Cellular Internet of Things

Framework, Optimization, and Challenges of NB-IoT

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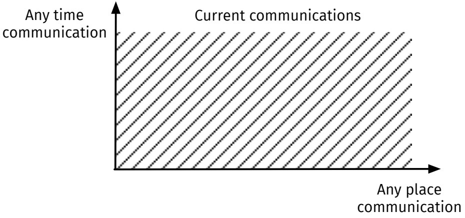
Tutorial Outcomes

- What are the main drivers for cellular IoT in 5G?
- What are the requirements and characteristics of mMTC in 5G?
- How does NB-IoT leverage and adapt 3GPP LTE infrastructure and mechanisms to meet 5G mMTC requirements?
- How do we evaluate the performance of an NB-IoT deployment in terms of coverage and capacity?
- What are the challenges for optimizing the performance of NB-IoT?

Outline

A New Dimension in Communications



Source: The Internet of Things, ITU Internet Reports, 2005

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- The Internet of Things (IoT) explores a new dimension in communications

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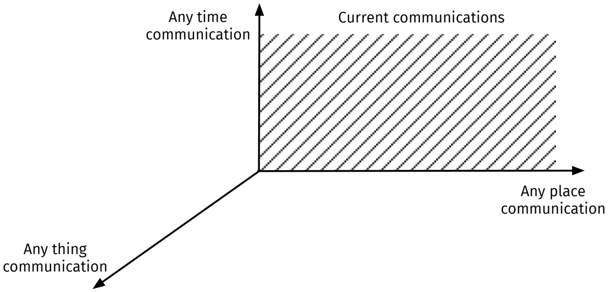

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IoT Scenarios

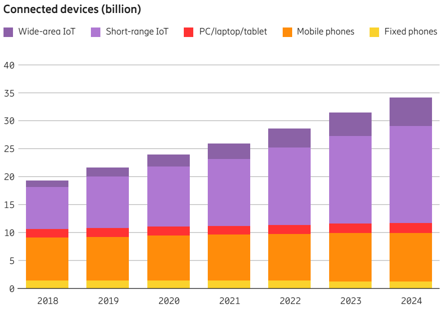
Internet of Things

The Internet of Things (IoT) generally refers to scenarios where network connectivity and computing capability extends to devices, sensors, and everyday items (ISOC IoT Overview, 2015).

Scenario	Example
Human	Wearables for health monitoring
Home	Heating, security automation
Retail	Self-checkout, inventory optimization
Vehicles	Condition-based maintenance
Cities	Traffic control, environmental monitoring

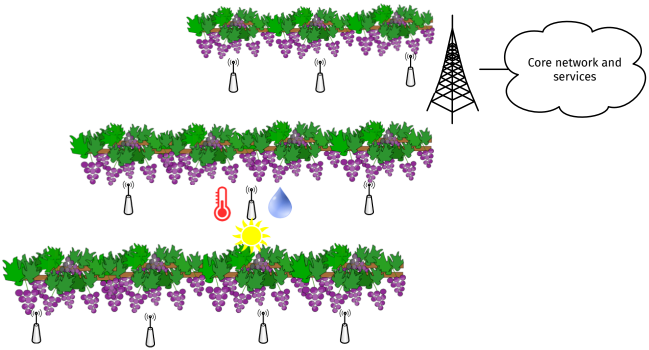
Evolution of IoT Devices

- The number of IoT devices will exceed the number of PCs and mobile phones



Source: Ericsson mobility report, 2019

The Case of IoT for Smart Agriculture



- Periodic sensing of microclimates in vineyards

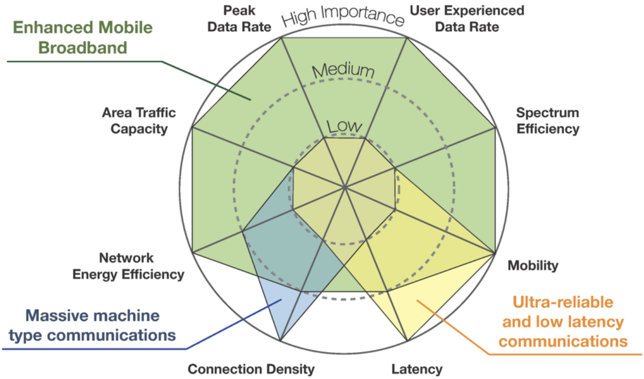
Constraints on the Devices and the Network

- Difficult physical accessibility and limited access to power sources
  - Wireless communications
  - Autonomy and long battery life operation
- Wide area coverage with a large number of communicating devices
  - Scalable deployment
  - Cost efficient devices
- Very loose bandwidth and latency constraints
  - Adaptive radio and access mechanisms

Challenge

Do existing wireless networking technologies satisfy these constraints?

Capabilities of IMT-2020



Source: IMT 2020 Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond, ITU-R M.2083

Massive Machine Type Communications

mMTC: Massive Machine Type Communications

mMTC requires improved network coverage, long device operational lifetime, and a high density of connections at low data rates

- Typical use cases for mMTC include:
  - Smart wearables
  - Smart cities
  - Smart agriculture

mMTC Requirements[3]

Indicator	Requirement
Coverage	164 dB maximum coupling loss at 160 bps
Connection density	1,000,000 devices per square kilometer
UE battery life	10 years battery lifetime (15 years desirable)[1]
Latency	10 s for a 20 byte application packet[2]

[1] For a 5 Wh battery for a device sending daily 200 bytes uplink data followed by 20 bytes downlink data at a maximum coupling loss of 164 dB

[2] In uplink at 164 dB maximum coupling loss and starting from the device being in the most battery efficient state

[3] 3GPP TR38.913, Study on Scenarios and Requirements for Next Generation Access Technologies (Release 14), 2017

Emergence of Low Power Wide Area Technologies

Low Power Wide Area Networks

Low power refers to the ability of an IoT device to function for many years on a single battery charge, while at the same time it is able to communicate from locations where shadowing and path loss would limit the usefulness of more traditional cellular technologies (3GPP Low Power Wide Area Technologies, GSMA White Paper, 2016)

- Low Power Wide Area (LPWA) technologies enable to address the mMTC requirements
- A large number of candidate technologies:
  - LoRaWAN, Sigfox, Ingenu, NB-IoT, etc.
- Two main design choices:
  - Adapt and leverage existing cellular technology (Cellular IoT)
  - Develop a clean-slate technology

The Cellular Internet of Things

- mMTC requirements have led to the development and standardization of three 3GPP Cellular IoT technologies:
  - *Extended Coverage GSM for the Internet of Things (EC-GSM-IoT)*
  - *LTE for Machine-Type Communications (LTE-M)*
  - *Narrowband Internet of Things (NB-IoT)*
- Cellular IoT technologies share some common specifications
  - Designed to operate in licensed frequency bands
  - Reuse or adapt concepts and components from existing cellular networks

