Cellular Internet of Things

Framework, Optimization, and Challenges of NB-IoT

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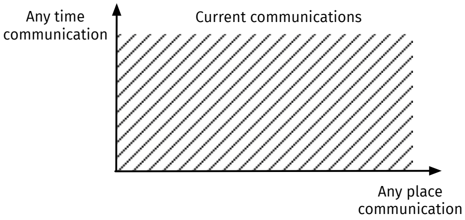
Tutorial Outcomes

- How do LPWAN complement traditional cellular and short-range wireless technologies?
- What are the fundamental mechanisms that enable to meet the LPWAN requirements?
- What are the major design choices made in the LoRaWAN and NB-IoT specifications?
- How do we evaluate the performance of a LoRaWAN and NB-IoT deployment in terms of coverage and capacity?
- What are the recent research directions for radio resource management in LoRaWAN and NB-IoT?

Outline

A New Dimension in Communications



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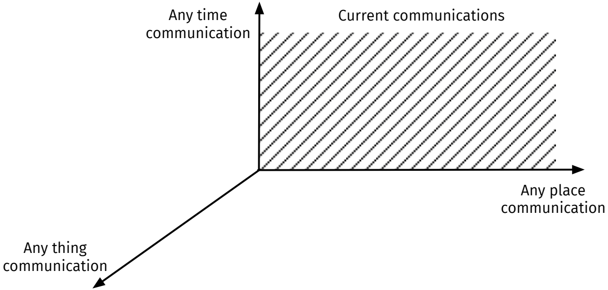
- Current communications brought the ABC (Always Best Connected) paradigm
- The Internet of Things (IoT) explores a new dimension in communications

A New Dimension in Communications



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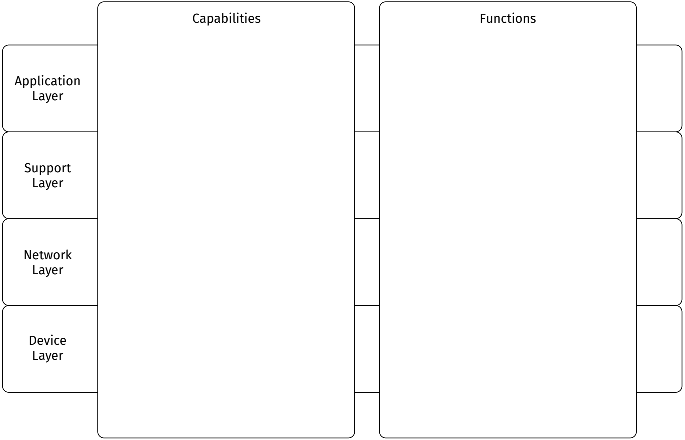
IoT Scenarios

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

IoT Reference Model



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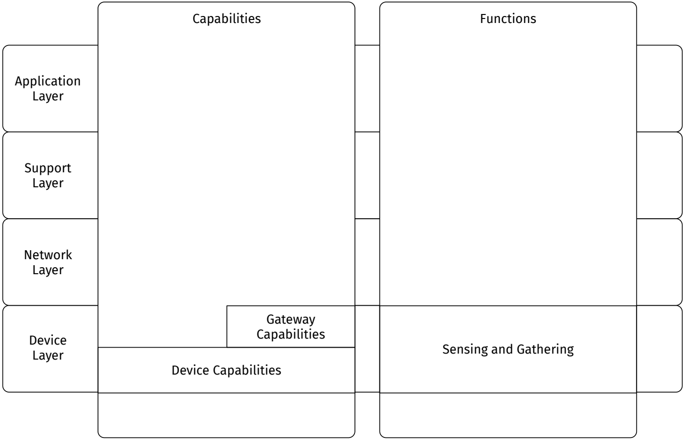
IoT Reference Model



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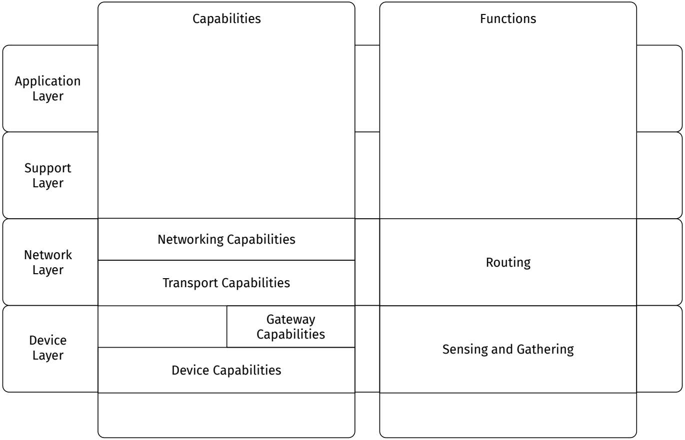

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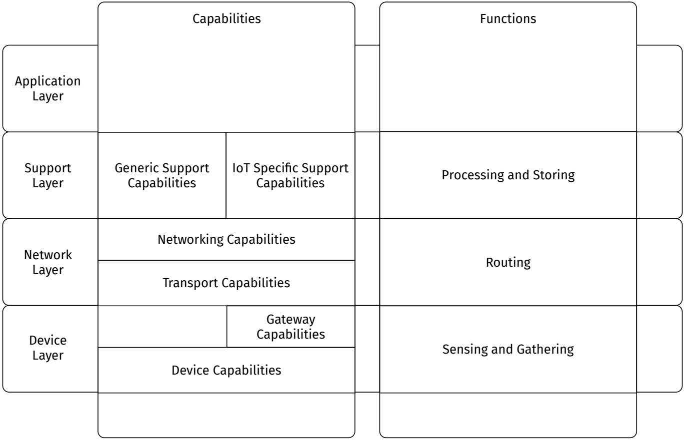

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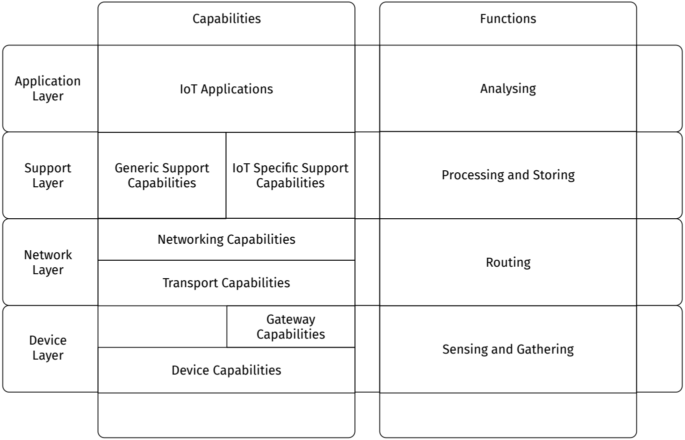

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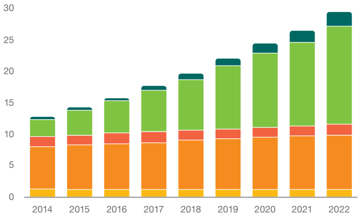
Evolution of IoT Devices

- The largest growth is expected for devices connected to a wide-area network

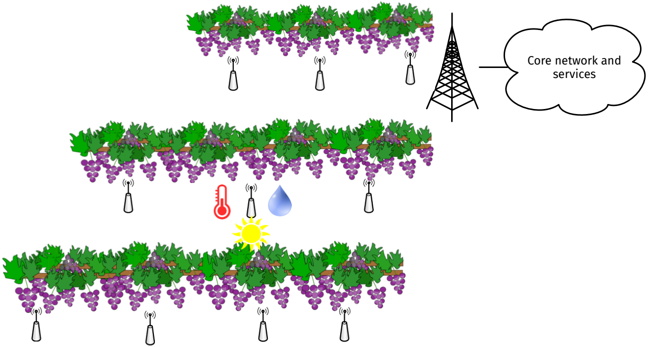
Connected devices (billions)



	2016	2022	CAGR
Wide-area IoT	0.4	2.1	30%
Short-range IoT	5.2	15.5	20%
PC/laptop/tablet	1.6	1.7	0%
Mobile phones	7.3	8.6	3%
Fixed phones	1.4	1.3	0%
	16 billion	29 billion	

Source: Ericsson mobility report, 2017

The Case of IoT for Smart Agriculture



- Periodic sensing of microclimates in vineyards

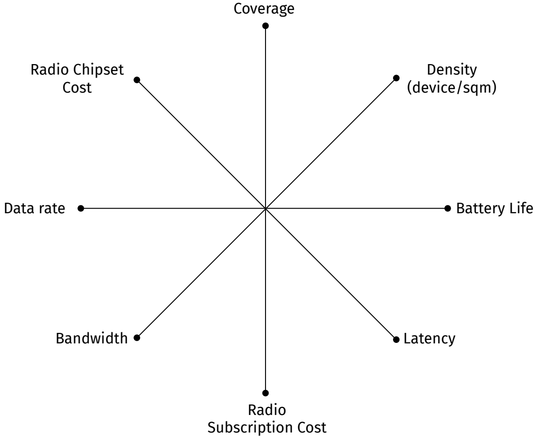
Constraints on the Device and Network Layers

- 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?

