

Low Power Wide Area Networks for the Internet of Things

Framework, Performance Evaluation, and Challenges of
LoRaWAN and NB-IoT

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Tutorial Outcomes

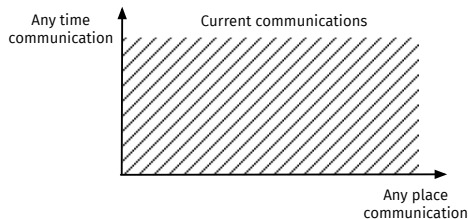
- How do LPWAN complement traditional cellular and short-range wireless technologies?
- What are the fundamental mechanisms that enable to meet the LPWAN requirements?
- What are the major design choices made in the LoRaWAN and NB-IoT specifications?
- How do we evaluate the performance of a LoRaWAN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



Outline

- 1 General Framework
- 2 Design Rationale
- 3 Technical Specification
- 4 Performance Evaluation
- 5 Experimentation

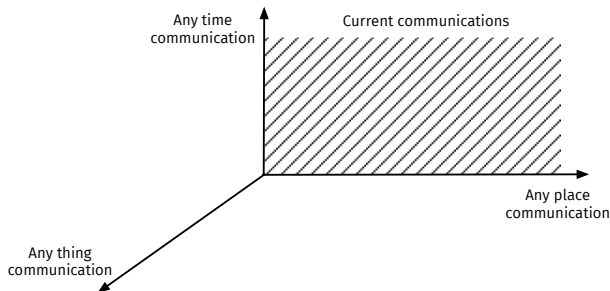
A New Dimension in Communications



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

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

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IoT Scenarios

Internet of Things

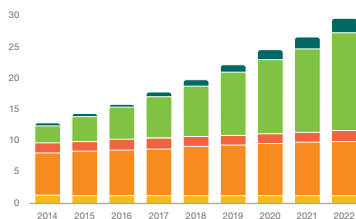
The Internet of Things (IoT) generally refers to scenarios where network connectivity and computing capability extends to devices, sensors, and everyday items (ISOC IoT Overview, 2015).






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

Evolution of IoT Devices

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

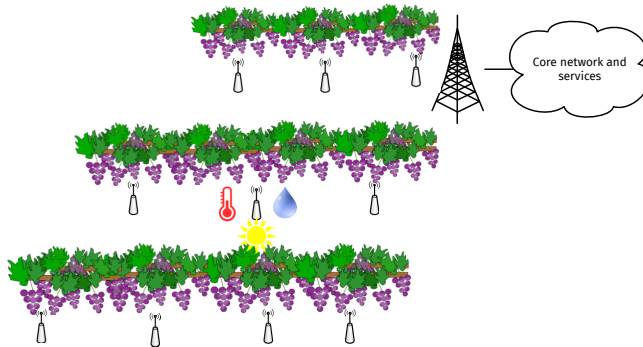
Connected devices (billions)



	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



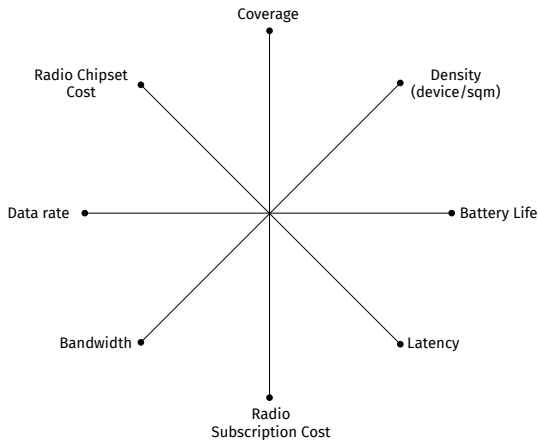
Constraints on the Device and Network Layers

- 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

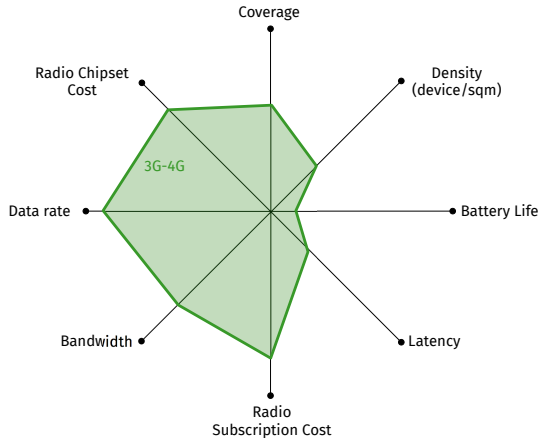
Do existing wireless networking technologies satisfy these constraints?

LPWAN Sweet Spot



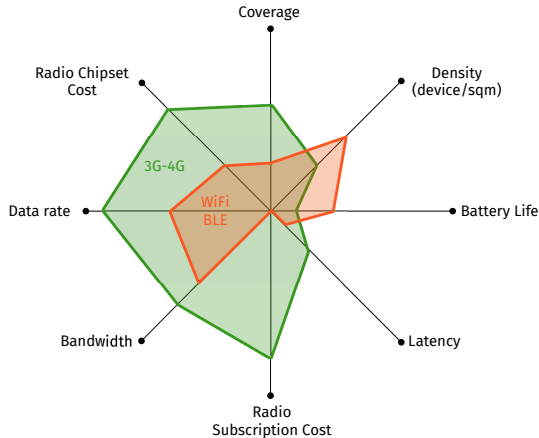
Source: Peter R. Egli, Low Power Wide Area Network, 2015