Cellular IoT 3GPP Standards

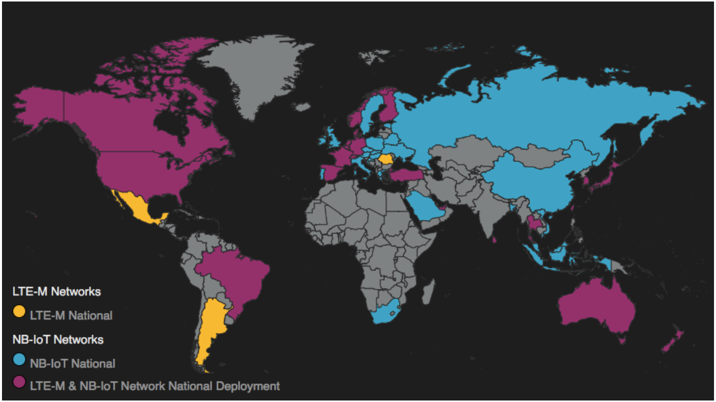
	EC-GSM-IoT	LTE-M	NB-IoT
Spectrum	GSM bands	LTE bands	LTE in-band, guard bands, SA
Peak data rate	240 kbps [4]	1 Mbps	250 kbps (UL multi-tone)
Bandwidth	200 kHz per ch.	1.08 MHz	180 kHz

[4] 8PSK, 4 slots

5G Design for mMTC

- Continuation of Cellular IoT standards LTE-M and NB-IoT
  - LTE-M and NB-IoT fulfill the mMTC 5G requirements
  - No specification of NR mMTC solution in Release 15
  - In the future, NB-IoT and LTE-M may operate in-band within an NR carrier
- NB-IoT and LTE-M address complementary use cases
  - NB-IoT is ideal for supporting very low data rate applications in extremely challenging radio conditions
  - LTE-M achieves greater data rates, lower latency and more accurate device positioning capabilities

Current Deployment of LTE-M and NB-IoT



Source: Mobile IoT Rollout Report, www.gsma.com

LoRaWAN: An Example of *Non-Cellular* LPWA technology

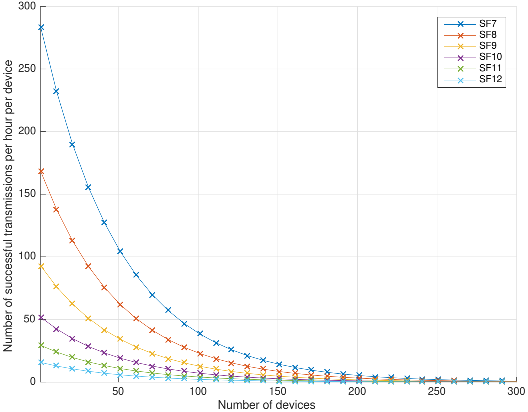
- LoRaWAN is a clean slate LPWA technology
  - Other non-cellular LPWA are being specified: Sigfox, Ingenu, Wi-SUN, etc.
- Uses a *new* robust modulation called LoRa
  - Variation of Chirp Spread Spectrum (CSS)
  - Uses spreading factors to increase the coverage
  - Data rates range from 300 bps to 5.5 kbps
- Operates in license-free bands (868 MHz in Europe)
  - Transmit power limited to 14 dBm (25 mW)
  - 1% per sub-band duty-cycle limitation
- Access is contention based
  - Devices transmit without any coordination on a randomly chosen channel
  - Simultaneous transmissions on the same channel and spreading factor *collide*

A Glimpse on LoRaWAN Design Challenges (1/2)

- Device reachability and battery lifetime
  - Class A devices open two short downlink receive windows only after an uplink transmission
- Network capacity and coverage
  - Use multiple orthogonal spreading factors simultaneously on the same channel
  - Higher spreading factors lead to lower sensitivity and larger coverage
  - Lower spreading factors lead to higher data rates
- Network architecture
  - Star-of-stars topology: devices, gateways, and network server

A Glimpse on LoRaWAN Design Challenges (2/2)

- Device rate
  - Collisions occur for concurrent transmissions on the same channel and spreading factor
  - ALOHA model enables to compute the device rate given the network load



Cellular versus Non-Cellular IoT

- Advantages of cellular technologies
  - Dedicated spectrum: coordinated interference and QoS support
  - Global standards: large support form vendors and service providers
  - Reuse of cellular infrastructure: easy installation, management, and operation of devices
- The largest growth is expected for cellular IoT devices

IoT connections (billion)

IoT	2018	2024	CAGR
Wide-area IoT	1.1	4.5	27%
Cellular IoT[2]	1.0	4.1	27%
Short-range IoT	7.5	17.8	15%
Total	**8.6**	**22.3**	**17%**

Source: Ericsson mobility report, 2019

Outline

NB-IoT Characteristics

- Main characteristics to meet the mMTC 5G Requirements:
  - Low device complexity and cost
  - Reliability under extreme coverage conditions
  - Low power consumption: long battery lifetime
  - High capacity: support for massive number of low-rate devices
  - Simplified network topology and deployment

Low Device Complexity and Cost

Device Complexity and Cost

- Devices are mainly composed of:
  - a processing unit: usually a microcontroller with a limited amount of memory
  - a sensing unit: sensors and analog to digital converters
  - a radio unit: usually a transceiver capable of bidirectional communications
- The radio unit complexity and cost are primarily related to the complexity of:
  - digital baseband processing
  - radio-frequency (RF) analog processing

Digital Baseband Processing

- Reduce baseband processing complexity through:
  - limiting message size
  - using simple channel codes
  - not using complex modulations or multiple-input multiple-output (MIMO) transmissions
  - supporting only half-duplex operation: no simultaneous transmission and reception

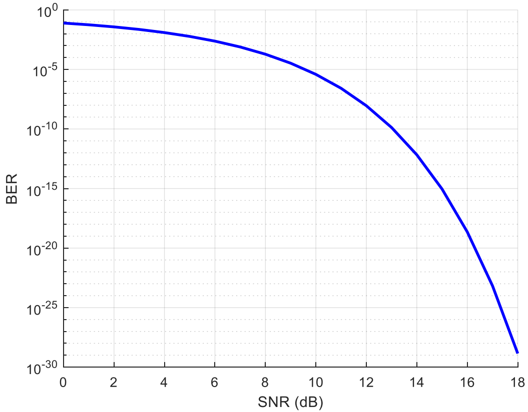
RF Processing

- Reduce RF processing complexity and cost through:
  - using one transmit-and-receive antenna
  - not using a duplexer (since only half-duplex operation is supported)
  - on-chip integrating power amplifier $\Rightarrow$ single-chip modem implementation (since transmit power is limited)

Reliability Under Extreme Coverage Conditions

Reliability and Radio Quality

- Reliability $\Rightarrow$ bit error rate (BER) $\leq$ target BER
- The SNR, or equivalently the carrier-to-noise ratio (CNR or C/N), is defined as the ratio of the received signal power C to the power of the noise N within the bandwidth of the transmitted signal



