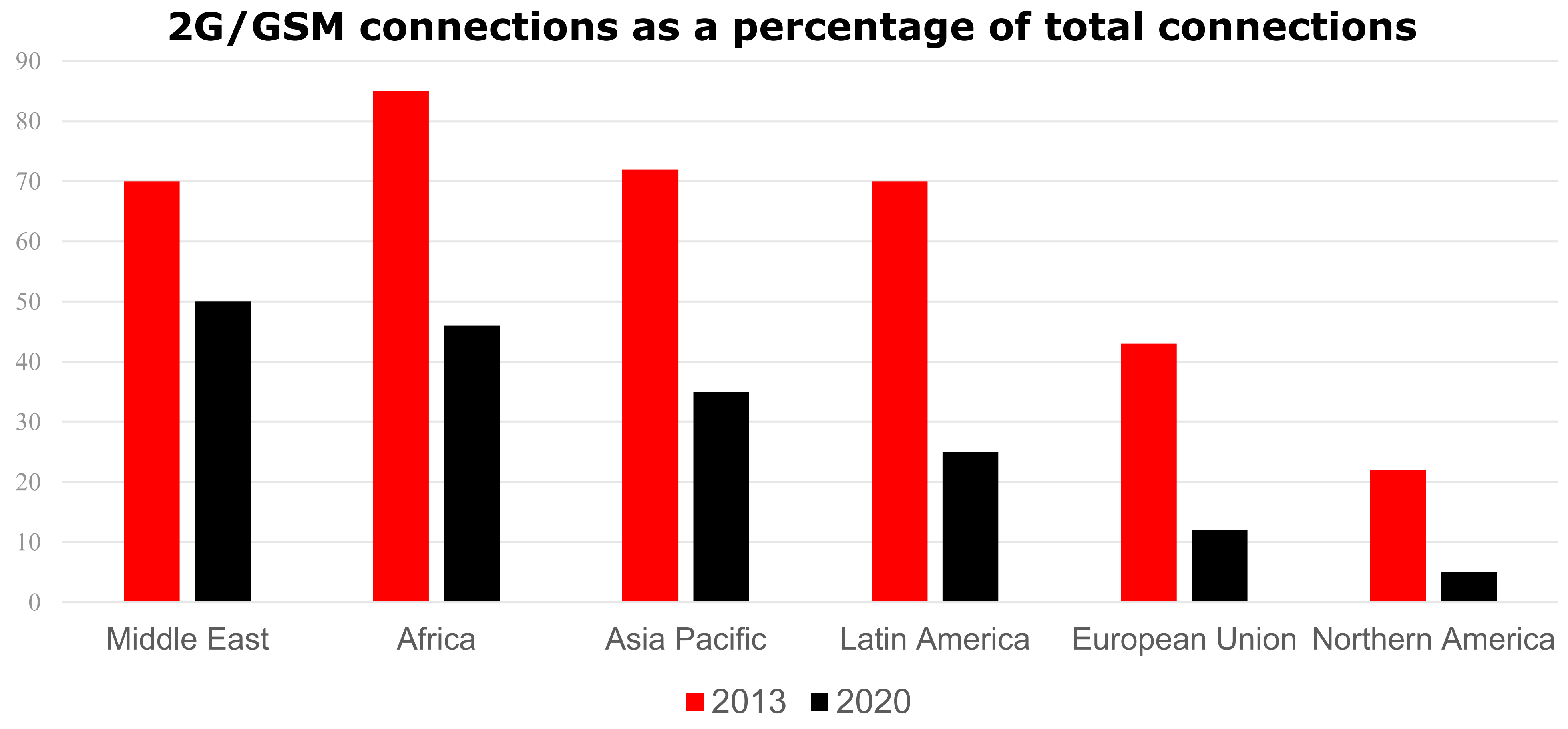
Operation modes

- **Standalone**: the NB-IoT signal is intended to occupy the liberated spectrum of the global system for mobile communications (GSM) system.
  - The NB-IoT signal still occupies **180 kHz** from the 200 kHz GSM carrier, with 10 kHz of band-guard on both sides of the spectrum.
  - Dedicated spectrum, without competing with regular mobile broadband services.
  - Suitable for areas where there is no existing cellular network (refarming of GSM).



NB-IoT

Operation modes

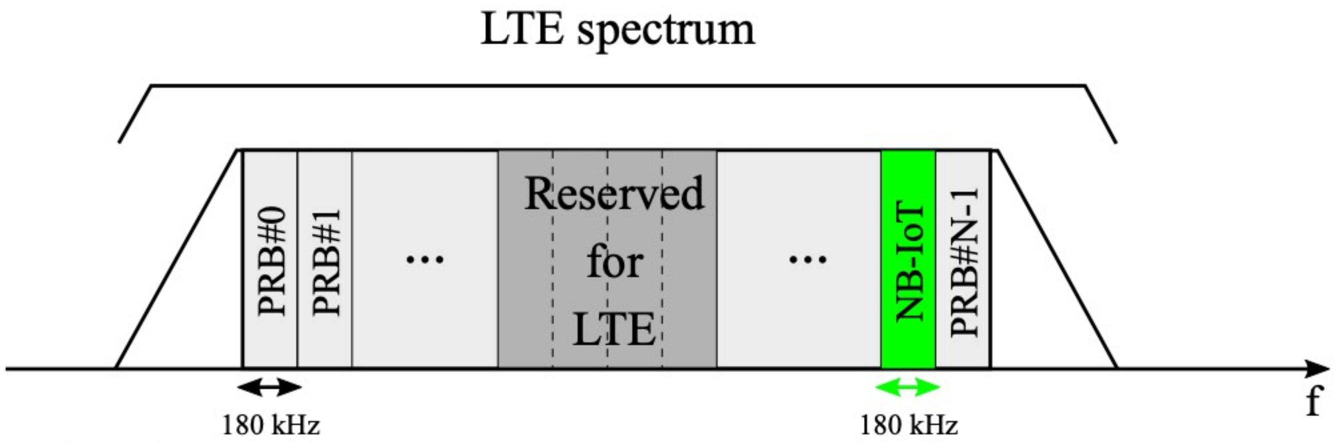


https://www.gsma.com/connectivity-for-good/spectrum/wp-content/uploads/2017/11/10-Day-2-Session-3-How-to-Implement-Spectrum-Refarming-Shola-Sanni.pdf