LPWAN Sweet Spot



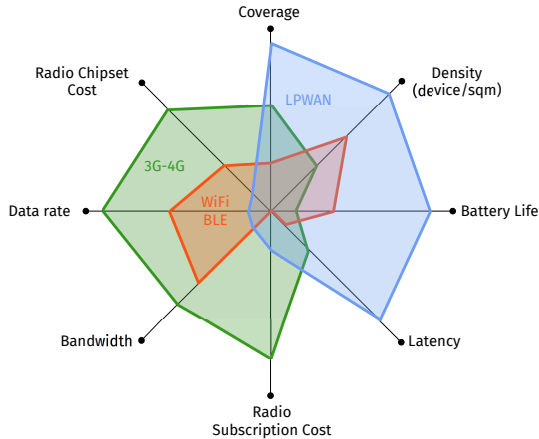
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LPWAN Sweet Spot



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LPWAN Sweet Spot



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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
Low power consumption	Devices operate for 10 years on a single charge
Low device unit cost	Below \$5 per module
Reliability	Completely unattended and resilient operation
Improved coverage	Outdoor and indoor penetration coverage
Security	Secure connectivity and strong authentication
Optimized data transfer	Supports small, intermittent blocks of data
Design complexity	Simplified network topology and deployment
Network scalability	Support of high density of devices



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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
⇒ LoRaWAN
- Adapt and leverage existing 4G technology to meet the LPWAN requirements
⇒ 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:
 - LoRaWAN: maximum application payload size between 51 and 222 bytes, depending on the spreading factor
 - NB-IoT: 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:
 - LoRaWAN: Hamming code
 - NB-IoT: LTE tail-biting convolution code (TBCC) in the DL; LTE turbo code, or repetition code in the UL
 - not using higher-order modulations or multiple-input multiple-output (MIMO) transmissions
 - LoRaWAN: LoRa
 - NB-IoT: 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

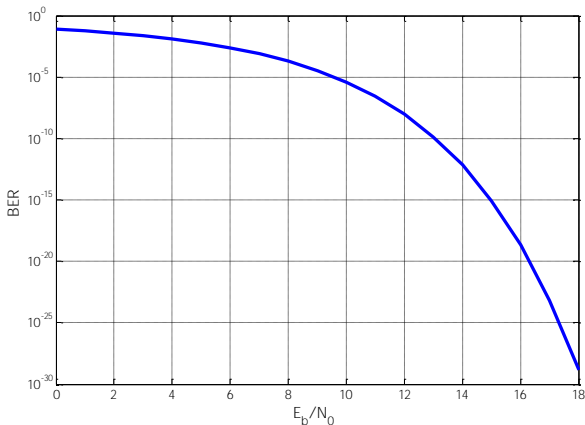
- Reduce RF processing complexity and cost through:
 - using one transmit-and-receive antenna
 - not using a duplexer (since only half-duplex operation is supported)
 - on-chip integrating power amplifier (since transmit power is limited)



Reliability under extreme coverage conditions

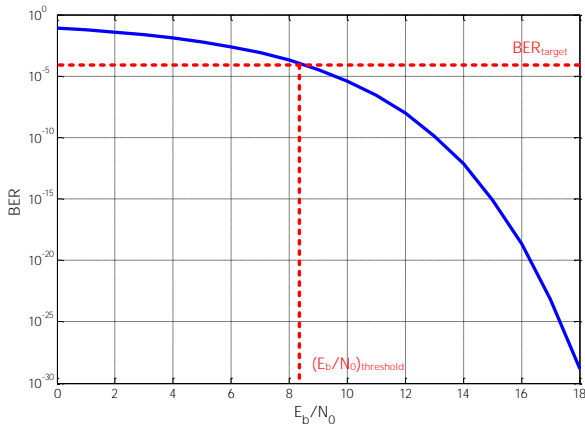
Radio Quality

- 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

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

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

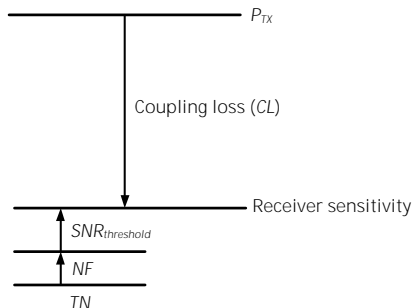
- $N \text{ (dBm)}$ is the background noise power at the receiver = $TN \text{ (dBm)} + NF \text{ (dB)}$
 - TN is the thermal noise caused by thermal agitation of charge carriers:
 $-174 + 10 \log_{10}(B)$
 - NF is the noise figure caused by RF components

Maximum Coupling Loss

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

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

where P_{Tx} is the transmit power in dBm.





How to Improve Coverage?

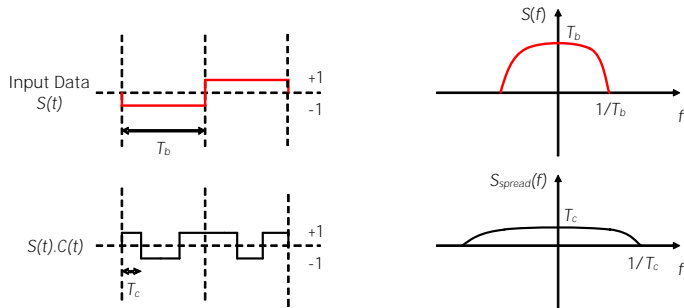
- Coverage targets are usually specified in terms of MCL
- Increasing P_{Tx} , or lowering NF , leads to higher device complexity and cost
 \Rightarrow inadequate solutions
- Reducing B leads to lower network capacity \Rightarrow inadequate solution
- Reducing $SNR_{threshold}$
 - LoRaWAN: optimised radio modulation that uses spread spectrum \Rightarrow LoRa
 - NB-IoT: repetitions and efficient HARQ retransmissions



Chirp Spread Spectrum in LoRaWAN

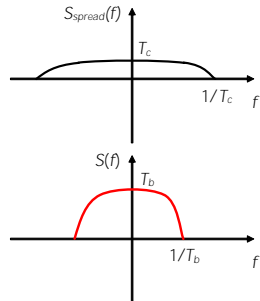
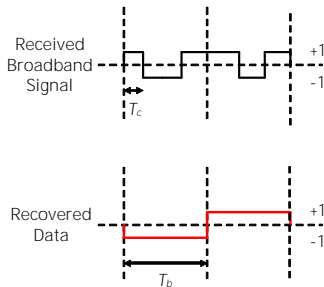
What is Spread Spectrum?