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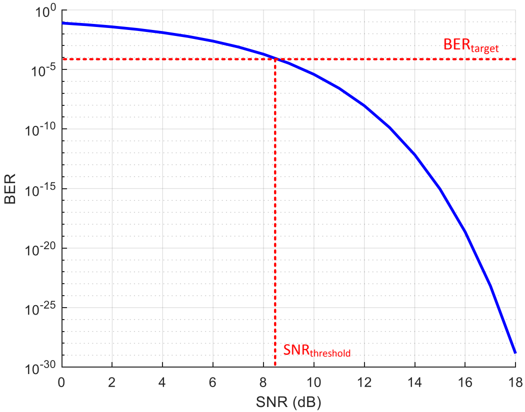


Receiver Sensitivity

$$BER \leq BER_{target} \quad \Leftrightarrow \quad SNR \geq SNR_{threshold}$$

$$\Leftrightarrow \quad S\,(\text{dBm}) \geq \underbrace{SNR_{threshold}\,(\text{dB}) + N\,(\text{dBm})}_{\text{Receiver sensitivity}}$$

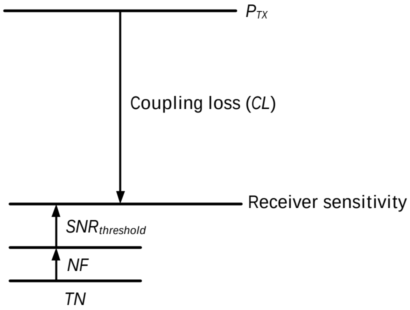
- N (dBm) is the background noise power at the receiver $=$ TN (dBm) $+NF$ (dB)
  - TN is the thermal noise caused by thermal agitation of charge carriers: $-174 + 10\log_{10}(B)$, B is the signal bandwidth (Hz)
  - NF is the noise figure caused by RF components

Maximum Coupling Loss

- The Maximum Coupling Loss (MCL) defines the maximum loss the system can cope with between a transmitter and a receiver:

$$MCL\ (\mathrm{dB}) = P_{Tx} - \underbrace{\left(SNR_{threshold} - 174 + 10\log_{10}(B) + NF\right)}_{\text{Receiver sensitivity}}$$

  - P_{Tx} is the transmit power (dBm)



How to Improve Coverage?

- Coverage targets are usually specified in terms of *MCL*
- Increasing P_{Tx}, or lowering NF, leads to higher device complexity and cost
- Reducing B leads to lower network capacity
- Improve coverage by reducing $SNR_{threshold}$ through repetitions and efficient HARQ retransmissions

Repetitions

Signal Combination

- Devices in extreme coverage conditions blindly repeat information (without any feedback from the receiver)
- The receiver accumulates the blindly transmitted signals and combines all the repetitions
- Repetitions compensate for the *SNR* degradation

$$\left(SNR\right)_R \text{ (dB)} = 10\log_{10}\left(R\right) + \left(SNR\right)_1$$

- $\left(SNR\right)_R$ is the ideal *SNR* after combining *R* transmissions
- $\left(SNR\right)_1$ is the *SNR* of a single transmission
- $G_p = 10\log_{10}\left(R\right)$ is the processing gain

$$\left(SNR\right)_R \geq SNR_{threshold} \Rightarrow \left(SNR\right)_1 \geq \underbrace{SNR_{threshold} - 10\log_{10}\left(R\right)}_{\text{Reduced } SNR_{threshold}}$$

Processing Gain

- The higher G_p is
  - the lower the SNR threshold of a single transmission is $\Rightarrow$ larger radio coverage
  - the lower the useful data rate is
- In practice, channel estimation (CE) is rarely perfect
- CE errors result in lower processing gain: realistic $G_p < 10\log_{10}(R)$
- Improve CE and consequently G_p through averaging the channel estimates over multiple consecutive subframes (very slowly time-variant channel): *Cross-subframe CE*

Low Power Consumption

Deep Sleep Mode

- Most of the IoT applications require infrequent transmission of small data volumes
- Idle devices may enter a deep sleep mode. They:
  - shut down their transceiver
  - keep track of time and scheduled events via a low-power oscillator (that is kept running)
- Devices wake up from deep sleep mode to:
  - transmit data
  - monitor paging channels

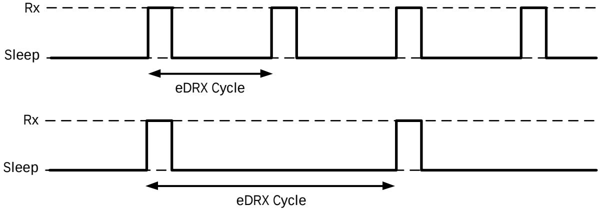
Battery Lifetime

- Battery lifetime is increased through:
  - optimizing device reachability:
    - Devices monitor paging channels periodically, or only after a mobile-originated data transfer (for a short period of time)
  - reducing signaling messages when a device needs to transmit data

Device Reachability

extended Discontinuous Reception (eDRX)

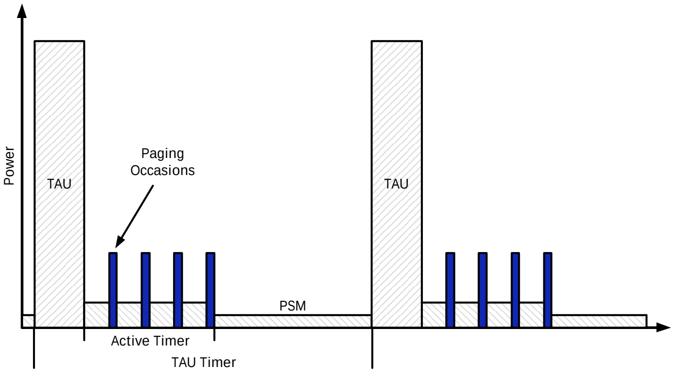
- An eDRX cycle is the time period between two paging occasions a device needs to monitor (up to 2 h, 54 min, and 46 s)
- In between these two occasions, the device is assumed to be in deep sleep mode
- The eDRX cycle is negotiated on a per-device basis



Two possible eDRX cycle configurations

Power-Saving Mode (PSM)

- In PSM, idle devices do not monitor paging channels $\Rightarrow$ unreachability
- A device leaves PSM to send application data or a periodic tracking area update message



Operation in PSM including periodic TAU

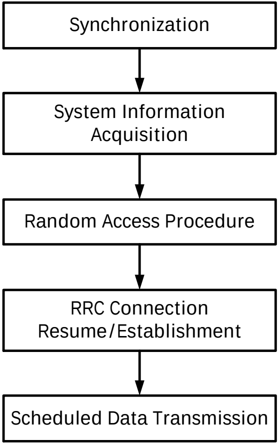
Power-Saving Mode (PSM)

- After data transfer, the device monitors paging occasions until an active timer expires
- When the active timer expires, the device re-enters PSM and is unreachable until the next mobile-originated event
- The tracking area update period is configurable on a per-device basis (up to a year)