NB-IoT

Operation modes

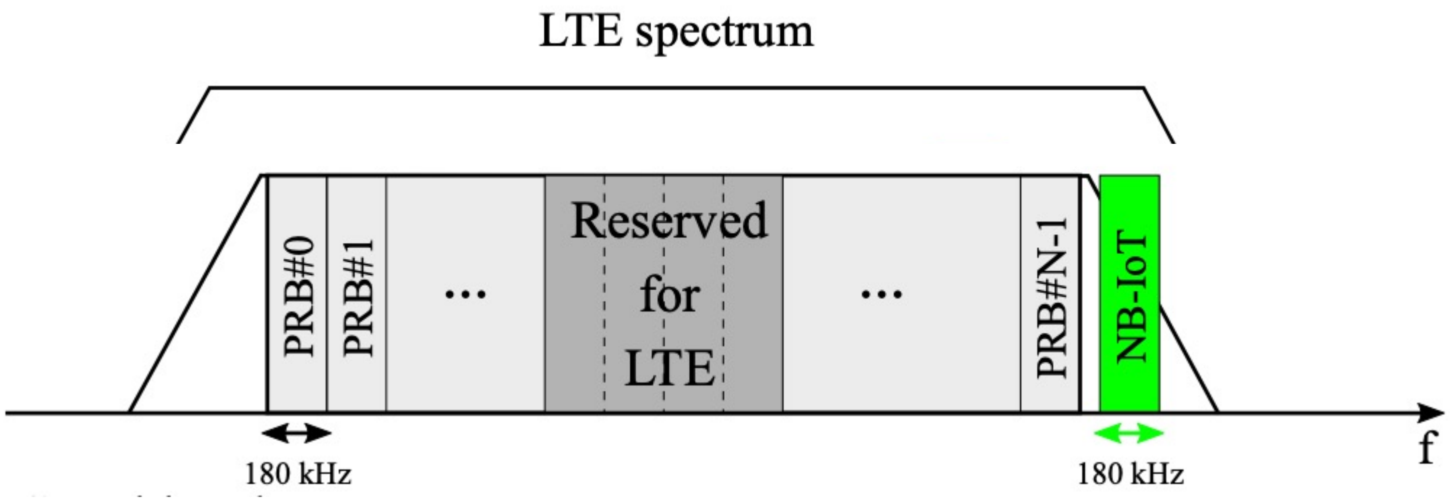
- **In-band**: the NB-IoT signal occupies one 180-KHz PRB from the LTE bandwidth.
  - It is the most privileged mode due to the benefits in terms of cost savings and ease of integration over the legacy LTE networks.
  - The NB-IoT anchor carrier can take **only a predefined set of possible PRBs to avoid overlapping with LTE transmissions** (especially essential channels and signals, such as the physical broadcast channel and the synchronization signals).



NB-IoT

Operation modes

- **Guard-band:** the NB-IoT signal occupies one PRB from the unused guard band PRBs of the LTE bandwidth.
  - This means that NB-IoT does not take away resources from the primary LTE service, allowing it to **coexist without impacting LTE performance**.

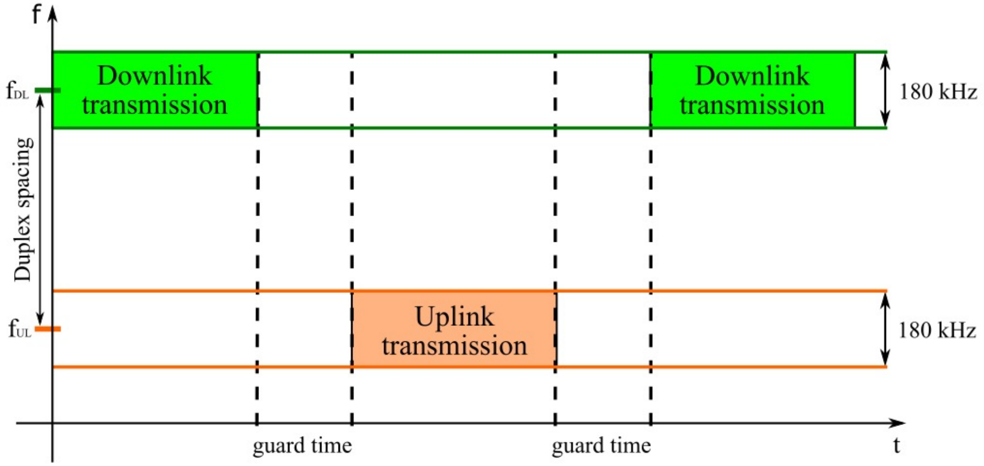


NB-IoT

PHY Layer

- Same design principles than for LTE:
  - **Orthogonal Frequency Division Multiple Access (OFDMA)**.
  - QPSK or BPSK modulation.
  - Maximum transport block size (TBS): 680 bits in downlink; 1000 bits in uplink.
  - Transmit power of 23 dBm.
  - **FDD** mode only + **half-duplex** (UE can either transmit or receive).