- Spread-spectrum techniques deliberately spread a signal in the frequency domain, resulting in a signal with a wider bandwidth
- Direct-sequence SS (DSSS), frequency-hopping SS (FHSS), time-hopping SS (THSS), and chirp SS (CSS) are forms of spread spectrum
- Spreading process in DSSS systems: at the transmitter, the input data $S(t)$ is multiplied with a spreading code $C(t)$



What is Spread Spectrum?

- De-spreading process in DSSS systems: at the receiver, $S(t)$ is re-covered by re-multiplying with the same spreading code $C(t)$





Why Spread Spectrum?

- Spread spectrum compensates for the SNR degradation

$$SNR = \frac{E_b}{N_0} \frac{R_b}{B} \Rightarrow \left(\frac{E_b}{N_0} \right)_{dB} = (SNR)_{dB} + G_p$$

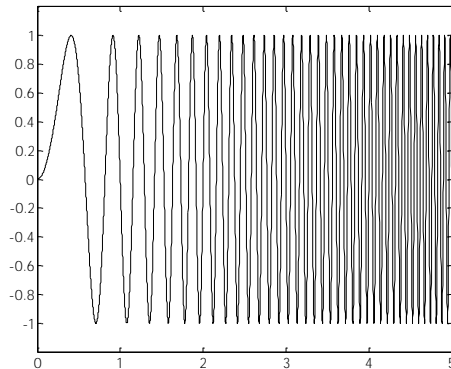
where G_p is the processing gain given by: $G_p = 10 \log_{10}(T_b B)$

$$SNR_{threshold} = \left(\frac{E_b}{N_0} \right)_{threshold} - G_p$$

- The higher G_p is
 - the lower $SNR_{threshold}$ is \Rightarrow larger radio coverage
 - the lower R_b is

Linear Chirp

- A linear chirp is a sinusoidal signal whose frequency linearly increases (*up-chirp*) or decreases (*down-chirp*) over time



A sinusoidal linear up-chirp in the time domain



Linear Chirp Theory

- A linear chirp waveform can be written as:

$$x(t) = a(t)\sin(2\pi f_0 t + \pi \mu t^2 + \phi_0)$$

where $a(t)$ is the envelope of the chirp signal which is zero outside a time interval of length T , f_0 the initial frequency, μ the chirp rate, or chirpyness, and ϕ_0 the initial phase.

- The instantaneous frequency $f(t)$ is defined as:

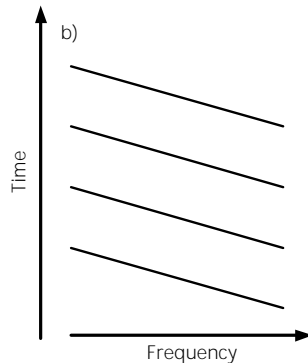
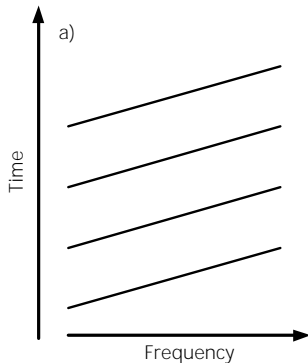
$$f(t) = \frac{1}{2\pi} \frac{d(2\pi f_0 t + \pi \mu t^2 + \phi_0)}{dt} = f_0 + \mu t$$

- The chirp rate μ represents the rate of change of the instantaneous frequency:

$$\mu = \frac{df(t)}{dt}$$

Spectrograms of Linear Chirps

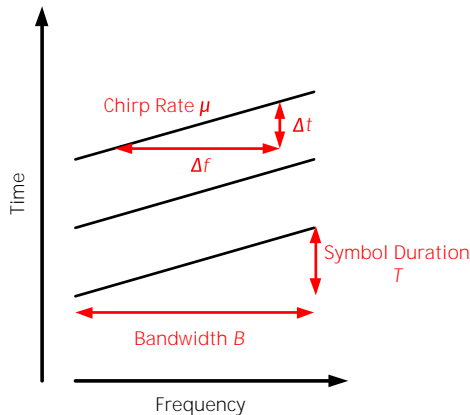
■ $\mu > 0 \Rightarrow$ *up-chirps*, $\mu < 0 \Rightarrow$ *down-chirps*



Spectrograms of linear *up-chirp* (a) and *down-chirp* (b)

Bandwidth Spreading

- The bandwidth B is defined as the range of the instantaneous frequency:
$$B = |\mu|T$$
- The processing gain is given by the time-bandwidth product TB

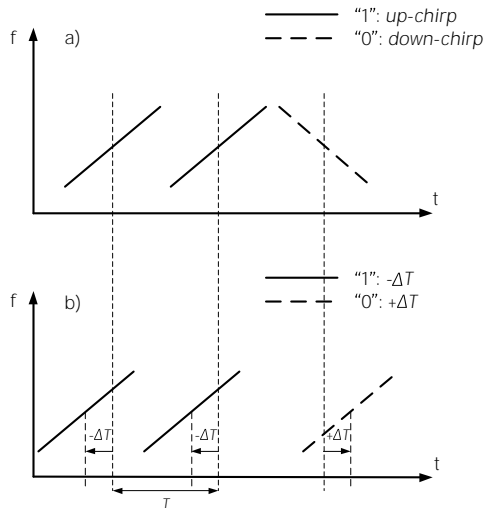




What is Chirp Spread Spectrum?