Data Transmission

Cell Access

- From idle to connected mode:

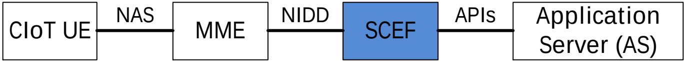


Data Transmission Optimization

- Signaling messages, that are required before a device transmits data, are reduced:
  - User Plane Cellular IoT (CIoT) Evolved Packet System (EPS) optimization procedure
    - Suspend/resume RRC connection (rather than release/re-establish RRC connection)
    - The device context is maintained at the UE, eNB, and MME during idle mode
  - Control Plane CIoT EPS optimization procedure
    - Transfer data over non-radio signaling (DoNAS, Data over Non-Access Stratum)
    - The IP packets are encapsulated in non-radio signaling messages and are sent to the MME
    - The MME extracts the IP packets and forwards them to the S-GW

Non-IP Data Delivery (NIDD)

- To further reduce device power consumption, non-IP data transfer is also supported
- Non-IP data is transferred over non-radio signaling:
  - Non-IP data is encapsulated in non-radio signaling messages and is sent to the MME
  - The MME extracts the data and forwards it to the SCEF (Service Capability Exposure Function)



Service Capability Exposure Function (SCEF)

- SCEF is defined in Release 13
- SCEF provides APIs for small data transfers and control messaging
- The APIs securely expose network capabilities and services. They enable many use cases:
    - Device trigger delivery: wake up and notify a UE to connect to the AS
    - UE reachability and monitoring: check if a UE is currently reachable. If not, send back a notification when it becomes reachable.
    - Network configuration and parameters: set the PSM and eDRX parameters

High Capacity

Support for Massive Number of Low-Rate Devices

- Trading off data rate for coverage
- Increase network capacity through using single-tone transmissions in the UL, when coupling loss is high

Why Single-Tone Transmissions?

- The channel capacity C is given by:

$$C = B\log_2(1 + \frac{S}{N}) = B\log_2(1 + \frac{S}{N_0 B})$$

  - N_0 is the noise power spectral density
- When coupling loss is high, $\frac{S}{N_0 B} \ll 1 \Rightarrow \ln(1 + \frac{S}{N_0 B}) \approx \frac{S}{N_0 B}$.

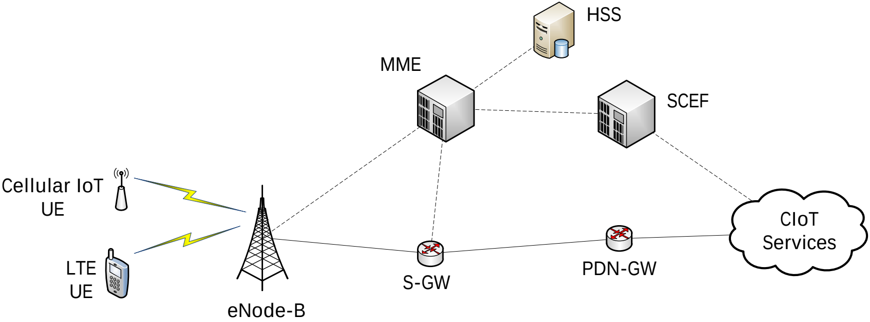
$$\Rightarrow C = \frac{S}{N_0}\log_2(e)$$

- As C no longer depends on B, allocating a single tone (subcarrier) for devices in bad coverage increases network capacity without loss of performance
- The uplink transmit power is concentrated on a narrower bandwidth, thus boosting the received SNR

Simplified Network Topology and Deployment

Network Topology and Deployment

- NB-IoT reuses LTE frequency bands and infrastructure (through software upgrade) $\Rightarrow$ fast time-to-market



SCEF: Service Capability Exposure Function

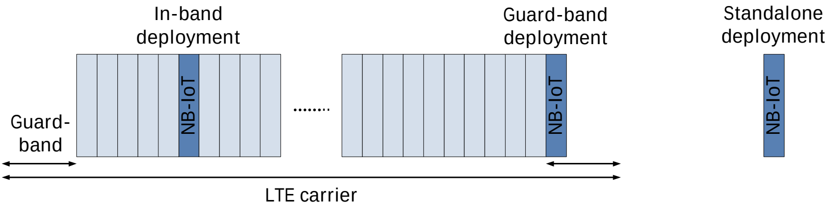
Outline

NB-IoT and LTE

- NB-IoT is part of the 3GPP specifications: Releases 13, 14, and 15
- NB-IoT adapts and leverages the LTE ecosystem:
  - it reuses many LTE design principles:
    - Transmission schemes
    - Protocol architecture
    - Bearer management
    - Security management
    - Mobility management
  - it reuses LTE infrastructure through software upgrade

Deployment Flexibility

- NB-IoT supports three operation modes: in-band (LTE), guard-band (LTE), and standalone (*e.g.*, refarm the GSM carrier)



- NB-IoT supports frequency division duplex (FDD) and time division duplex (TDD) modes

Radio Interface

- Channel bandwidth: 180 kHz $\equiv$ 1 LTE Physical Resource Block (PRB) in the frequency domain
- Transmission schemes:
  - OFDMA (subcarrier spacing $\Delta f = 15$ kHz) in the DL
  - SC-FDMA ($\Delta f = 15$ kHz or 3.75 kHz) in the UL
- Smallest schedulable unit:
  - 1 PRB = 180 kHz (12 subcarriers) over 1 ms (1 subframe) in the DL
  - 1 Resource Unit (RU) in the UL
    - 180 kHz (12 subcarriers) over 1 ms
    - 90 kHz (6 subcarriers) over 2 ms
    - 45 kHz (3 subcarriers) over 4 ms
    - 15 kHz (1 subcarrier) over 8 ms
    - 3.75 kHz (1 subcarrier) over 32 ms

Radio Interface

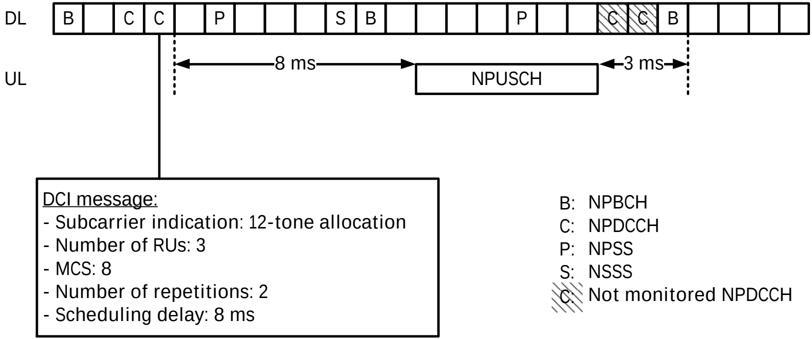
- Maximum Transport Block Size (TBS):
  - 680 bits (R13), or 2536 bits (R14), mapped over up to 10 subframes (10 ms) in the DL
  - 1000 bits (R13), or 2536 bits (R14), mapped over up to 10 RUs in the UL
- Modulations:
  - QPSK in the DL
  - QPSK (for multi-tone transmission), $\pi/4$-QPSK, or $\pi/2$-BPSK (for single-tone transmission) in the UL
- Channel codes:
  - LTE tail-biting convolution code (TBCC) in the DL
  - LTE turbo code (for data transfer) and repetition code (for HARQ feedback) in the UL
- Repetitions for coverage enhancement:
  - up to 2048 repetitions in the DL and up to 128 repetitions in the UL
  - 20 dB coverage enhancement over GPRS $\Rightarrow$ sevenfold increase in coverage area (in an open environment), or (deep) indoor penetration
  - Transmission gaps can be configured to avoid long transmissions