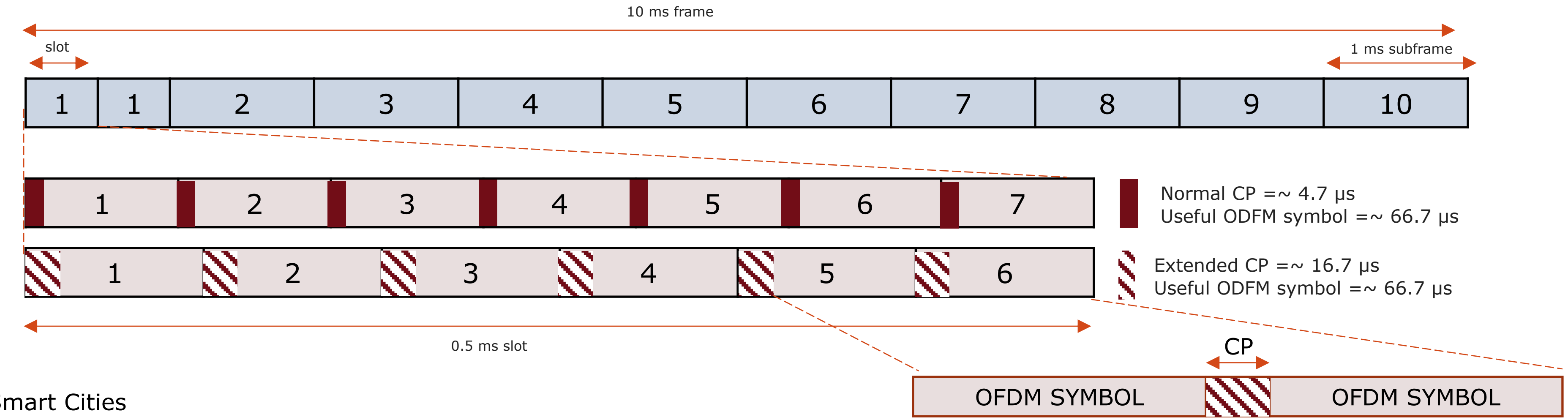
Kanj, Matthieu, Vincent Savaux, and Mathieu Le Guen. "A tutorial on NB-IoT physical layer design." *IEEE Communications Surveys & Tutorials* 22.4 (2020): 2408-2446.



NB-IoT

Frame structure

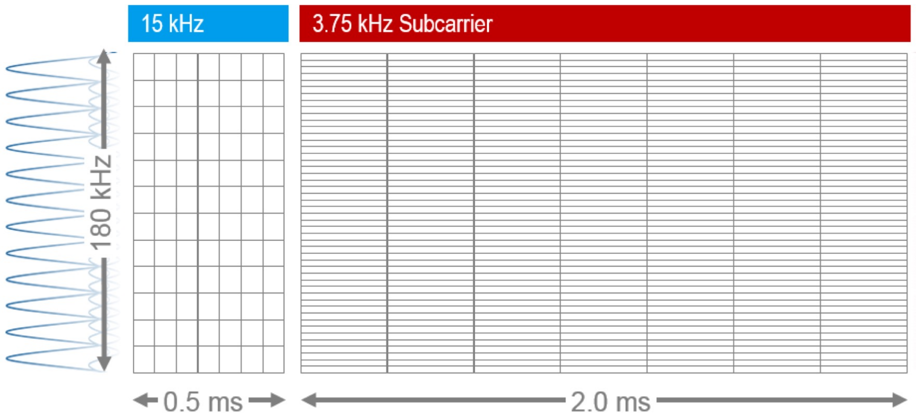
- Time: fixed slot duration of **10 ms**
  - Within each frame, 10 subframes of 1 ms.
  - Within each subframe, 2 slots of 0.5 ms.
  - Within each slot, 7 (normal CP) or 6 (extended CP) OFDM symbols
- Frequency: **Physical Resource Blocks (PRB)** of 12 subcarriers.
  - Subcarrier spacing of 15 kHz: the PRB has a bandwidth of 12*15= **180 kHz**.



NB-IoT

Frame structure

- In **uplink**, NB-IoT supports allocating one or more of the 12 subcarriers (aka **tones**) of a single PRB to different UEs.
  - **Multi-tone transmission**: SC-FDMA with 15 kHz subcarrier spacing and 0.5 ms slot. It increases data rates and reduces transmission delays and power consumption.
    - Multi-tone (3 tones, 6 tones, and 12 tones).
  - **Single-tone transmission**: 15 kHz (0.5 ms slot) or 3.75 kHz (2 ms slot).
    - With 3.75 kHz, we have 48 (vs. 12) subcarrier within the 180-KHz PRB.



Narrowband Internet of Things Measurements: Application Note
https://scdn.rohde-schwarz.com/ur/pws/dl_downloads/dl_application/application_notes/1ma296/1MA296_2e_NB-IoT_Measurements.pdf

Frame structure

- NB-IoT defines a new **uplink** resource mapping via **Resource Unit (RU)**.
- RU is a combination of a number of subcarriers (in the frequency domain) and a number of slots (in the time domain).
- RU can take several different types of **configurations**.

<table>
<tr><th>Subcarrier spacing</th><th># tones in RU (subcarriers)</th><th># slots in RU</th><th># symbols in slot</th><th>Slot duration</th><th>RU duration</th></tr>
<tr><td>3.75 KHz</td><td>1</td><td>16</td><td rowspan="6">7
normal CP</td><td>2 ms</td><td>32 ms</td></tr>
<tr><td rowspan="5">15 KHz</td><td>1</td><td>16</td><td rowspan="5">0.5 ms</td><td>8 ms</td></tr>
<tr><td>3</td><td>8</td><td>4 ms</td></tr>
<tr><td>6</td><td>4</td><td>2 ms</td></tr>
<tr><td>12</td><td>2</td><td>1 ms</td></tr>
</table>