LPWAN Sweet Spot



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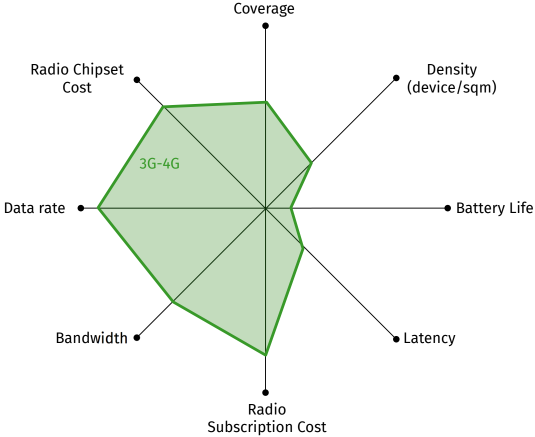

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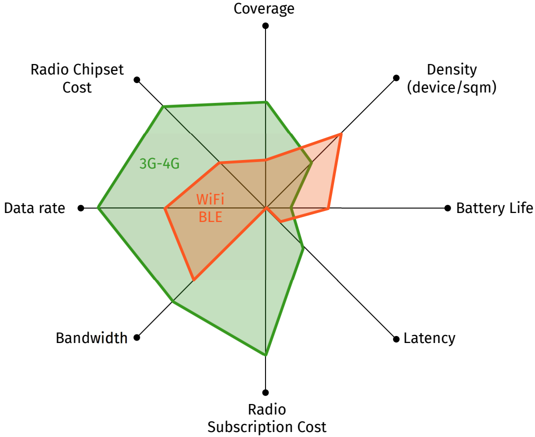

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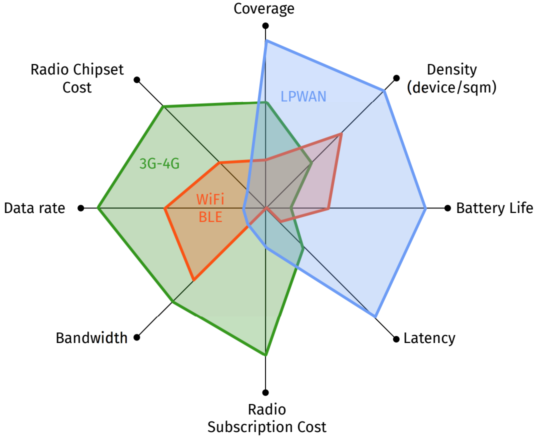

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LPWAN Scenarios

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)

- Typical scenarios for LPWAN (Usman Raza et al., Low Power Wide Area Networks: An Overview, IEEE Communications Surveys & Tutorials, 2017)
  - Smart grid
  - Industrial asset monitoring
  - Critical infrastructure monitoring
  - Agriculture

LPWAN Requirements

Indicator	Requirement
Power consumption	Devices operate for 10 years on a single charge
Device unit cost	Below $5 per module
Dependability	Completely unattended and resilient operation
Coverage	Improved outdoor and indoor penetration coverage
Security	Secure connectivity and strong authentication
Data transfer	Supports small, intermittent blocks of data
Design complexity	Simplified network topology and deployment
Network scalability	Support of high density of devices

LPWAN Technologies

Various technologies are currently being designed to meet the LPWAN requirements: LoRaWAN, NB-IoT, Sigfox, Wi-SUN, Ingenu, etc.

Outline

Revisiting LPWAN 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

Objectives and Approaches

- Develop a *clean-slate* technology that meets the LPWAN requirements
  $\Rightarrow$ LoRaWAN
- Adapt and leverage existing 4G technology to meet the LPWAN requirements
  $\Rightarrow$ NB-IoT

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: Downlink (DL) Transport Block Size (TBS) = 680 bits (R13), or 2536 bits (R14); Uplink (UL) TBS = 1000 bits (R13), or 2536 bits (R14)
  - using simple channel codes: LTE tail-biting convolution code (TBCC) in the DL; LTE turbo code, or repetition code in the UL
  - not using complex modulations or multiple-input multiple-output (MIMO) transmissions: QPSK in the DL; QPSK in the UL multi-tone; $\pi/4$-QPSK, or $\pi/2$-BPSK in the UL single-tone
  - supporting only half-duplex operation: no simultaneous transmission and reception

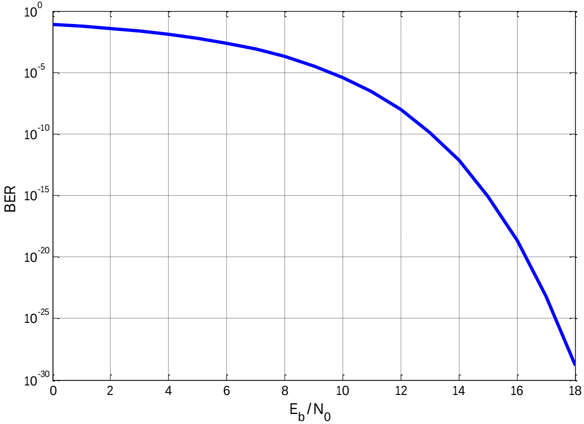
RF Processing

- 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

Radio Quality

- Reliability $\Rightarrow$ bit error rate (BER) $\leq$ target BER
- The energy per bit to noise power spectral density ratio (E_b/N_0) is defined as the ratio of the energy per bit (E_b) to the noise power spectral density (N_0)



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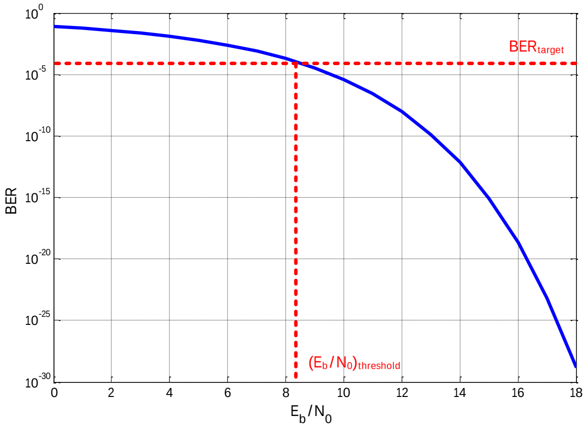


Radio Quality

$$BER \leq BER_{target} \Leftrightarrow \frac{E_b}{N_0} \geq \left(\frac{E_b}{N_0}\right)_{threshold}$$

- $(E_b/N_0)_{threshold}$ does not depend on the signal bandwidth and bit-rate
- 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

$$SNR = \frac{C}{N} = \frac{E_b/T_b}{N_0 B} = \frac{E_b}{N_0}\frac{R_b}{B}$$

where B is the signal bandwidth in Hz, and R_b is the bit-rate in b/s.