Uplink Scheduling

- Scheduling information is transmitted in the Downlink Control Information (DCI) message
- UL scheduling information includes:
  - resource allocation (in time and frequency domains): subcarrier indication and number of RUs
  - Modulation and Coding Scheme (MCS)
  - number of repetitions
  - scheduling delay: time gap between the last DCI and the first scheduled UL subframe ($\geq$ 8 ms)
- A TB can be mapped over multiple RUs, allowing more redundancy bits for channel coding
- The scheduling delay allows the device to decode the DCI message, switch to transmission mode, and prepare for the UL transmission
- After data transmission, the device has at least 3 ms to switch to reception mode and monitor the next DCI message

Uplink Scheduling

- An uplink scheduling example[5]:



[5] O. Liberg et al., *Cellular Internet of Things - Technologies, Standards, and Performance*. Cambridge, MA, USA: American Press, 2017.

Downlink Scheduling

- The general aspects of DL scheduling are similar to those of UL scheduling
- DL scheduling information includes:
  - resource allocation: number of subframes per repetition
  - MCS
  - number of repetitions
  - scheduling delay ($\geq$ 4 ms)
  - HARQ-Ack resource: subcarrier index and time offset
- Resources for HARQ feedback are also scheduled
- After HARQ feedback transmission, the device has at least 3 ms to switch to reception mode and monitor the next DCI message

Power Control

- Closed-loop power control requires constant feedback and measurements, and is consequently power consuming
  - Open-loop power control is supported
- Power control for UL data channels:
  - If the number of repetitions is greater than 2, the transmit power P is the maximum device power: $P = P_{max}$
    - R13 defined two device power classes: $P_{max} = 20$ and 23 dBm
    - R14 introduced one additional device power class: $P_{max} = 14$ dBm
  - If the number of repetitions is 1 or 2, the transmit power is determined by:

$$P\,(\text{dBm}) = \max\left\{P_{max}, P_{target} + \alpha L + 10\log_{10}(M)\right\}$$

    - P_{target} is the target received power
    - L is the estimated path loss
    - α is a path loss adjustment factor
    - M is a bandwidth adjustment factor

Power Control

- M relates P_{target} to target SNR

Bandwidth (kHz)	M
3.75	1/4
15	1
45	3
90	6
180	12

- P_{max}, P_{target}, and α are provided by higher-layer configuration signaling

Outline

Cell Range Estimation

Link Budget

- The link budget is a measure of all the gains and losses from the transmitter, through the propagation channel, to the target receiver
- The link budget can be expressed as:

$$P_{Rx} = P_{Tx} + G_{System} - L_{System} - L_{Channel} - M$$

  - P_{Rx} = median received power
  - P_{Tx} = transmit power
  - G_{System} = system gains (*e.g.*, antenna, diversity, and amplifier gains)
  - L_{System} = system losses (*e.g.*, cable and connector losses)
  - $L_{Channel}$ = median path loss
  - M = additional margins

Additional Margins

- Fading margin
- Interference margin
- Penetration margin:
  - indoor penetration loss (first wall): $\sim$ 18 dB (in dense urban environment), $\sim$ 15 dB (in urban environment), and $\sim$ 10 — 12 dB (in rural environment)
  - deep indoor penetration loss (second wall): +3 dB
- Body loss

Maximum Allowable Path Loss and Cell Range

- The maximum allowable path loss (*MAPL*) is expressed as:

$$MAPL = \max L_{Channel} \mid P_{Rx} \geq \text{receiver sensitivity}$$

$$\Rightarrow MAPL = P_{Tx} + G_{System} - L_{System} - M - \text{receiver sensitivity}$$

- The maximum allowable distance between the transmitter and the target receiver (cell range) depends on the *MAPL* and the channel model[6]
- Transmission and reception parameters are determined so as to achieve balanced links (*i.e.*, uplink *MAPL* = downlink *MAPL*)

[6] R. El Chall, S. Lahoud, and M. El Helou, "LoRaWAN Network: Radio Propagation Models and Performance Evaluation in Various Environments in Lebanon," in *IEEE Internet of Things Journal*, vol. 6, no. 2, pp. 2366-2378, April 2019.

Illustration: Uplink Link Budget Analysis

(a)	P_{Tx} (dBm)	23
(b)	G_{System} = base station antenna gain (dBi)	12
(c)	L_{System} = base station cable loss (dB)	3
(d)	M (dB)	16
(e)	B (Hz)	3750
(f)	Receiver NF (dB)	3
(g)	Receiver N (dBm) = $-174 + 10\log_{10}(e) + (f)$	-135.3
(h)	Required SINR[7] at the receiver (dB)	-12.74
(i)	Receiver sensitivity (dBm) = $(g) + (h)$	-148
	Uplink *MAPL* (dB) = $(a) + (b) - (c) - (d) - (i)$	**164**
	Uplink cell range[8] - urban environment (km)	**11**

[7] Target transmission data rate = 160 b/s

[8] Okumura-Hata model: base station antenna height = 30 m, device antenna height = 1 m, carrier frequency = 862 MHz

Link-Level Performance Evaluation

Channel Capacity

- The channel capacity C is given by:

$$C = B \cdot B_{eff} \cdot \log_2 \left(1 + \frac{SNR}{SNR_{eff}}\right)$$

  - B_{eff} = NB-IoT bandwidth efficiency
  - SNR_{eff} = NB-IoT SNR efficiency
- B_{eff} and SNR_{eff} are obtained through curve fitting to the 3GPP link-level simulation results[9,10]:

	UL (multi-tone)	UL (single-tone)	DL
B_{eff}	0.35	0.35	0.58
SNR_{eff}	1	0.60	1.90

[9] "Consideration on Uplink Data Transmission for NB-IoT," 3GPP, Report R1-160480, 2016.

[10] "Further Considerations on NB-PDSCH Design for NB-IoT," 3GPP, Report R1-161860, 2016.