NB-IoT

Frame structure

Subcarrier spacing	# tones in RU (subcarriers)	# slots in RU	# symbols in slot	Slot duration	RU duration
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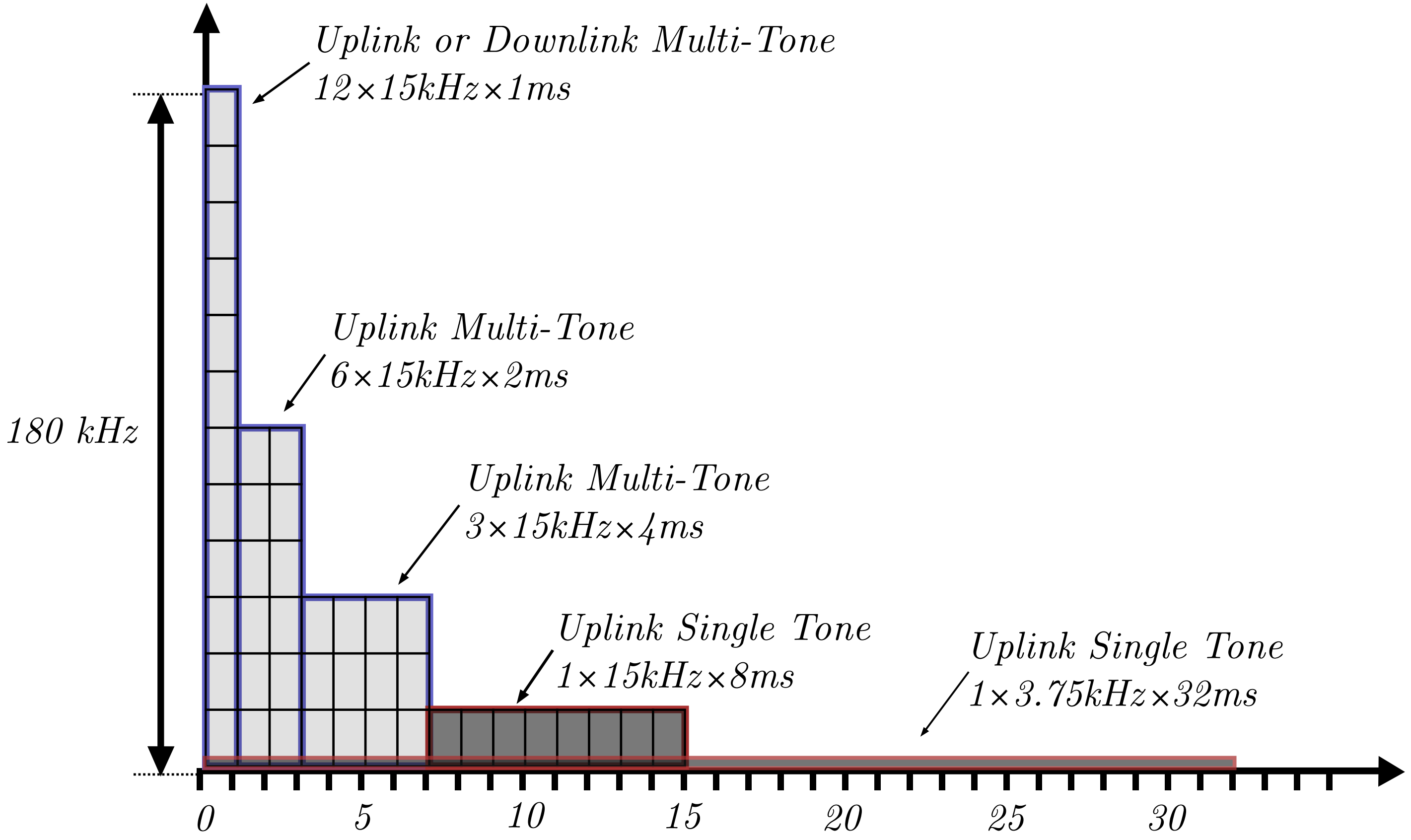
Possible RU configuration options



Matz, Andreas Philipp, et al. "A systematic analysis of narrowband IoT quality of service." Sensors 20.6 (2020): 1636.

NB-IoT

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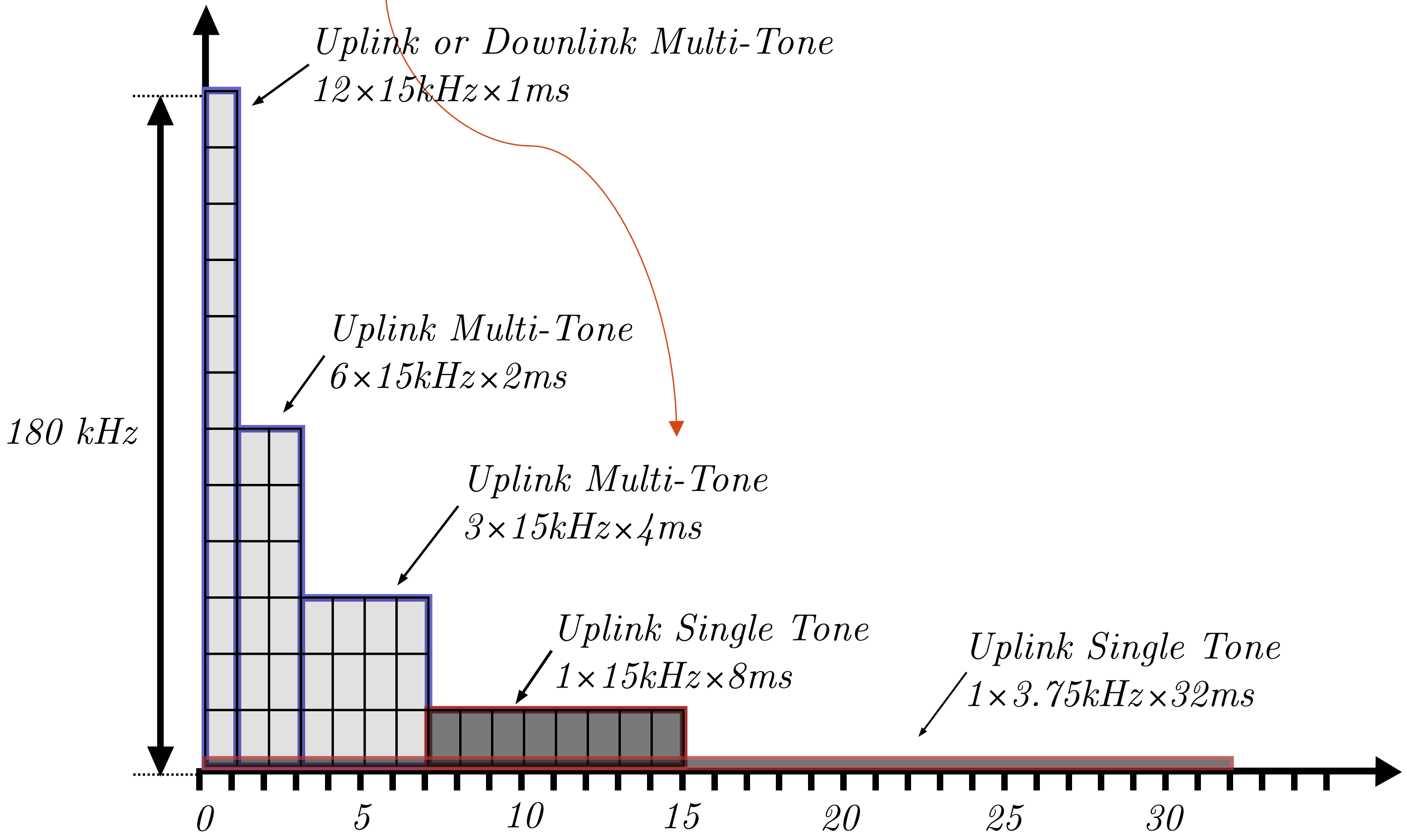
Possible RU configuration options



Matz, Andreas Philipp, et al. "A systematic analysis of narrowband IoT quality of service." Sensors 20.6 (2020): 1636.