Receiver Sensitivity

$$BER \leq BER_{target} \quad \Leftrightarrow \quad SNR \geq \underbrace{\left(\frac{E_b}{N_0}\right)_{threshold} \frac{R_b}{B}}_{SNR_{threshold}}$$

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

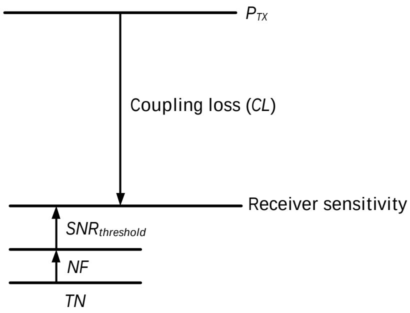
- N (dBm) is the background noise power at the receiver $= TN$ (dBm) $+NF$ (dB)
  - TN is the thermal noise caused by thermal agitation of charge carriers: $-174 + 10\log_{10}(B)$
  - NF is the noise figure caused by RF components

Maximum Coupling Loss

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

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

where P_{Tx} is the transmit power in 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

  $\Rightarrow$ inadequate solutions
- Reducing B leads to lower network capacity $\Rightarrow$ inadequate solution
- Reducing $SNR_{threshold}$ through repetitions and efficient HARQ retransmissions

Repetitions in NB-IoT

Signal Combination

- Users 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

$$(SNR)_N \text{ (dB)} = \underbrace{10\log_{10}(N)}_{G_p} + (SNR)_1$$

where $(SNR)_N$ is the ideal *SNR* after combining *N* transmissions and $(SNR)_1$ is the *SNR* of a single transmission.

$$(SNR)_N \geq SNR_{threshold} \Rightarrow (SNR)_1 \geq \underbrace{SNR_{threshold} - 10\log_{10}(N)}_{\text{Reduced } SNR_{threshold}}$$

Real vs. Ideal Processing Gain

- In practice, combining two signals is rarely perfect: signal impairments will result in a lower overall processing gain
- For N between 2 and 16, the ideal gain can be achieved without any visible degradation[1]

[1] Simulations have been carried out for EC-GSM-IoT in O. Liberg et al., *Cellular Internet of Things - Technologies, Standards, and Performance*. Cambridge, MA, USA: American Press, 2017.

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
  - open receive windows, or monitor paging channels

Battery Lifetime

- Battery lifetime is increased through:
  - optimizing device reachability: devices monitor paging channels either periodically, or only after a mobile-originated data transfer (for a short period of time).
    extended Discontinuous Reception (eDRX) and *Power-Saving Mode (PSM)* support these operations.
  - reducing signaling messages when a device needs to transmit data: suspend/resume (rather than release/re-establish) user plane connection, or transfer data over non-radio signaling

High Capacity

Support for Massive Number of Low-Rate Devices

- Trading off data rate for coverage
- How to increase network capacity?
    - NB-IoT uses single-tone transmissions in the UL when coupling loss is high

Why Single-Tone Transmissions?

- The channel capacity C is given by:

$$C = B\log_2(1+\frac{S}{N}) = B\log_2(1+\frac{S}{N_0B})$$

- When coupling loss is high, $\frac{S}{N_0B} \ll 1 \Rightarrow \ln(1+\frac{S}{N_0B}) \approx \frac{S}{N_0B}$.

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

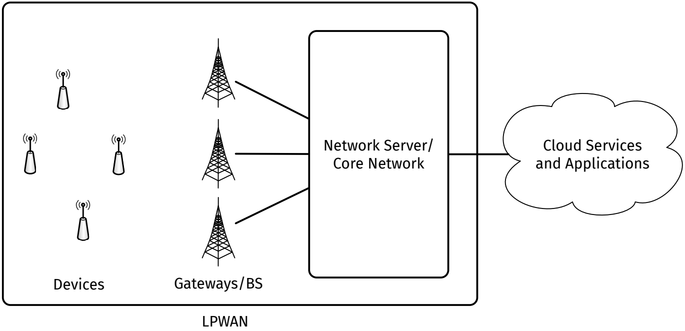
C no longer depends on B

$\Rightarrow$ allocate a single tone (subcarrier) for devices in bad coverage to increase network capacity without loss of performance

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



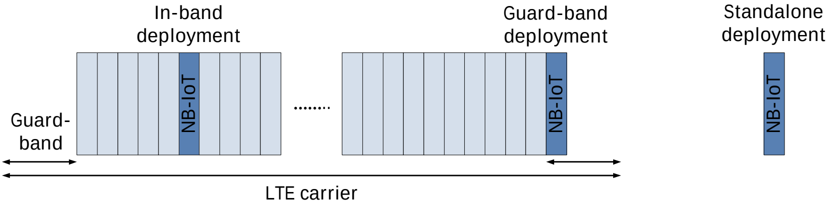
Outline

What is NB-IoT?

- NB-IoT is part of the 3GPP LTE specifications: Releases 13 and 14
- 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)



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
- Maximum Transport Block Size (TBS):
  - 680 bits (R13), or 2536 bits (R14), mapped over up to 10 subframes (10 ms) in the DL

Radio Interface

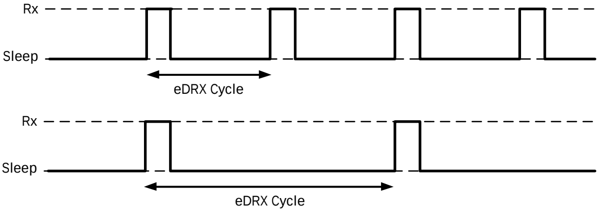
  - 1000 bits (R13), or 2536 bits (R14), mapped over up to 10 RUs in the UL
- Modulations:
  - QPSK in the DL
  - QPSK (for multi-tone transmission), $\pi/4$-QPSK, or $\pi/2$-BPSK (for single-tone transmission) in the UL
- Channel codes:
  - LTE tail-biting convolution code (TBCC) in the DL
  - LTE turbo 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

Device Reachability

- To reduce device power consumption, devices that have had no traffic for a predefined period of time (inactivity timer) are switched to idle mode
- Idle devices monitor paging channels either periodically, or only after a mobile-originated data transfer (for a short period of time)
    - extended Discontinuous Reception (eDRX)
    - Power-Saving Mode (PSM)

extended Discontinuous Reception (eDRX)

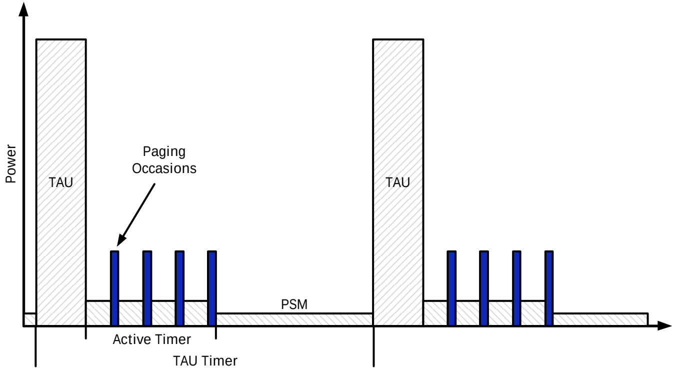
- An eDRX cycle is the time period between two paging occasions a device needs to monitor (up to 2 h, 54 min, and 46 s)
- In between these two occasions, the device is assumed to be in deep sleep mode
- The eDRX cycle is negotiated on a per-device basis



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



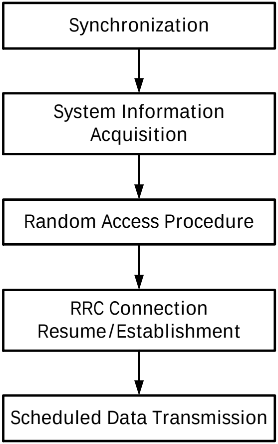
Operation in PSM including periodic TAU

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)

Cell Access

- From idle to connected mode:

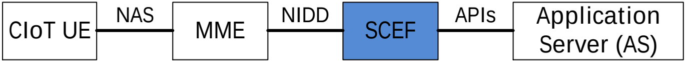


Data Transport

- 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)

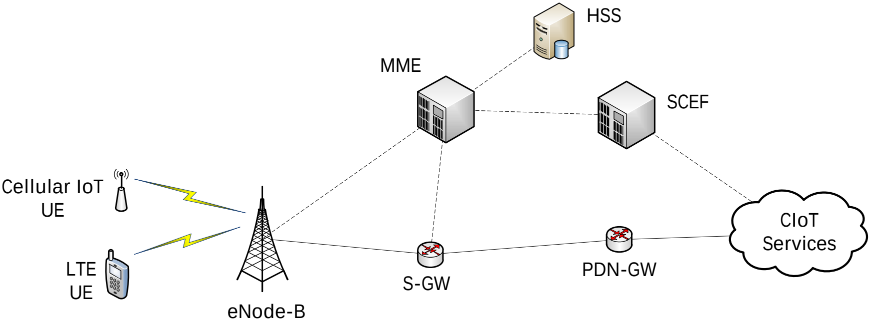
- To further reduce device power consumption, non-IP data transfer is also supported
- Non-IP data is transferred over non-radio signaling:
    - Non-IP data is encapsulated in non-radio signaling messages and is sent to the MME
    - The MME extracts the data and forwards it to the SCEF (Service Capability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