Transmission Data Rate and $SNR_{threshold}$

- The transmission data rate R_b (b/s) can be expressed as:

$$R_b = \frac{TBS + CRC}{N_{RU} \cdot T_{RU}}$$

  - TBS = transport block size (bits)
  - CRC = cyclic redundancy check code size (bits)
  - N_{RU} = number of allocated RUs
  - T_{RU} = RU duration (s)
- As the receiver combines R transmissions (repetitions), reliability requires:

$$(SNR)_R \geq \underbrace{\left(2^{\frac{R_b}{B \cdot B_{eff}}} - 1\right) \cdot SNR_{eff}}_{SNR_{threshold}}$$

Ideal vs. Realistic Processing Gain

- Ideal CE $\Rightarrow (SNR)_R = R \cdot (SNR)_1$

$$(SNR)_{1,\ threshold} = \frac{\left(2^{\frac{R_b}{B \cdot B_{eff}}} - 1\right) \cdot SNR_{eff}}{R}$$

  - $(SNR)_{1,\ threshold}$ = SNR threshold of a single transmission

- Realistic CE[11,12]:

$$\left(2^{\frac{R_b}{BW \cdot BW_{eff}}} - 1\right) \cdot SNR_{eff} = \frac{R \cdot \left(\sigma + (SNR)_{1,\ threshold}\right)}{\left(\sigma + 1 + \frac{\sigma}{(SNR)_{1,\ threshold}}\right) \cdot \left(1 + \frac{\sigma}{2 \cdot (SNR)_{1,\ threshold}}\right)}$$

  - σ = estimation error
  - $(SNR)_{1,\ threshold}$ is solved iteratively

[11] Y. D. Beyene, R. Jantti, K. Ruttik and S. Iraji, "On the Performance of Narrow-Band Internet of Things (NB-IoT)," in *2017 IEEE Wireless Communications and Networking Conference (WCNC)*, San Francisco, CA, 2017.

[12] P. Andres-Maldonado, P. Ameigeiras, J. Prados-Garzon, J. Navarro-Ortiz and J. M. Lopez-Soler, "An Analytical Performance Evaluation Framework for NB-IoT," in *IEEE Internet of Things Journal*, vol. 6, no. 4, pp. 7232-7240, Aug. 2019.

Estimation Error

- σ is obtained through link-level simulations and can be expressed (in dB) as:

$$\sigma_{dB} = c_1 \cdot (SNR)_{1,\ threshold,\ dB} + c_2$$

  - $(SNR)_{1,\ threshold,\ dB}$ = SNR threshold of a single transmission (dB)
  - c_1 and c_2 are constants that depend on the cross-subframe window

Cross-subframe window (ms)	c_1 (UL)	c_2 (UL)	c_1 (DL)	c_2 (DL)
1	-0.4896	4.4971	-0.4998	14.5262
2	-0.4844	3.0252	-0.4995	13.0035
4	-0.4780	1.5869	-0.4990	11.5017
8	-0.4725	0.1239	-0.4992	9.9952
16	-0.4475	-1.1335	-0.4969	8.5077

Spectral Efficiency

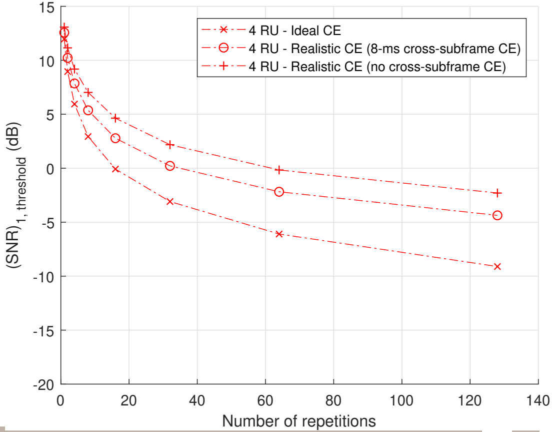
- Using R repetitions, the useful data rate is $D = R_b/R$
- The spectral efficiency γ (b/s/Hz) can be defined as:

$$\gamma = \frac{D}{B} = \frac{TBS + CRC}{R \cdot B \cdot N_{RU} \cdot T_{RU}}$$

- The higher R is
  - the lower $(SNR)_{1,\ threshold}$ is $\Rightarrow$ larger radio coverage
  - the lower D is

$(SNR)_1$ Threshold

- Cross-subframe CE improves realistic G_p and decreases $(SNR)_{1,\ threshold}$
- As R is higher, $(SNR)_{1,\ threshold}$ decreases leading to an increase in σ
- As N_{RU} is higher, the channel coding rate decreases leading to a decrease in $(SNR)_{1,\ threshold}$



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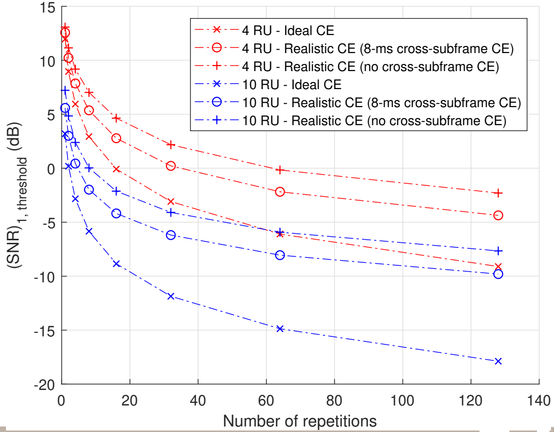
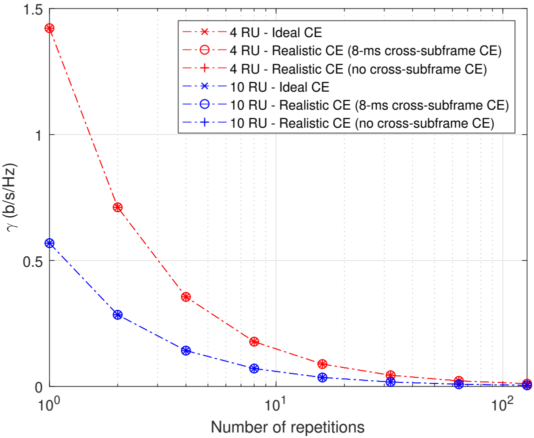


Spectral Efficiency

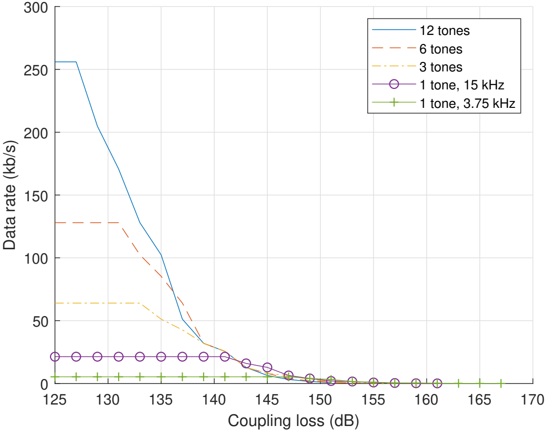
- Ideal CE achieves similar spectral efficiency with lower $(SNR)_{1,\ threshold}$
- As N_{RU} is higher, the channel coding rate decreases leading to a decrease in γ