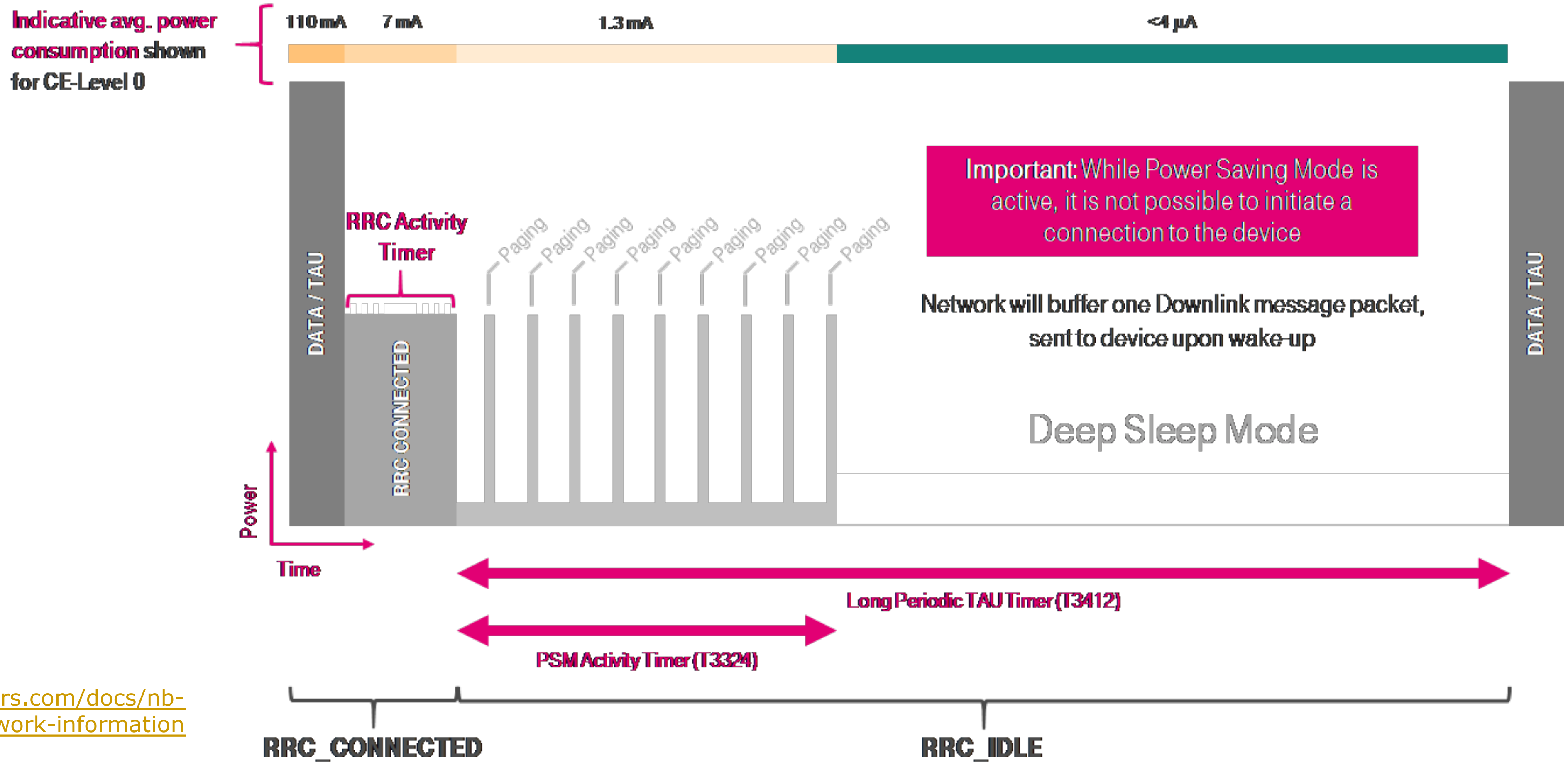
NB-IoT

MAC Layer

- **Power-Saving Mode (PSM)**: It helps conserve battery power.
- Disable parts of the protocol stack and drop power consumption into the micro-Ampere range **while remaining attached to the network** (no reconnection).
  - PSM Activity Timer: Time during which the device remains in Idle Mode.
  - Long-Periodic TAU Timer: Time between two Tracking Area Updates.
- During the deep-sleep mode, the network retains the state information and the IoT device remains registered with the network.
- If a device awakes before the expiration of the time interval to send data, a reattach procedure is not required, and energy is saved.