- Chirp Spread Spectrum (CSS) is a spread spectrum technique that uses wideband linear frequency modulated chirps to encode information
- Encoding information using *up-chirp* and *down-chirp* signals:
 - Example: “1” \Rightarrow transmit an *up-chirp*, “0” \Rightarrow transmit a *down-chirp*
 - Chirps are transmitted in equidistant time steps
- Encoding information using only one chirp waveform with Pulse-Position Modulation (PPM):
 - M bits are encoded by transmitting a single *chirp* in one of 2^M possible time shifts \Rightarrow bit-rate = M/T in b/s
 - Chirps are not transmitted in equidistant time steps
- At the receiver, the wanted information is re-covered through de-chirping

Example: Binary Orthogonal Keying (BOK) Schemes



a) BOK using up- and down-chirps b) BOK using PPM



Advantages of CSS

- CSS is robust to interference, multipath fading, and Doppler effect
- Time and frequency offsets between transmitter and receiver are equivalent, greatly reducing the complexity of the receiver design

Why CSS?

CSS provides a low-complexity, low-cost, low-power, yet robust alternative to the traditional SS techniques



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 degradation¹

¹Simulations 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



Battery Lifetime

- As most of the IoT applications require infrequent transmission of small data volumes, battery lifetime is increased through:
 - optimizing device reachability:
 - LoRaWAN: Class A devices open two short DL receive windows only after an uplink transmission.
Class B devices extend Class A by adding scheduled receive windows.
 - NB-IoT: 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.



Battery Lifetime

- reducing signaling messages when a device needs to transmit data
 - LoRaWAN: uncoordinated data transmission
 - NB-IoT: the device context is maintained during power-saving states, avoiding unnecessary signaling
- Idle devices enter in 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 to:
 - transmit data
 - open receive windows, or monitor paging channels



High capacity



Support for Massive Number of Low-Rate Devices

- Trading off data rate for coverage
- How to increase network capacity?
 - LoRaWAN uses multiple orthogonal spreading factors simultaneously on the same channel
 - 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:

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

- When coupling loss is high, $\frac{S}{N_0 B} \ll 1 \Rightarrow \ln \left(1 + \frac{S}{N_0 B} \right) \approx \frac{S}{N_0 B}$.

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

C no longer depends on B

\Rightarrow allocate a single tone (subcarrier) for devices in bad coverage to avoid resource wastage



Simplified Network Topology and Deployment



Network Topology and Deployment

- LoRaWAN has a simple network architecture and operates in license-free bands \Rightarrow low-cost deployment
- NB-IoT reuses LTE frequency bands and infrastructure (through software upgrade) \Rightarrow fast time-to-market



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LoRaWAN



What is LoRa?

Definition of LoRa

LoRa is a wireless modulation technique that uses Chirp Spread Spectrum (CSS) in combination with Pulse-Position Modulation (PPM).

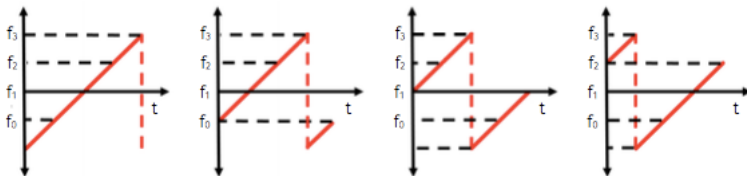
- Processing gain given by $g_p = BT$
- Spreading factor SF given by $\log_2(g_p)$
- Considering a coding rate CR , the bit-rate is given by:

$$R_b = SF \cdot \frac{B}{2^{SF}} \cdot \frac{4}{4 + CR}$$

$$\text{with } 1 \leq CR \leq 4$$

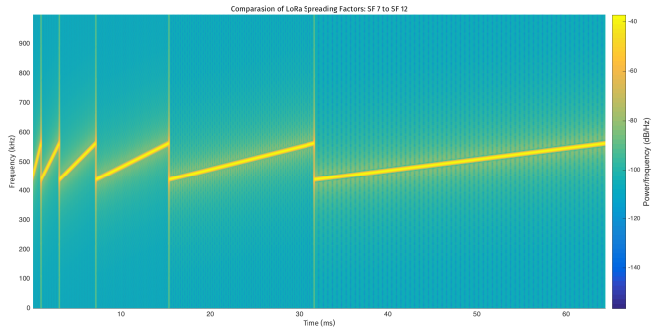
LoRa Symbols

- $\log_2(g_p)$ bits are encoded by transmitting a single *chirp* in g_p possible cyclic time shifts
- Example: $g_p = 4 \Rightarrow 2$ bits/symbol



LoRa Spreading Factors

- LoRa uses spreading factors from 7 to 12





LoRa Radio Optimization

Spreading Factor	Bit Rate (kb/s)	Sensitivity (dBm)
6	9.375	-118
7	5.468	-123
8	3.125	-126
9	1.757	-129
10	0.976	-132
11	0.537	-134.5
12	0.293	-137

($CR = 1$ and $B = 125$ kHz)

- Higher spreading factors lead to lower sensitivity and larger coverage
- Lower spreading factors lead to higher data rates



LoRa Channels

- Operates in license-free bands all around the world
 - 433, 868 (EU), 915 MHz
- EU 863-870MHz ISM Band
 - Default radiated transmit output power by devices: 14 dBm
 - Minimum set of three channels, maximum of 16 channels