Physical Architecture



SCEF: Service Capability Exposure Function

Mobility Management

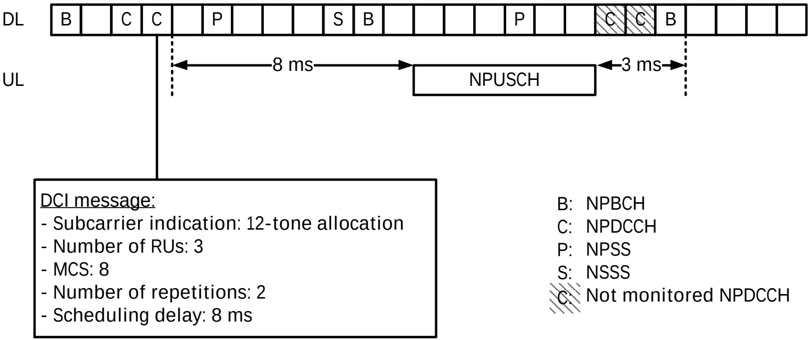
- Mobility management is limited to idle mode and is performed through cell reselection (with tracking area updates)
- Handover management is not supported, as NB-IoT is designed for infrequent and short messages
  - Connected devices do not perform mobility measurements
  - In case of connection loss (persistent link-layer failures), they switch to idle mode
  - In idle mode, they initiate cell reselection and then switch back to connected mode

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[2]:



[2] 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

  $\Rightarrow$ 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:

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

where P_{target} is the target received power, L is the estimated path loss, α is a path loss adjustment factor, and 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

Link Budget Analysis

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 of a network wireless link can be expressed as:

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

where:

P_{Rx} = the expected received power

P_{Tx} = the transmitted power

G_{System} = system gains such as antenna gains

L_{System} = system losses such as feed-line losses

$L_{Channel}$ = 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
- Protection margin

Maximum Allowable Path Loss

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

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

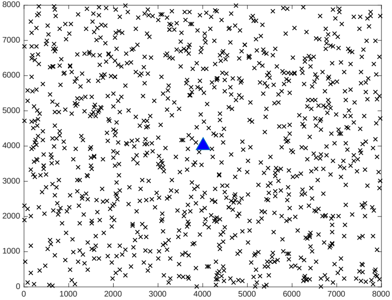
$$\Rightarrow MAPL = P_{Tx} + G_{System} - L_{System} - M - \text{receiver sensitivity}$$

- The maximum allowable distance between a transmitter and a receiver (cell range) depends on the *MAPL* and the channel model

Coverage of LoRaWAN

Evaluation Scenario

- Area
  - Surface: square of 8 Km $\times$ 8 Km
  - Number of end-devices: 1000
  - Distribution of end-devices: uniform
  - Single gateway
  - Environment type: urban
- Radio link
  - Bandwidth: 125 kHz
  - Transmit power: 14 dBm
  - Gateway height: 30 m
  - End-device height: 1.5 m
  - Antenna gains: 6 dBi
  - Noise floor: -153 dBm
  - Pathloss: Okumura-Hata
  - Shadow fading: lognormal $\mathcal{N}(0, 8)$



Pathloss Model

- Using the Okumura-Hata urban model, the pathloss between device i and the gateway is proportional to the logarithm of the distance $d(i,g)$ in Km:

$$L_{Channel}(i) = A + B\log_{10}(d(i,g))$$

- The two parameters A and B depend on the antenna heights ($h_b = 30$ m for the gateway and $h_d = 1.5$ m for the end-device) and the central frequency $f_c = 868$ MHz

$$A = 69.55 + 26.16\log_{10}(f_c) - 13.82\log_{10}(h_b) - 3.2(\log 10(11.75h_d))^2 + 4.97$$

$$B = 44.9 - 6.55\log_{10}(h_b)$$

Link Budget

- We consider the following parameters:
  - Transmit power: $P_{Tx} = 14$ dBm
  - Antenna gain: $G_{System} = 6$ dBi
  - Fading and protection margin: $M = 10$ dB
  - Noise floor: $N = -153$ dBm
- We can now compute the received power $P_{RX}(i)$ and $\text{SNR}(i)$ at the gateway for end-device i:

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

$$\text{SNR}(i) = P_{Rx}(i) - N$$

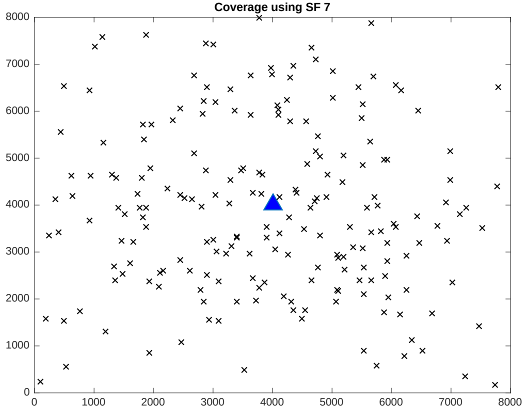
Spreading Factor Selection

- The spreading factor for each end-device is selected using the following matching table (Source: SX1276/77/78/79 Semtech datasheet):

SNR Interval (dB)	Spreading Factor
[-7.5, $+\infty$[	7
[-10, -7.5[	8
[-12.5, -10[	9
[-15, -12.5[	10
[-17.5, -15[	11
[-20, -17.5[	12

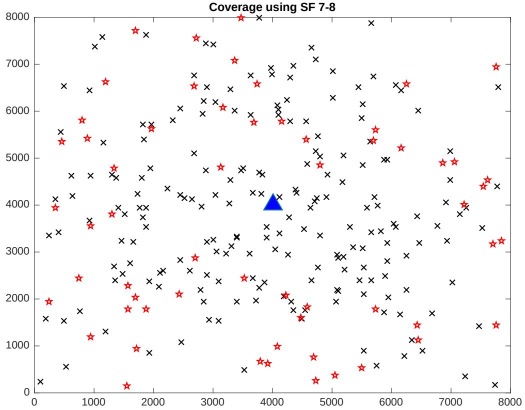
- Note that for SNR values lower that -20 dB, the end-device is considered out of coverage of the gateway

Coverage Study



Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	40.50	51.60	61.60	70.40	77.70	86.10

Coverage Study



Spreading Factor	7	8	9	10	11	12
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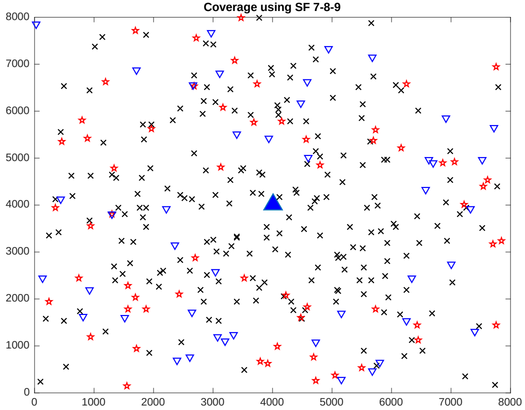
Coverage Study



Spreading Factor	7	8	9	10	11	12
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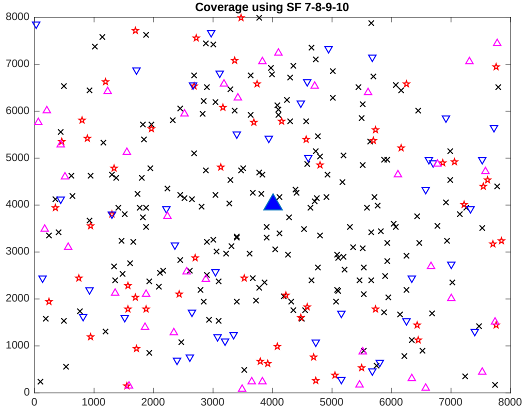
Coverage Study