NB-IoT

MAC Layer



https://docs.iotcreators.com/docs/nb-iot-network-information

NB-IoT

MAC Layer

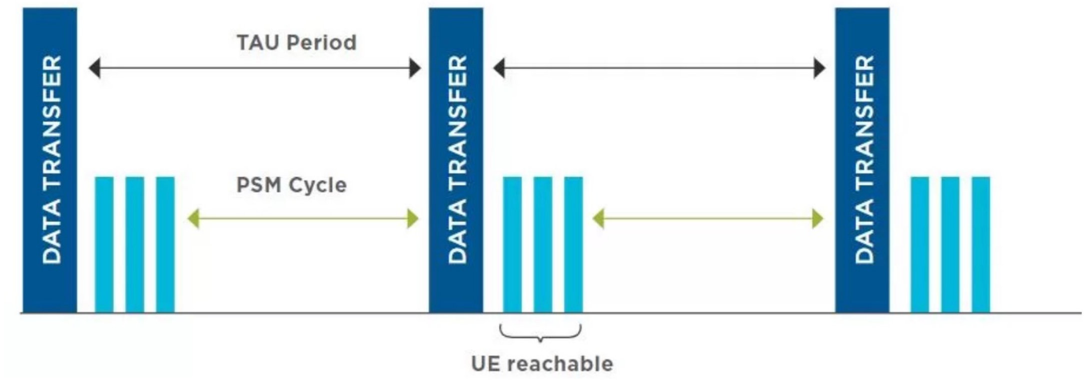
- **Extended Idle mode DRX (eDRX)**: It allows the device to enter a sleep mode while still monitoring the network for incoming data.
- This approach reduces UE power consumption and prolongs UE battery life.
- The device can extend the time it remains in the sleep mode before waking up to check for incoming data.
  - "eDRX cycle" from 1.28 seconds to 40.96 seconds, depending on the configuration.
- eDRX is suitable for use cases where the device needs to receive data more frequently than in PSM, but still not constantly (e.g., in smart parking systems where the device needs to receive data periodically to check for parking spaces).

NB-IoT

MAC Layer

- eDRX can be used without or in conjunction with PSM to obtain power savings.
  - eDRX can offer better latency than PSM as the device is still monitoring the network for incoming data while in sleep mode.
  - eDRX provides a good compromise between device reachability and power consumption.

Power-Saving Mode (PSM)



Extended Idle mode DRX (eDRX)

NB-IoT

MAC Layer

- Repetition: NB-IoT adjusts data **repetition** counts based on signal strength.
  - Up to 2048 (128) repetitions in downlink (uplink).
  - Achieves **coverage** extension up to 10 km (at cell edges, repetition counts is increased).
  - It improves **sensitivity:** Each doubling of the repetitions improves the sensitivity by **~3 dB** due to coherent addition of the symbols and incoherent addition of thermal noise.
  - Accumulating repetitions takes time: trade-off between latency and sensitivity.
- The appropriate number of repetitions is **adjusted dynamically**, which assigns an Enhanced Coverage Level (ECL) to each device based on the received uplink and reported downlink signal level (somehow similar to SF in LoRa).
  - Higher ECL → more problematic radio conditions → higher number of repetitions.
  - Computed based on the **maximum coupling loss (MCL)** parameter.

NB-IoT

Recall from LoRa theory:

$$S = -174 + 10\log(B) + NF + SNR_m$$

Link budget

- Maximum coupling loss (MCL) of **164 dB.**
  - It is chosen by 3GPP as a metric to evaluate coverage performance of wireless networks.

Parameter	15 KHz	3.75 KHz
(1) Transmit power (dBm)	23.0	23.0
(2) Thermal noise density (dBm/Hz)	-174	-174
(3) Receiver noise figure (dB)	3	3
(4) Occupied channel bandwidth (Hz)	15000	3750
(5) Effective noise power = (2) + (3) + 10*log ((4)) (dBm)	-129.2	-135.3
(6) Required SNR (SNR_m) (dB)	-11.8	-5.7
(7) Receiver sensitivity (S) = (5) + (6) (dBm)	-141.0	-141.0
(8) Max coupling loss = (1) - (7) (dB)	164.0	164.0

NB-IoT

Link budget (comparison)

- MCL is a critical parameter in the planning and optimization of wireless networks, as it **determines the coverage area, the cell size, the antenna height, the transmission power, and the frequency allocation**.

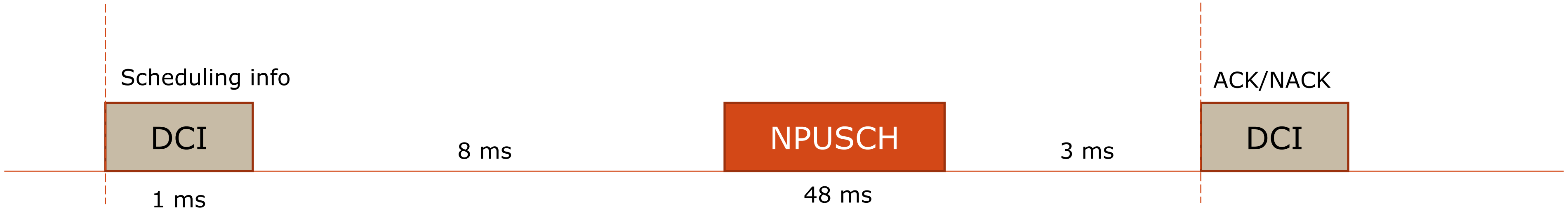
Radio Access Technology	Maximum Coupling Loss (MCL) [dB]
E-GPRS	~ 164 dB
LTE	~ 144 dB
LTE-M	~ 160 dB
NB-IoT	~ 164 dB
Sigfox	~ 162 dB
LoRa	~ 157 dB

NB-IoT

Data rate (uplink single-tone)

Subcarrier spacing	# tones in RU (subcarriers)	# slots in RU	# symbols in slot	Slot duration	RU duration
3.75 KHz	1	16	7 normal CP	2 ms	32 ms
15 KHz	1	16		0.5 ms	8 ms
	3	8			4 ms
	6	4			2 ms
	12	2			1 ms

- Maximum transport block size (TBS): 1000 bits.
- Maximum MCS: 10.
- Minimum number of RUs: 6.
- Minimum RU duration: 8 ms (obtained with 15 KHz subcarrier spacing).
- The min. time to transmit 1000 bits is $N_{rep} \cdot N_{RU} \cdot T_{RU} = 1 \cdot 6 \cdot 8 = 48$ ms.
- Peak data rate is 1000 bits / 48 ms = **20.8 Kbps.**
- Considering the overhead for scheduling: 1000 bits / (48+12) ms = **16.7 Kbps.**