Modulation	Bw [kHz]	Freq [MHz]	Data Rate	Nb Channels	Duty cycle
LoRa	125	868.10	DR0 to DR5	3	<1%
		868.30	0.3-5 kbps		
		868.50			



Duty Cycle Limitation

- The LoRaWAN enforces a per sub-band duty-cycle limitation (ETSI)
 - Each time a frame is transmitted in a given sub-band, the time of emission and the on-air duration of the frame are recorded for this sub-band
 - The same sub-band cannot be used again during the next T_{off} seconds where:

$$T_{off} = \frac{TimeOnAir}{DutyCycleSubband} - TimeOnAir$$

- During the unavailable time of a given sub-band, the device may still be able to transmit on another sub-band
- The device adapts its channel hopping sequence according to the sub-band availability

Example

A device just transmitted a 0.5 s long frame on one default channel. This channel is in a sub-band allowing 1% duty-cycle. Therefore this whole sub-band (868 – 868.6) will be unavailable for 49.5 s



From LoRa to LoRaWAN

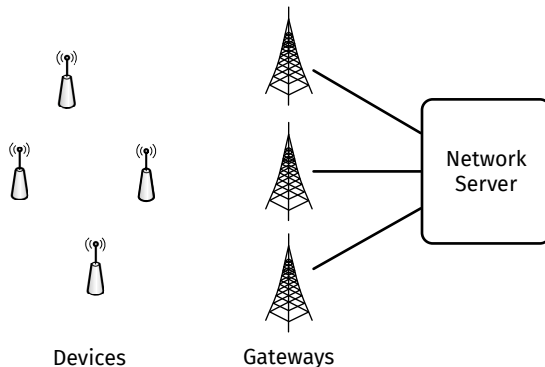
■ LoRa

- Modulation technique for LPWAN

■ LoRaWAN

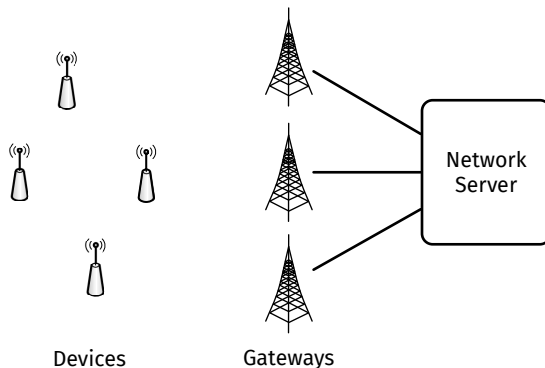
- Uses LoRa modulation on physical layer
- Proposes a MAC layer for access control
- Specified by LoRa Alliance (LoRaWAN specification 1.1)

End-Devices



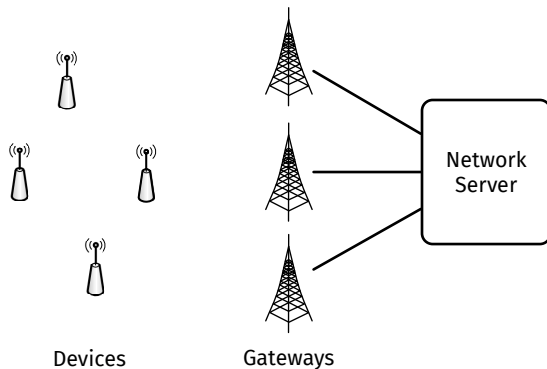
- End-devices are also called motes or devices
- Communicate to one or more gateways via a wireless interface using single hop LoRa or FSK

Gateways



- Gateways are also called concentrators or base stations
- Forward Frames between devices and network server
- Connected to the network server via IP interfaces

Network Server



- Network server is a central server located at the backend
- Provides mobility, frame control, and security functions
- Adapts data transmission rates



LoRaWAN General Characteristics

- LoRaWAN network architecture is typically laid out in a star-of-stars topology
- All end-point communication is generally bi-directional
 - Uplink communications are predominant
- Data rates ranging from 300 bps to 5.5 kbps
 - Two high-speed channels at 11 kbps and 50 kbps (FSK modulation)
 - Eight channels: bandwidth 125 kHz or 250 kHz
 - Support for adaptive data rate (power and spreading factor control)
- Secure bi-directional communication, mobility, and localization
 - Device authentication, message encryption, and frame counter



Uplink transmission

- Uncoordinated data transmission
 - Devices transmit without any coordination on a randomly chosen channel
 - Regulated maximum transmit duty cycle
 - Regulated maximum transmit duration (or dwell time)

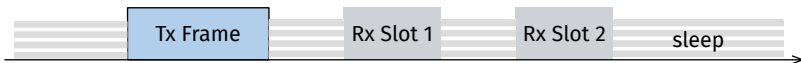
LoRaWAN Access Method

LoRaWAN is an ALOHA-type protocol: transmission by the device is based on its own communication needs with a small variation based on a random time basis

Device Classes

■ Class A

- Each uplink transmission is followed by two short downlink receive windows
- Adapted for applications that only require downlink communication from the server shortly after the end-device has sent an uplink transmission



■ Class B

- In addition to class A, receive windows are opened at scheduled times
- A time synchronized Beacon is sent by the gateway

■ Class C

- Nearly always open receive windows (unless transmitting)



MAC Commands

- Commands are exchanged between devices and NS, not visible to the application layer
- Examples
 - Indicate the quality of reception of the device
 - Indicate the battery level of a device
 - Request the device to change data rate, transmit power, repetition rate or channel
 - Sets the maximum aggregated transmit duty-cycle of a device
 - Change to the frequency and the data rate set for the second receive window (RX2) following each uplink



Adaptive Data Rate

■ Objectives

- Increase battery life
- Maximize network capacity

■ Data rate validation

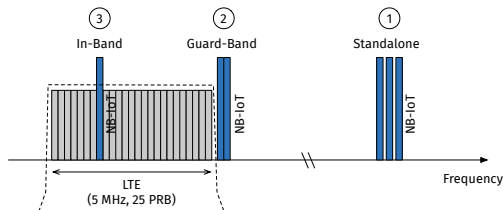
- A device periodically sets the ADR acknowledgment bit and waits for an acknowledgment from the network
- If an ACK is not received, the device switches to the next lower data rate that provides a longer radio range



NB-IoT

What is NB-IoT?