Spreading Factor	7	8	9	10	11	12
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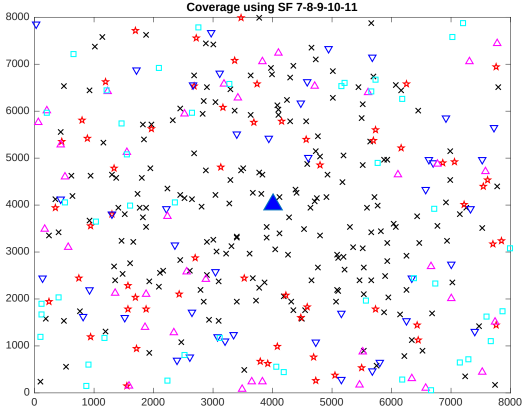
Coverage Study



Spreading Factor	7	8	9	10	11	12
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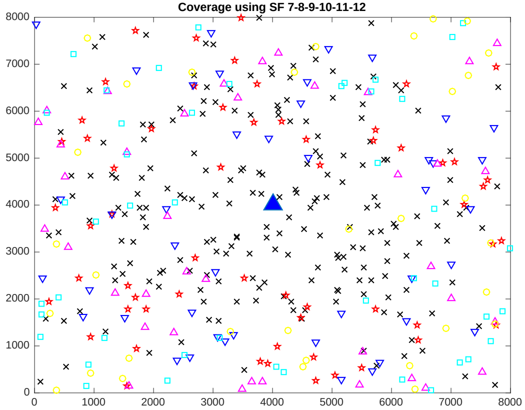
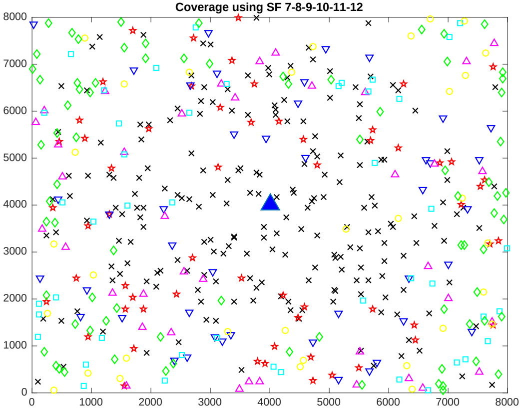
Coverage Study



Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	40.50	51.60	61.60	70.40	77.70	86.10

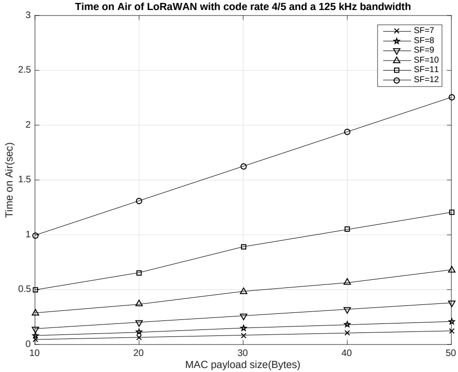
Coverage Study



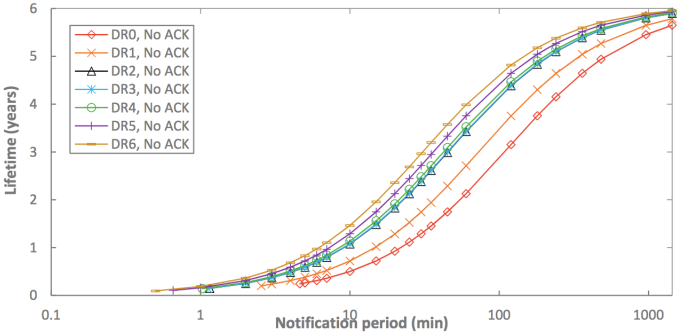
Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	40.50	51.60	61.60	70.40	77.70	86.10

Spreading Factor and Time on Air

- The Time on Air is defined as the time required to transmit a packet in a sub-band
- The selection of the spreading factor impacts the Time on Air and consequently determines the duty cycle limitation



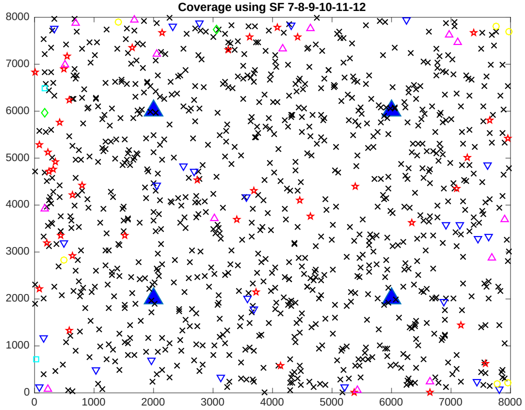
Spreading Factor and Energy Consumption



Source: Lluís Casals *et al.*, Modeling the Energy Performance of LoRaWAN, Sensors, 2017

- DR0 to DR5 correspond to spreading factors 12 to 7 with a bandwidth of 125 kHz. DR6 correspond to spreading factor 7 and a bandwidth of 250 kHz
- For an end-device sending packets every 100 minutes, changing the spreading factor from 12 to 7 increases its lifetime by almost 1.5 years

Enhancing the Coverage with Multiple Gateways

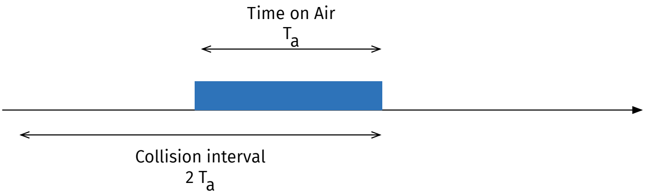


Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	88.70	94.50	97.60	99.20	99.60	100.00

Capacity of LoRaWAN

Pure ALOHA Model

- The start times of the packets in an ALOHA channel is modeled as a Poisson point process with parameter λ packets/second



- If each packet in the channel lasts T_a seconds, the normalized channel traffic can be defined as

$$G = \lambda T_a$$

- The normalized throughput of the ALOHA random access channel is given by

$$S = G \exp(-2G)$$

ALOHA Model for LoRaWAN

- We consider the case where only one spreading factor and one sub-channel are available
- The general case of multiple sub-channels and spreading factors can be easily inferred
  - Multiple spreading factors are orthogonal
  - Packets are uniformly transmitted on available sub-channels
- The time to transmit a packet of l bytes (size of MAC payload) on spreading factor s is denoted $T_a(l, s)$
- Given a duty cycle limitation of $d = 1\%$, the packet generation rate for each end-device operating on spreading factor s must verify:

$$\lambda(s) \leq \frac{d}{T_a(l, s)}$$

- The normalized channel traffic for N end-devices is obtained as follows:

$$G = N.\lambda(s).T_a(s)$$

Capacity Formulas for LoRaWAN

- We consider a LoRaWAN network with N end-devices and one gateway
  - One spreading factor s and one sub-channel are available
  - Transmit attempts are done according to a Poisson distribution
  - All end-devices have the same packet generation rate $\lambda(s)$
  - All packets have the same length of l bytes
- The normalized throughput of the LoRaWAN network is given by:

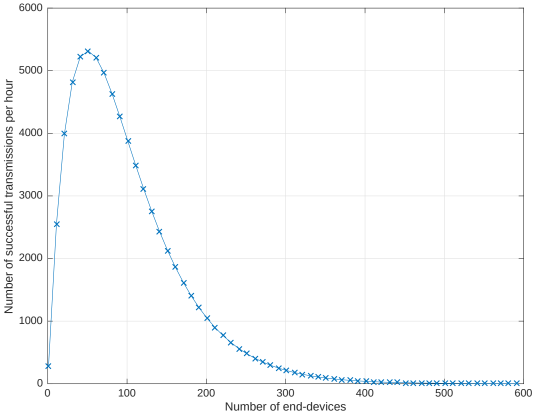
$$S = G\exp(-2G) = N\lambda(s)T_a(l,s)\exp(-2N\lambda(s)T_a(l,s))$$