TBS = 1000 bits, CRC = 24 bits, T_{RU} = 1, and B = 180 kHz

Useful Data Rate

- When coupling loss is low, multi-tone transmission provides higher data rate
- When coupling loss is high, all transmission formats provide similar data rate
- When coupling loss is very high, only single-tone transmission is possible

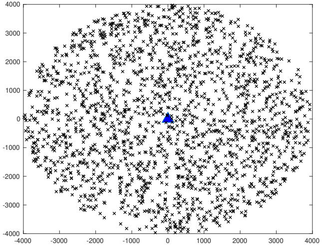


TBS = 1000 bits, *CRC* = 24 bits, 8-ms cross-subframe CE

System-level Performance Evaluation

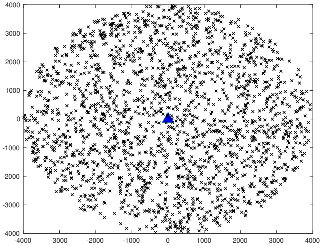
From Link-Level to System-Level Performance

- Link-level performance evaluation considers a single NB-IoT communication link between a pair of devices in an isolate noise-only scenario
- System-level performance evaluation builds on link level results to consider a network with multiple concurrent communication links as in a realistic scenario
  - Gain deeper insight into the different network factors that affect the rate
  - Analyse cell planning strategies and compute device performance indicators
  - Modify scheduling algorithms and study their performance



Evaluation Scenario

- Study area
  - Surface: circular cell of radius 4 km
  - Distribution of devices: uniform
  - Single Base Station
  - Environment type: urban
- Uplink link budget
  - Parameters as in link level study
  - Shadow fading: $\mathcal{N}(0, 8)$
  - Interference: $IF = 3$ dB
  - Penetration loss: $L_{penetration} = 15$ dB
  - 50% of indoor devices



Computing the Device Rates (1/2)

- The uplink SINR for each device i and each transmission format t

$$SINR(i,t) = P_{TX} + G_{system} - L_{system} - L_{channel}(i) - \beta(i)L_{penetration} - N(t) - IF$$

  - $L_{channel}(i)$ channel loss with shadow fading
  - $N(t) = -174 + 10\log_{10}(B(t)) + NF$
  - $\beta(i) = 1$ for an indoor device, and 0 otherwise

- The corresponding maximum data rate after *link adaptation*

$$D(i,t) = \max_{m}(\max_{r}(D(m,r,t)))$$

$$\text{with } SINR(i,t) \geq SINR_{threshold}(m,r,t)$$

Computing the Device Rates (2/2)

- The maximum data rate for each device i assuming that multi-tone and single-tone transmissions provide similar spectral efficiencies respectively

$$D(i) = \max_t D(i,t)$$

- The device data rate for average radio conditions

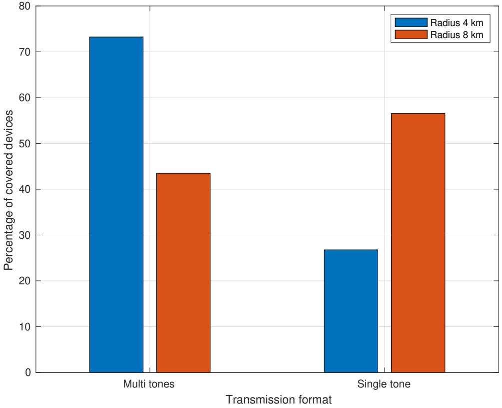
$$\bar{D} = \frac{\sum_i D(i)}{I}$$

- The average device rate after scheduling

$$d = \frac{\bar{D}}{I}$$

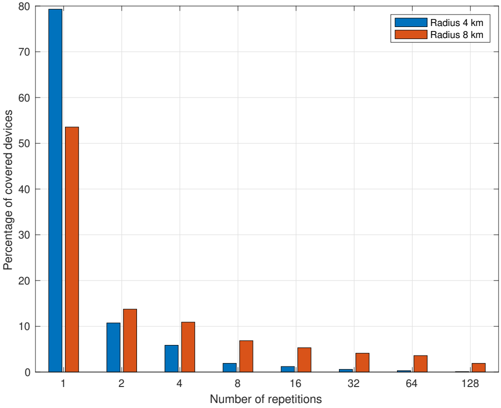
Transmission Formats

- For a cell radius of 4 km, good radio conditions enable to exploit the spectral efficiency of multi-tone transmissions
- For larger cells, single tone transmissions achieve better signal quality and become more attractive



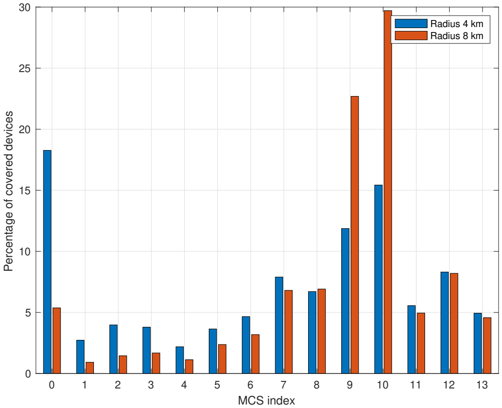
Repetitions

- Only 20% of devices use more than one repetition for a cell radius of 4 km
- 45% of devices use two or more repetitions in harsh radio conditions



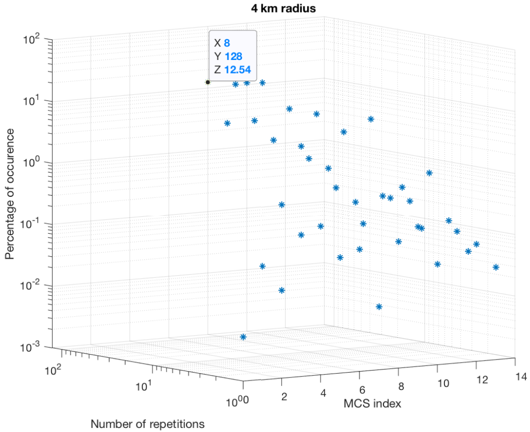
Modulation and Coding Schemes

- For a cell radius of 4 km, 50% of devices use high MCS index (greater or equal than 9) in order to increase data rates
- For larger cells, 70% of devices use high MCS index!