- 3GPP radio technology standard: releases R13 and R14
- Reutilizes cellular telecommunication bands
 - Three possible operation modes: in-band, guard-band, or standalone
- Reutilizes cellular telecommunication infrastructure
- Shares common characteristics with LTE networks
 - Modulation technique
 - Access method
 - Core network functions





NB-IoT Characteristics

- Radio resource: 1 LTE Physical Resource Block (PRB)
 - Bandwidth: 180 kHz
 - Duration: 0.5 ms
- Multiple access: Downlink OFDMA, Uplink SC-FDMA
- Modulation scheme
 - Downlink: QPSK
 - Uplink: QPSK (multi-tone), $\pi/4$ -QPSK, or $\pi/2$ -BPSK (single-tone)
- Link budget: 164 dB
- Data rate: ~ 250 kbps in the DL and ~ 250 kbps in the UL (multi-tone)



Leveraging LTE mechanisms in NB-IoT

- Communication channels
 - Broadcast channel
 - Shared control channels (uplink and downlink)
- Access method
 - Cell acquisition and registration
 - Random access procedure
 - Scheduling of uplink and downlink transmissions
- Localization and mobility management (in idle mode)

NB-IoT Access Method

NB-IoT access is performed in two steps: random access then scheduled transmission



Optimizing LTE mechanisms for NB-IoT

■ Coverage extension

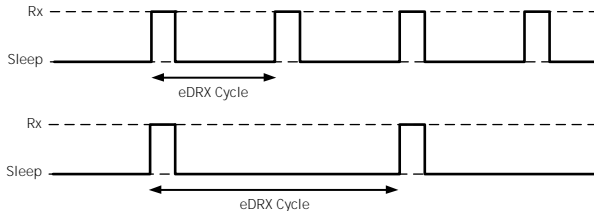
- Repeating the same transmission several times, available on all channels
- Achieves extra coverage (up to 20 dB compared to GPRS)

■ Energy saving

- Monitoring 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)

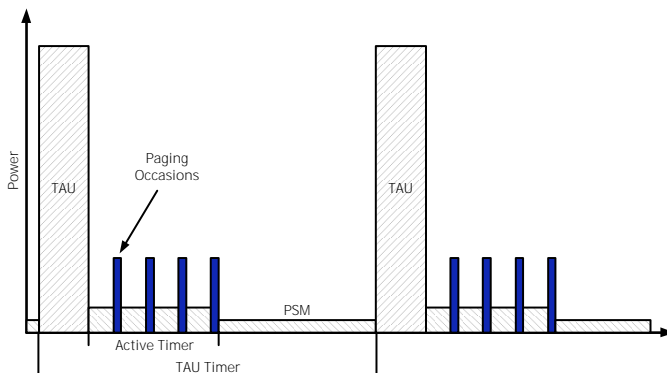
- How often an idle device monitors paging channels?
- An eDRX cycle is the time period between two paging occasions the device needs to monitor (up to 2 h, 54 min, and 46 s)
- In between these two occasions, the device is assumed to be in deep sleep mode
- eDRX cycle is negotiated on a per device basis



Two possible eDRX cycle configurations

Power-Saving Mode (PSM)

- In PSM, an idle device does 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 (up to a year)



Outline

- 1 General Framework
- 2 Design Rationale
- 3 Technical Specification
- 4 Performance Evaluation**
- 5 Experimentation



Link Budget



Enhanced Network Capacity

- LoRa employs orthogonal spreading factors which enables multiple spread signals to be transmitted at the same time and on the same channel
- Modulated signals at different spreading factors appear as noise to the target receiver
- The equivalent capacity of a single 125 kHz LoRa channel is:

$$\begin{aligned} & SF12 + SF11 + SF10 + SF9 + SF8 + SF7 + SF6 \\ &= 293 + 537 + 976 + 1757 + 3125 + 5468 + 9375 \\ &= 21531 \text{ b/s} = 21.321 \text{ kb/s} \end{aligned}$$



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

$L_{Channel}$ = losses due to the propagation channel

M = fading margin and protection margin



Coverage of LoRaWAN

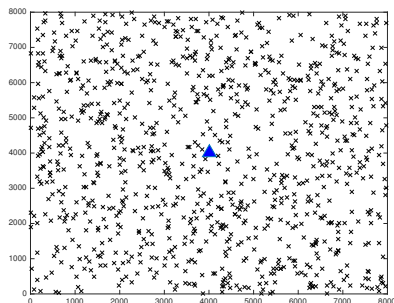
Evaluation Scenario

■ 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: 3 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
 - Sum of antenna gains: $G_{System} = 6$ dBi
 - Fading and protection margin: $M = 10$ dB
 - Noise floor: $N = -153$ dBm
- We can now compute the received power $P_{Rx}(i)$ and SNR(i) for end-device i :