- The total number of transmitted packets per second that are successfully received by the gateway (referred to as successful transmissions in the following) is obtained by:

$$\frac{1}{T_a(l,s)} \times S$$

Successful Transmissions per Hour

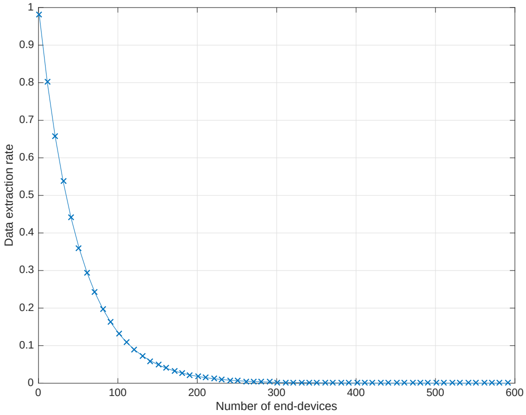
- The number of successful transmissions per hour decreases for more than 50 end-devices



l=50 bytes, SF=7, $\lambda(s) = \frac{d}{T_a(l,s)}$

Data Extraction Rate

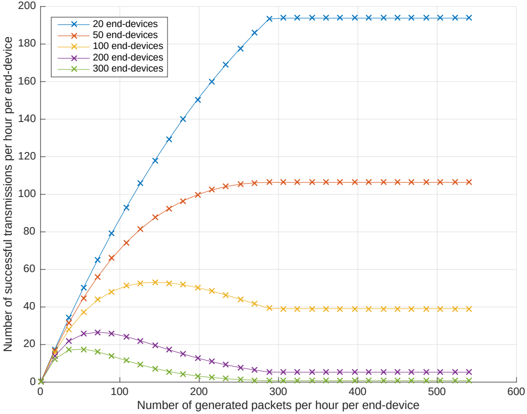
- For 100 end-devices the percentage of successful transmissions is equal to 14% (the average number of successfully transmitted packets per end-device equals 40 per hour, out of 289 generated packets)



l=50 bytes, SF=7, $\lambda(s) = \frac{d}{T_a(l,s)}$

Packet Generation Rate

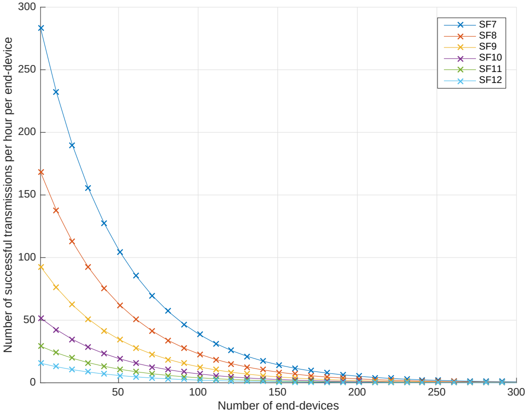
- For small number of end-devices, the throughput is limited by the duty cycle
- For large number of end-devices, the throughput is limited by collisions



l=50 bytes, SF=7

Spreading Factors and Successful Transmissions

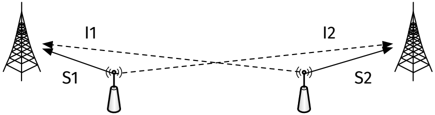
- For 50 end-devices, the average number of successful transmissions per end-device per hour increases from 6 to 106 when SF decreases from 12 to 7



l=50 bytes, $\lambda(s) = \frac{d}{T_a(l,s)}$

Collisions and Capture Effect

- It is assumed by default that all transmitted signals that collide will fail to be received
- In practice, the strongest received signal may be successfully received despite the presence of interfering signals $\Rightarrow$ capture effect
- The capture effect depends on:
  - The receiver sensitivity
  - The signal to noise plus interference ratio SINR
- The presence of multiple receivers favors the capture effect



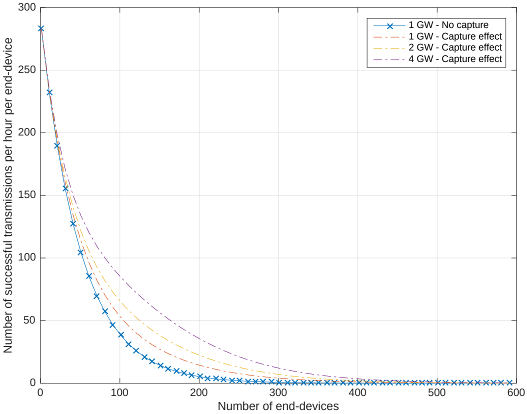
Applying the Capture Effect for LoRaWAN

- We consider a LoRaWAN network with N end-devices and r gateways
- We take $G = N\lambda(s)T_a(l,s)$, where $\lambda(s)$ is the packet generation rate of each end-device, and $T_a(l,s)$ the time to transmit a packet of l bytes
- We assume that a packet is successfully received by one gateway if the corresponding received signal power is higher than the maximum interferer
  - We consider an additional margin of Δ dB (Δ equals 3 dB or 6 dB in practice)
- The probability of successful transmission of one packet when n collisions occur is denoted by $P_{cap}(n,\Delta)$
- The normalized throughput of the LoRaWAN network is given by:

$$S = G\exp(-2G)(1 + \sum_{n=2}^{N} \frac{(2G)^n}{n!}(1-(1-P_{cap}(n,\Delta))^r))$$

Successful Transmissions with Capture Effect

- For 100 end-devices, the number of successful transmissions per hour per end-device increases from 38 to 52 when considering the capture effect with one gateway, and reaches 84 with 4 gateways

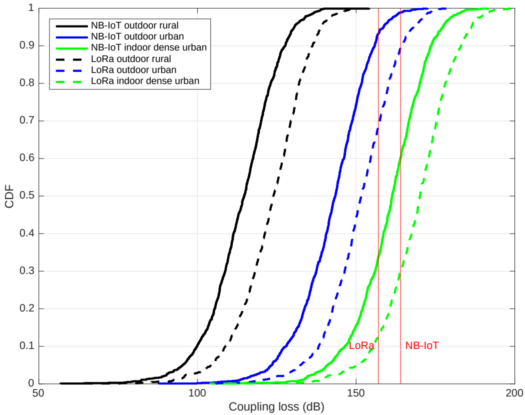


l=50 bytes, SF=7, $\lambda(s) = \frac{d}{T_a(l,s)}$, $\Delta = 6$ dB

Coverage Comparison of LoRaWAN and NB-IoT

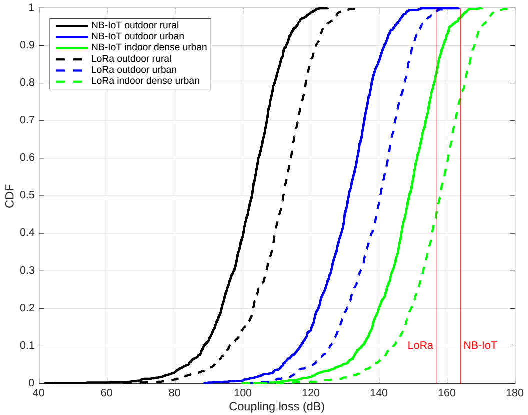
Coupling Loss

- Coverage outage $\Rightarrow$ coupling loss $> MCL$ (NB-IoT: 164 dB, LoRaWAN: 157 dB)
- In indoor dense urban environments, the outage probability of LoRaWAN is 87% (with a single gateway)



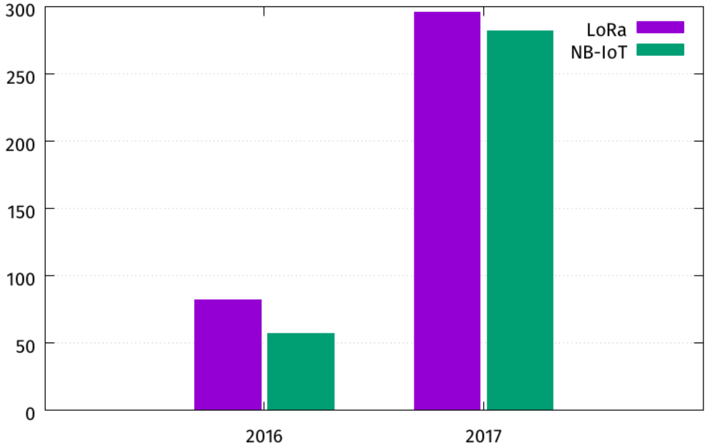
Enhancing the Coverage with Multiple Gateways

- Network densification decreases the outage probability of LoRaWAN to 55%
- LoRaWAN has coverage limitations in comparison with NB-IoT