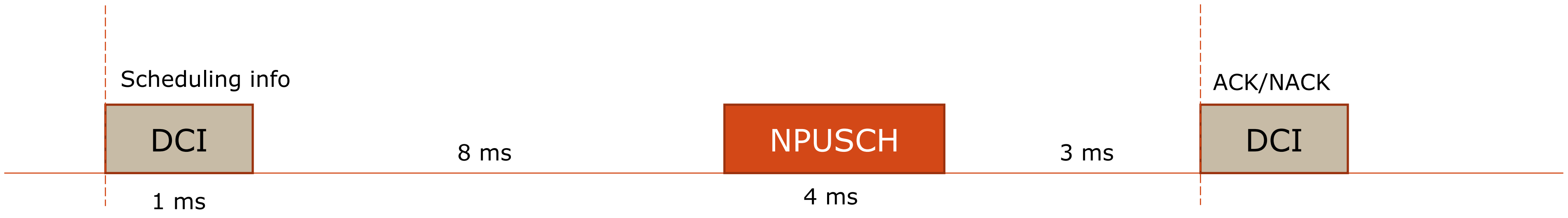


NB-IoT

Data rate (uplink multi-tone)

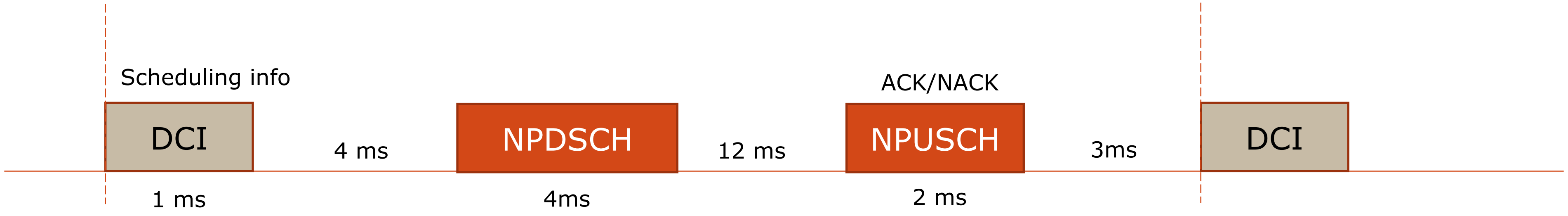
Subcarrier spacing	# tones in RU (subcarriers)	# slots in RU	# symbols in slot	Slot duration	RU duration
3.75 KHz	1	16	7 normal CP	2 ms	32 ms
15 KHz	1	16		0.5 ms	8 ms
	3	8			4 ms
	6	4			2 ms
	12	2			1 ms

- Maximum transport block size (TBS): 1000 bits.
- Maximum MCS: 12.
- Minimum number of RUs: 4.
- Minimum RU duration: 1 ms (obtained with 12 tones).
- The min. time to transmit 1000 bits is $N_{rep} \cdot N_{RU} \cdot T_{RU} = 1 \cdot 4 \cdot 1 = 4$ ms.
- Peak data rate is 1000 bits / 4 ms = **250 Kbps.**
- Considering the overhead for scheduling: 1000 bits / (4+12) ms = **62.5 Kbps.**



Data rate (downlink)

- Maximum transport block size (TBS): 680 bits
- Maximum MCS: 10.
- Min. number of subframes: 4 (or 3, if MCS 12 is used).
- Minimum subframe duration: 1 ms.
- The min. time to transmit 680 bits is $N_{rep} \cdot N_{SF} \cdot T_{SF} = 1 \cdot 4 \cdot 1 = 4$ ms.
- Peak data rate is 680 bits / 4 ms = **170 Kbps.**
- Considering the overhead for scheduling: 680 bits / (4+22) ms = **26.2 Kbps.**



UNIVERSITÀ DEGLI STUDI DI PADOVA

MIME – Master's degree ICT Internet Multimedia Engineering

09 – IoT technologies (long-range)
Summary

Marco Giordani (marco.giordani@unipd.it)
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IoT technologies (long-range)