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

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

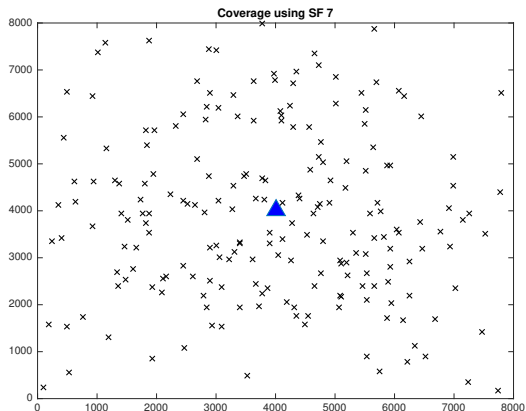
Spreading Factor Selection

- The spreading factor for each end-device is selected using the following matching table:

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

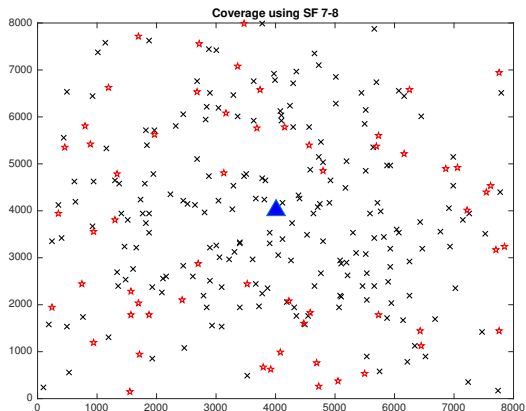
- Note that for SNR values lower than -20 dB, the end-device is considered out of coverage of the gateway

Coverage Study



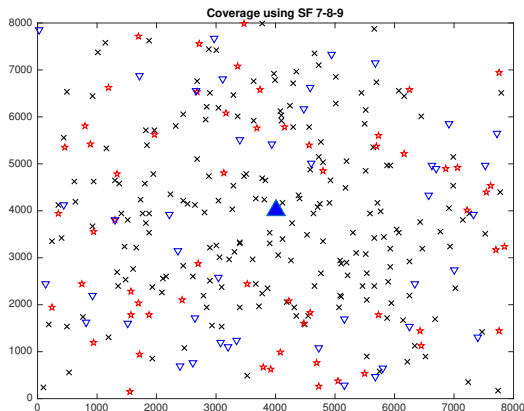
Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	40.50	51.60	61.60	70.40	77.70	86.10

Coverage Study



Spreading Factor	7	8	9	10	11	12
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

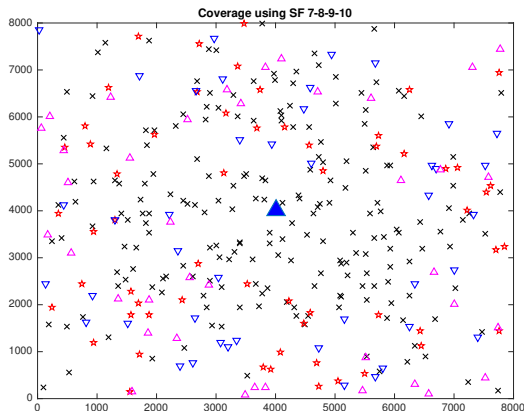
61.60

70.40

77.70

86.10

Coverage Study



Spreading Factor

7

8

9

10

11

12

Cumulative coverage (%)

40.50

51.60

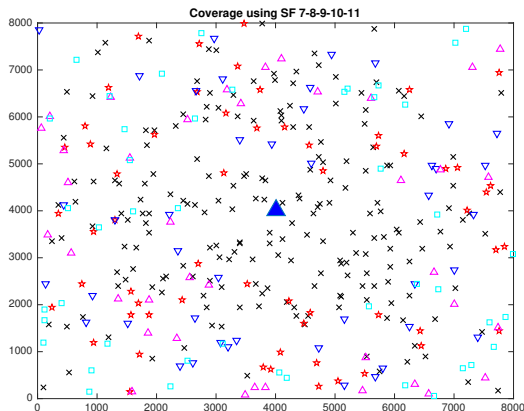
61.60

70.40

77.70

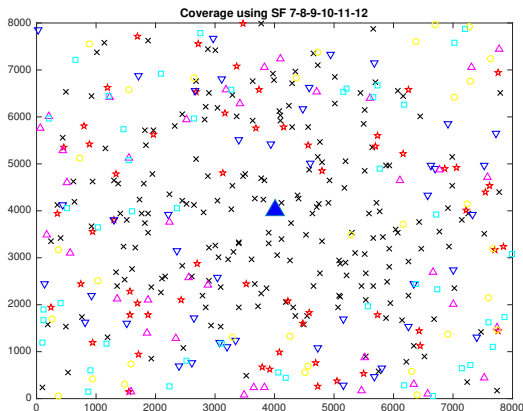
86.10

Coverage Study



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

Coverage Study



Spreading Factor

7

8

9

10

11

12

Cumulative coverage (%)

40.50

51.60

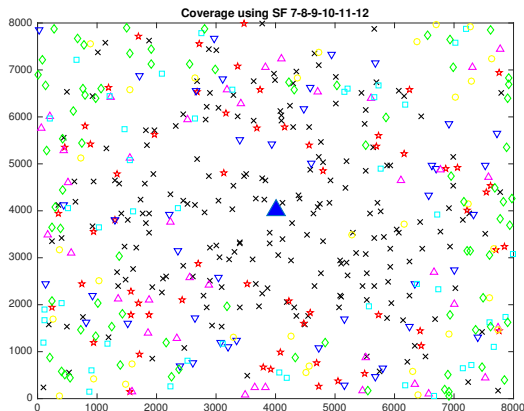
61.60

70.40

77.70

86.10

Coverage Study



Spreading Factor

7

8

9

10

11

12

Cumulative coverage (%)