Outline

Interest of the Scientific Community



LoRa and NB-IoT in titles of scientific publications. Source: Google scholar, 2018

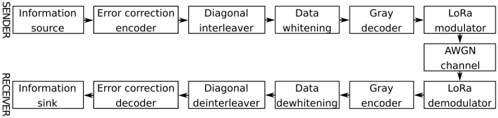
Analyzing the Limits of LoRaWAN

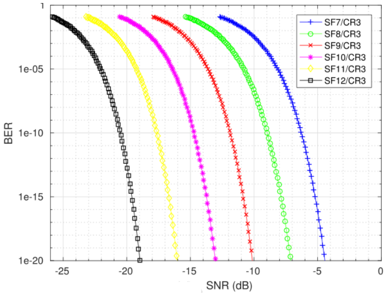
Research Approaches for Analyzing LoRaWAN

- The research studies analyze the performance of LoRaWAN networks considering different criteria:
  - Capacity
  - Coverage
  - Energy
  - Delay
  - Fairness
- The research studies use different methods to obtain the performance results:
  - Simulation
  - Mathematical modeling
  - Measurement campaigns

Simulation of the LoRa Bit Error Rate[3]

- Implementation of the LoRa physical layer in ns-3
- Simulation of the Bit Error Rate (BER): $\log_{10}(BER(SNR)) = \alpha \exp(\beta SNR)$

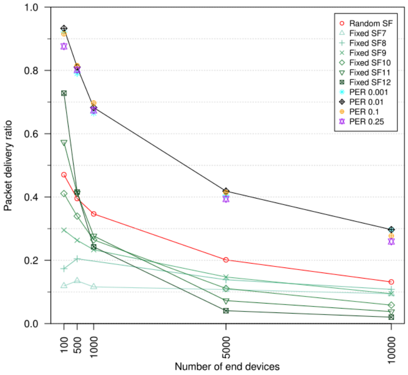




[3] Van den Abeele, Floris, et al. "Scalability analysis of large-scale LoRaWAN networks in ns-3." IEEE Internet of Things Journal 4.6 (2017)

Basic Assignment of Spreading Factors[4]

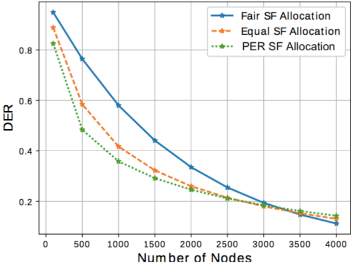
- Assigning spreading factors based on a packet error ratio threshold gives the highest Packet Delivery Ratio (PDR)
- However, this basic assignment leads to unfairness between end-devices using different spreading factors

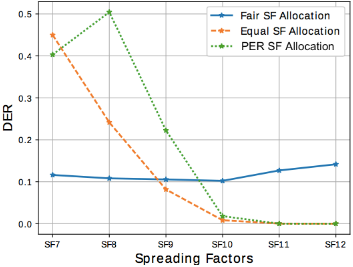


[4] Van den Abeele, Floris, et al. "Scalability analysis of large-scale LoRaWAN networks in ns-3." IEEE Internet of Things Journal 4.6 (2017)

Fair Assignment of Spreading Factors[5]

- Fairness is achieved by minimizing the maximum collision on spreading factors: $\min \max_s p_{coll,s}$
  - The minimum is reached for a fraction p_s of end-devices using spreading factor s given by $p_s = \frac{s}{2^s} / \sum_{i=7}^{12} \frac{i}{2i}$
- Fairness does not hinder the data extraction rate DER (the ratio of received packets to transmitted packets over a period of time)

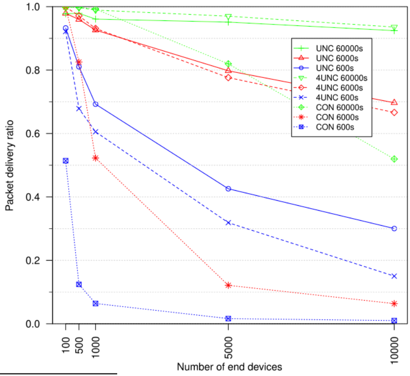




[5] Reynders, Brecht, Wannes Meert, and Sofie Pollin. "Power and spreading factor control in low power wide area networks." 2017 IEEE International Conference on Communications (ICC) (2017)

Impact of Confirmed Messages[6]

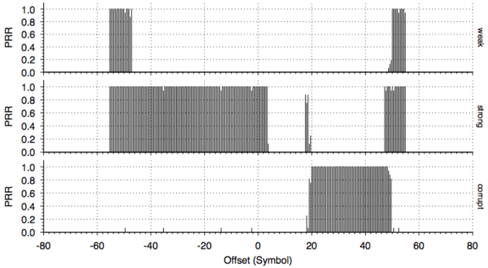
- Repeating unconfirmed messages or using confirmed mode increases the PDR only when the traffic load is very low
- For high traffic load, the PDR of confirmed mode is limited by the duty cycle and half-duplex transmission



[6] Van den Abeele, Floris, et al. "Scalability analysis of large-scale LoRaWAN networks in ns-3." IEEE Internet of Things Journal 4.6 (2017)

Measurement of the Capture Effect[7]

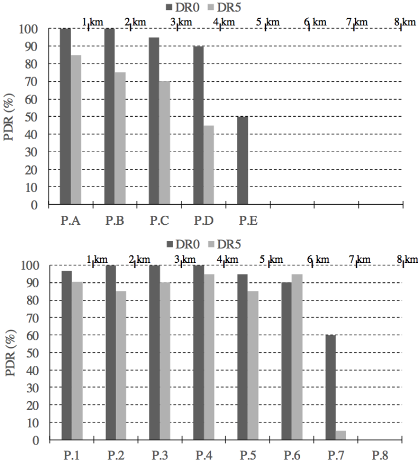
- Experimentation (55.25 symbols packet length) shows the packet reception rate as function of transmission offset relative to the weak node in symbols
- A strong transmission can be successfully decoded when it arrives one packet time early up to at most 3 symbols late
- Capture model integrated in a discrete-event simulator (LoRaSim)



[7] Bor, Martin C., et al. "Do LoRa low-power wide-area networks scale?." Proceedings of the 19th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems. ACM (2016)

Experimental Study of Coverage[8]

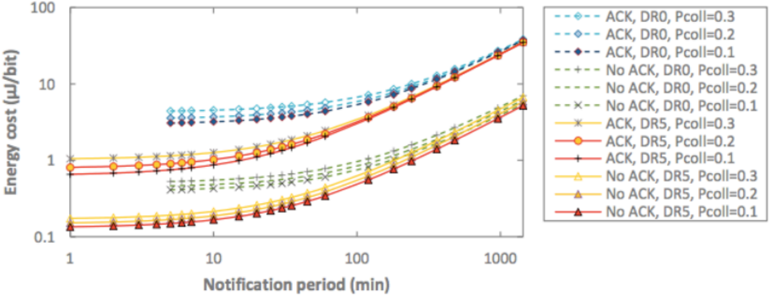
- PDR in a nomadic test for urban (top) and suburban (bottom) scenarios near Murcia



[8] Sanchez-Iborra, Ramon, et al. "Performance Evaluation of LoRa Considering Scenario Conditions." Sensors 18.3 (2018)

Energy Model for LoRaWAN Devices[9]

- Model the current consumption of different LoRaWAN end-devices
  - Identify the different states of the end-device, and measure the respective current consumption and duration (e.g., wake up, transmission, receive window, sleep)
- Example of using the model: collisions increase the energy required per delivered payload bit especially for confirmed mode



[9] Casals, Lluís, et al. "Modeling the Energy Performance of LoRaWAN." Sensors 17.10 (2017)

Model for the Macro-Diversity Gain[10]