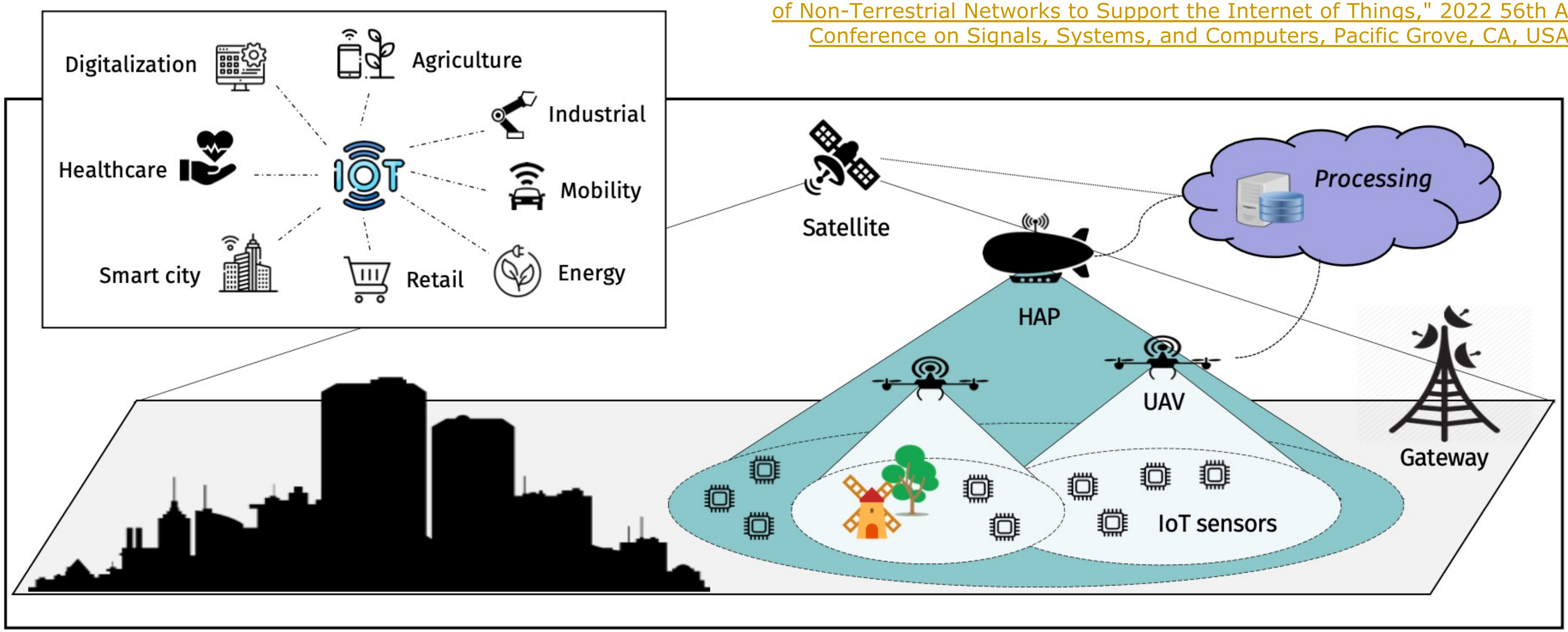
Comparison

Parameter	Sigfox	LoRa	NB-IoT
Spectrum	Unlicensed	Unlicensed	Licensed
Modulation	UNB	CSS	QPSK
Bandwidth (UL)	100 Hz	125 kHz (Class A)	180 KHz
Peak data rate (UL)	100 bps	6 kbps (SF7)	250 Kbps
Max. range	50 km	12+ km (SF12)	10 km
Energy consumption	Very low	Low	Low
Tx. power (UL)	14 dBm	14 dBm	23 dBm
Interference immunity	Immune (UNB) + Repetition	Spreading Factor	Repetition
Sensitivity threshold	-140 dBm	$-127 - 2.5(SF_k - 7)$	-141
Duty cycle	Yes	Yes	No
MCL [dB]	162 dB	157 dB	164 dB
Device cost	Low	Moderate	Moderate

IoT technologies (long-range)

Case study: satellite-IoT

D. Wang, A. Traspadini, M. Giordani, M. -S. Alouini and M. Zorzi, "On the Performance of Non-Terrestrial Networks to Support the Internet of Things," 2022 56th Asilomar Conference on Signals, Systems, and Computers, Pacific Grove, CA, USA, 2022,



IoT technologies (long-range)

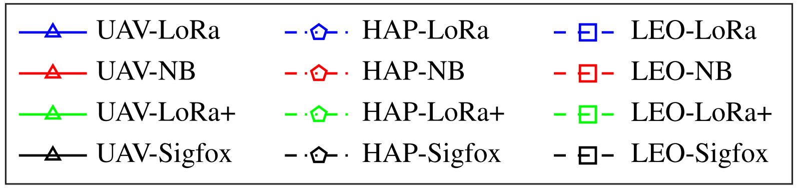
Case study: satellite-IoT

UAV	HAP	GEO/LEO satellites
Fly at low altitude	Quick deployment	Huge coverage
High flexibility	Large geographical coverage	
Deployed on-demand	Low deployment costs	
High propulsion energy	Low energy consumption (solar-powered)	
Small coverage umbrella	Difficult stabilization	Huge delays and attenuation

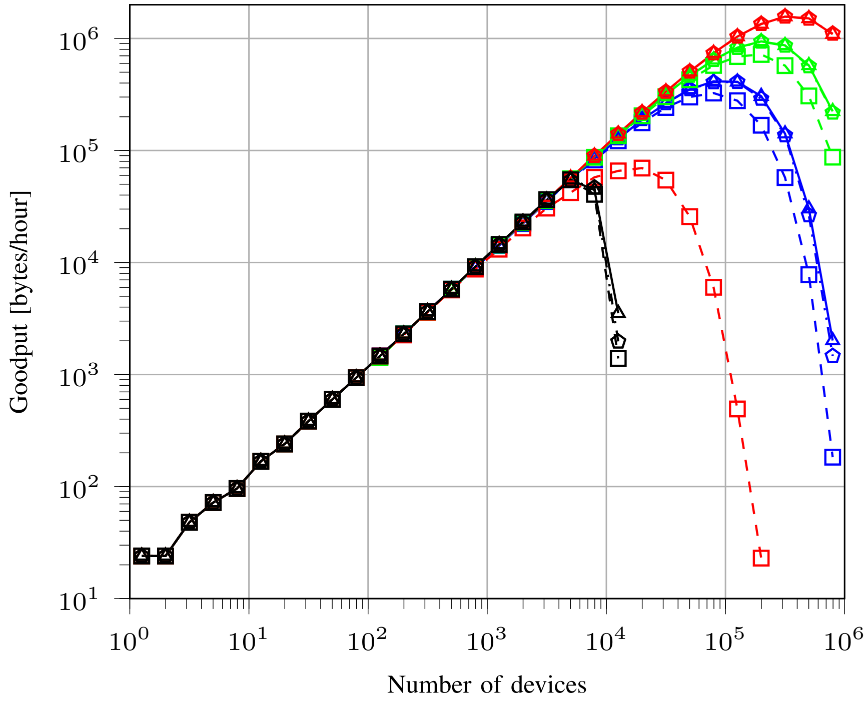
IoT technologies (long-range)

Case study: satellite-IoT

- Goodput increases (higher load), then decreases (interference).
- LEO<HAP<UAV due to the longer link (more severe impact of the path loss).



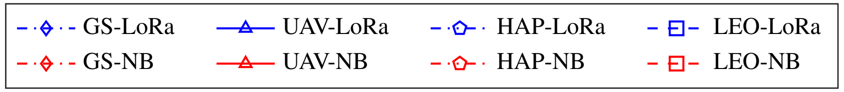
Platform	Sigfox	LoRa	NB-IoT
UAV			
HAP			
LEO			



IoT technologies (long-range)

Case study: satellite-IoT

- LoRa>NB-IoT: lower sensitivity.
- LEO>HAP>GS: LOS, lower visibility constraints, SF to minimize interference.
- LoRa is the best option for LEO under both coverage and goodput metrics.



Platform	LoRa		NB-IoT	
	R (km)	α (°)	R (km)	α (°)
GS	14.3	N/A	8.7	N/A
UAV	8.4	4	6.8	5
HAP	104.6	10.3	90.4	12
LEO	1465	14.7	470	48