Link Adaptation: MCS index and Repetitions

- In order to combat harsh radio conditions and maximize rates, high MCS index is used jointly with a large number of repetitions



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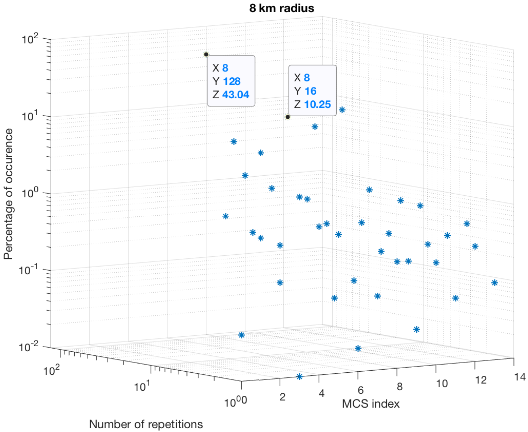
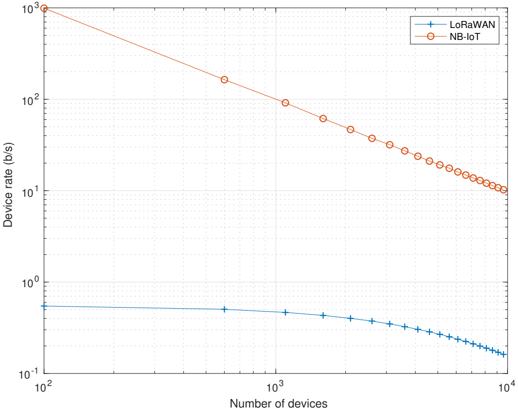


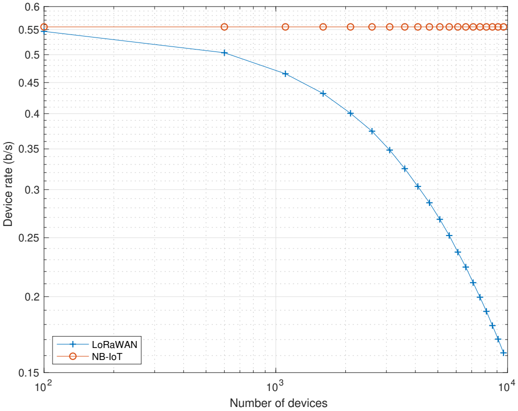
Network Capacity for NB-IoT and LoRaWAN

- The average rate decreases linearly with the number of devices for NB-IoT, while it drastically drops beyond 1000 devices for LoRaWAN



Network Capacity with Constant Arrival Rate

- If we consider an arrival rate of 5 packets per hour on each device, LoRaWAN does not succeed in delivering such service for more than 1000 devices



Coverage Comparison of NB-IoT and LoRaWAN

Outage Probability and Receiver Sensitivity

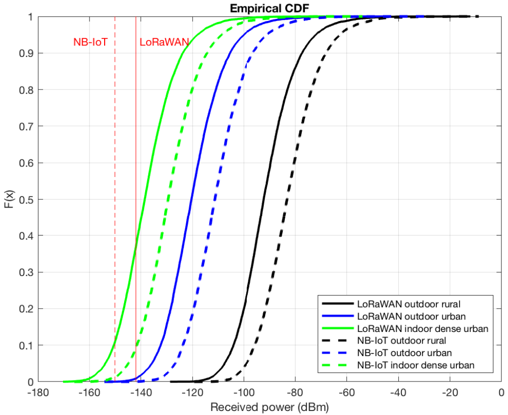
- Coverage outage is observed when the received power is less than the sensitivity
- Receiver sensitivity is given at different target rates:

	100 b/s	200 b/s
NB-IoT	-150.1 dBm	-147 dBm
LoRaWAN	-142 dBm	-139 dBm

- Coverage is computed for different environments (path loss formulas)
  - Outdoor rural
  - Outdoor urban
  - Indoor dense urban (penetration margin of 18 dB)
- Best coverage is computed for single-tone transmission and $\Delta f = 3.75$ kHz

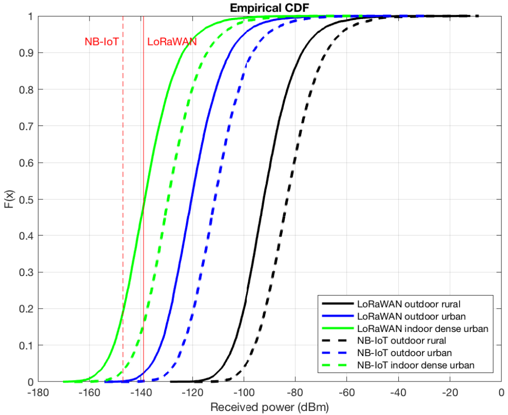
Coverage Comparison (1/3)

- The outage probability of NB-IoT at 100 b/s is almost null for all cases whereas it reaches 36% for LoRaWAN in indoor dense urban environments



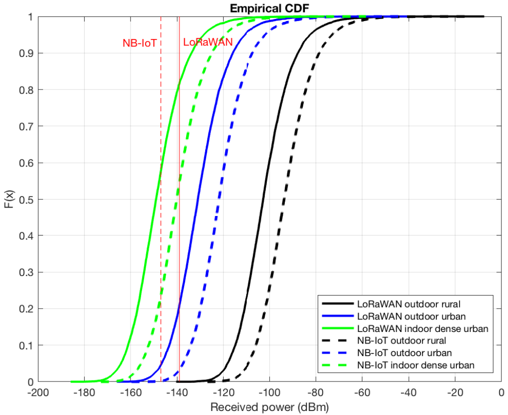
Coverage Comparison (2/3)

- The outage probability of NB-IoT at 200 b/s is slightly degraded in indoor dense urban environments



Coverage Comparison (3/3)

- For a larger cell radius (8 km), LoRaWAN exhibits severe coverage limitation at 200 b/s in comparison with NB-IoT



Conclusions (1/3)

- How does NB-IoT meet the 5G mMTC requirements?
  - Complexity: short messages, low complexity codes and modulations
  - Energy: Optimized reachability and reduced signaling
  - Coverage: Low receiver sensitivity
  - Capacity: Multi-tone and single-tone transmissions
  - Cost: Reuse 4G architecture

Conclusions (2/3)

- How do we evaluate the performance of an NB-IoT deployment in terms of coverage and capacity?
  - Link-level evaluation shows the impact of the radio parameters (repetitions, MCS, and transmission formats) on the the performance of the communication
  - System-level evaluation shows the impact of the user load and distribution on the network performance (cell planning, deployment optimization, etc.)

Typical performance of NB-IoT

- In order to maximize data rates, multi-tone transmissions are preferred for good radio conditions, while single-tone enable to combat harsh conditions
- No coverage outage is observed for a cell radius of 4 km in an indoor dense urban environment
- The capacity of a deployment can scale up to 200 000 devices sending 5 packets per hour

Conclusions (3/3)

- What are the challenges for optimizing the performance of NB-IoT?
  - Adaptation of the radio propagation models
  - Interference mitigation
  - Link adaptation and resource allocation
  - Support for quality of service such as delay bounded transmission
  - Energy efficiency maximization and power management

Feedback and Tutorial Material

- We appreciate if you could take five minutes to complete the following evaluation form:

  http://tiny.cc/iot5g

- Your feedback is important to us in order to continually improve our tutorial
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  https://github.com/samerlahoud/tutorial-lpwan-iot

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