- End-device and gateway positions form a stationary Poisson point process with spatial density λ_m and λ_b, respectively
- The spatial density of end-devices that are transmitting a packet is $p\lambda_m$
- The transmit success probability is defined as

$$p_s = \mathbb{P}\{SINR = \frac{P_r}{I+N} \approx \frac{P_r}{I} \geq \theta\}$$

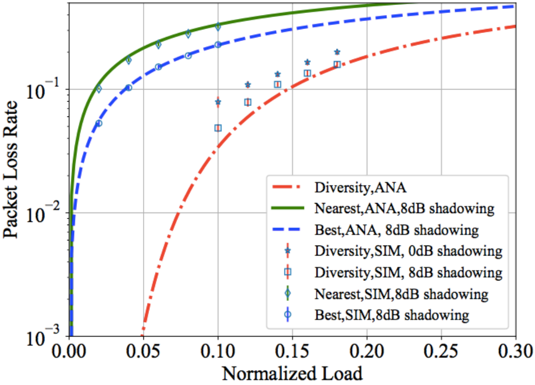
- With macro reception diversity, the transmission fails if and only if none of the gateways has received the packet
- Let γ be the path-loss exponent, H an exponentially distributed random variable with unit mean, χ a zero-mean Gaussian r.v. with variance σ^2, the network packet loss rate P_f can be written as:

$$P_f = \exp\left(-\frac{\lambda_b}{A\theta^{\frac{2}{\gamma}} p\lambda_m}\right)$$

[10] Song, Qipeng, Xavier Lagrange, and Loutfi Nuaymi. "Evaluation of Macro Diversity Gain in Long Range ALOHA Networks." IEEE Communications Letters 21.11 (2017)

Evaluation of Macro-Diversity[11]

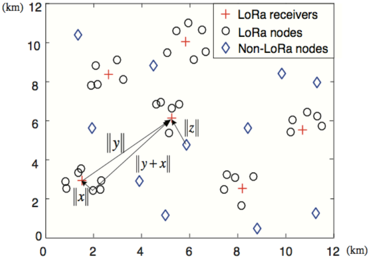
- Macro diversity leads to lower packet loss rate than the cases where the end-device attaches to the nearest gateway or to the gateway corresponding to the strongest received power



[11] Song, Qipeng, Xavier Lagrange, and Loutfi Nuaymi. "Evaluation of Macro Diversity Gain in Long Range ALOHA Networks." IEEE Communications Letters 21.11 (2017)

Model for the Coexistence of LoRa with Other Technologies[12]

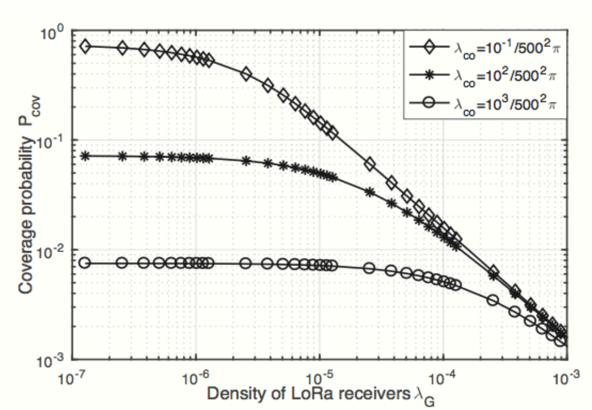
- Coexistence of LoRa and non-LoRa nodes
  - LoRa nodes position form a Matern cluster process (PPP cluster center is formed by LoRa gateways and the end-devices in each cluster form the children process)
  - Non-LoRa nodes are modelled as PPP
- In the SINR expression, interference is the sum of three terms: intra-cluster, inter-cluster, and coexistence



[12] Qin, Zhijin, et al. "Modelling and analysis of low-power wide-area networks." IEEE International Conference on Communications (ICC) (2017)

Coverage of LoRa with Coexisting Technologies[13]

- The coverage probability monotonically decreases with the density of gateways and non LoRa nodes



[13] Qin, Zhijin, et al. "Modelling and analysis of low-power wide-area networks." IEEE International Conference on Communications (ICC) (2017)

Going Beyond LoRaWAN

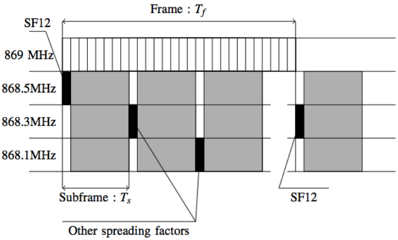
Disentangling Interfering Transmissions[14]

- Exploit hardware imperfections in LoRa transmitters to resolve collisions
  - Signals from colliding transmitters are likely to experience a small frequency offset
- Decode useful data
  - Frequency offset remains constant over a packet between chirps but data does not
- Attribute data to users
  - Data bits occur on integer peak locations in the Fourier transform, while frequency offsets need not
- Results: decoding collisions and extending range of LoRa transmission

[14] Eletreby, Rashad, et al. "Empowering Low-Power Wide Area Networks in Urban Settings." Proceedings of the Conference of the ACM Special Interest Group on Data Communication (2017)

Scheduling for Improving Reliability[15]

- Two-step lightweight scheduling
  - Gateway schedules nodes in a coarse-grained manner through dynamically specifying the allowed transmission powers and spreading factors on each channel
  - Based on the gateway scheduling information, an end-device determines its own transmission power, spreading factor, and when and on which channel to transmit
- Results: increase throughput and fairness for large scenarios



[15] Reynders, Brecht, et al. "Improving Reliability and Scalability of LoRaWANs Through Lightweight Scheduling." IEEE Internet of Things Journal (2018)

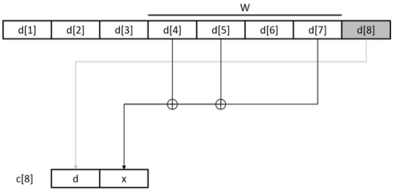
Learning for Improving Latency[16]

- Derive closed-form expressions for the probability of a successful transmission into one channel with a simple acknowledgement
- Derive the expression of the latency for different frequency access schemes
- Selection of the best channel requires the knowledge of the probability of collision in the channels
    - MAB problem (acknowledgement as a reward) with reinforcement learning algorithms
- Results: increase success probability and reduce latency over time

[16] Bonnefoi, Rémi, Christophe Moy, and Jacques Palicot. "Improvement of the LPWAN AMI backhaul's latency thanks to reinforcement learning algorithms." EURASIP Journal on Wireless Communications and Networking 2018.1 (2018)

Application Layer Coding for Data Recovery[17]

- Thorough characterization of losses in LoRaWAN: channel outage, burstiness $\Rightarrow$ Gilbert Elliot model for bursty erasure channels
- Spread the redundant information from the data in one frame across other frames



- Results: tuning the coding parameters and increasing data recovery ratio

[17] Marcelis, Paul J., Vijay S. Rao, and R. Venkatesha Prasad. "DaRe: Data recovery through application layer coding for LoRaWAN.", IEEE/ACM Second International Conference on Internet-of-Things Design and Implementation (IoTDI) (2017)

Conclusions (1/4)

- How do LPWAN complement traditional cellular and short-range wireless technologies?
  - LPWAN devices function for many years on a single battery charge
  - LPWAN devices communicate from locations where shadowing and path loss would limit the usefulness of more traditional cellular technologies
- What are the fundamental mechanisms that enable to meet the LPWAN requirements?
  - Short messages, low complexity codes and modulations
  - Low receiver sensitivity
  - Optimized reachability and low signaling
  - Multiple transmissions on the same channel
  - Simplified architecture

Conclusions (2/4)

- What are the major design choices made in the LoRaWAN and NB-IoT specifications?

	LoRaWAN	NB-IoT
Reliability	CSS-based LoRa	Repetitions
Power consumption	Short receive windows	eDRX, PSM modes
Capacity	Multiple SFs	Single tone transmission
Deployment	Simple architecture	Architecture reuse

Conclusions (3/4)

- How do we evaluate the performance of a LoRaWAN and NB-IoT deployment in terms of coverage and capacity?
  - Combination of simulation, mathematical modeling and measurement campaigns
  - Performance evaluations should take into account collisions and duty cycle in LoRaWAN, scheduling and signaling in NB-IoT

Global performance

- LoRaWAN shows coverage limitations compared to NB-IoT especially in indoor dense urban environments
- Collisions hinder the performance of LoRaWAN in heavy loaded networks

Conclusions (4/4)

- What are the recent research directions for radio resource management in LoRaWAN and NB-IoT?
  - Adaptation of the radio propagation models
  - Interference mitigation and scheduling
  - Support for quality of service such as delay bounded transmission
  - Maximization of the energy efficiency
  - Providing IPv6 connectivity to the device (IETF lpwan working group)

Feedback and Tutorial Material

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

  https://goo.gl/Ex7mg9

- 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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