40.50

51.60

61.60

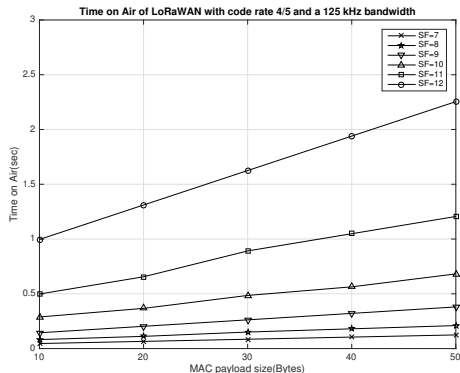
70.40

77.70

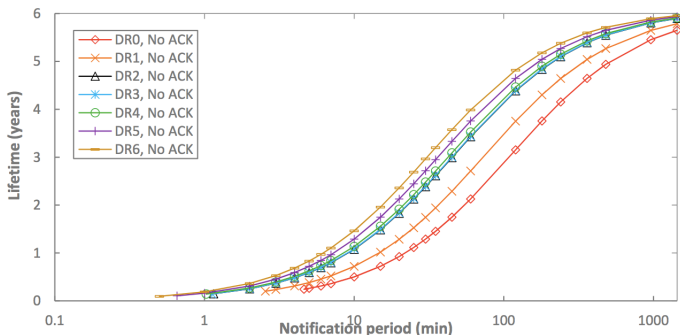
86.10

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



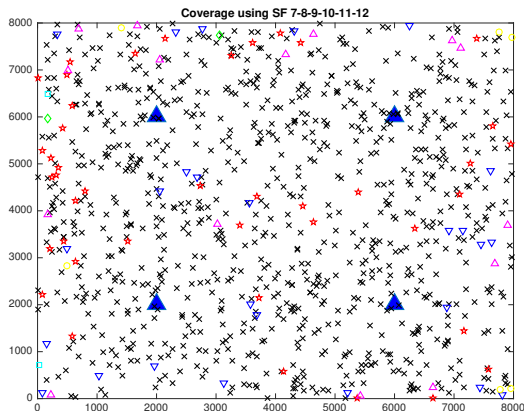
Spreading Factor and Energy Consumption



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

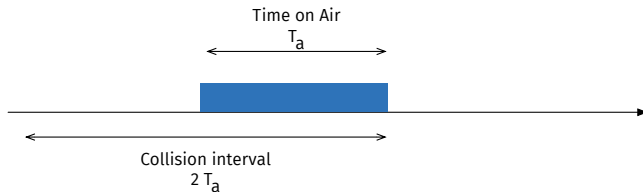
100.00



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:

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



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:

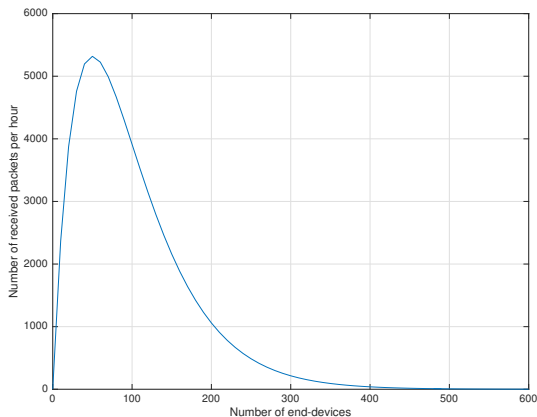
$$S = G \exp(-2G) = N\lambda(s)T_a(l, s) \exp(-2N\lambda(s)T_a(l, s))$$

- The total number of successfully received packets per second is obtained by:

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

Received Packets per Hour

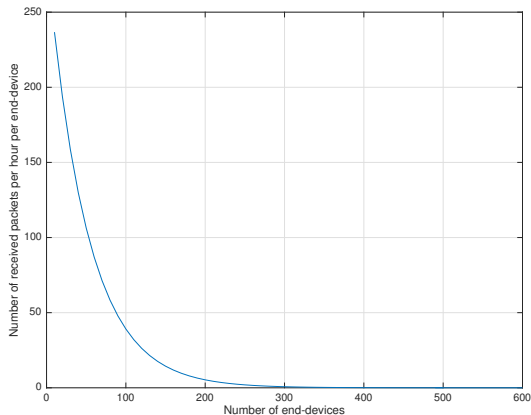
- The number of received packets per hour decreases after 50 end-devices



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

Received Packets per End-Device per Hour

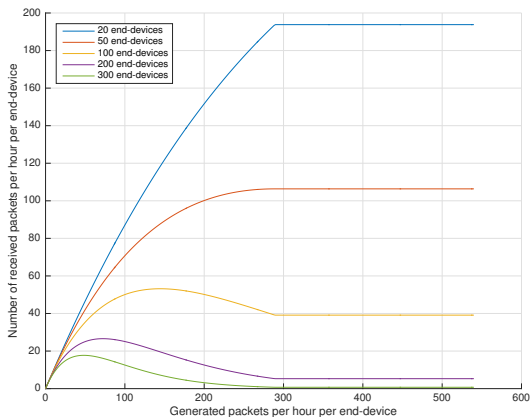
- For 100 end-devices generating 289 packets per hour, the average number of received packets per end-device equals 40 per hour



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

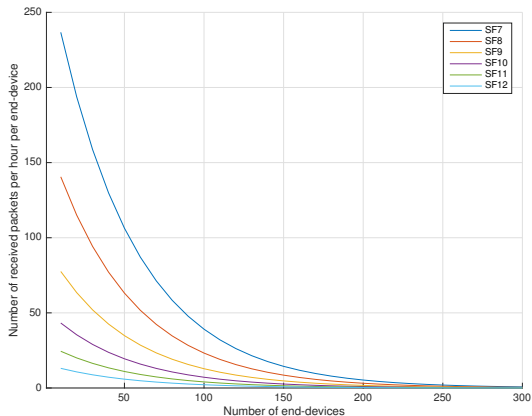
Packet Generation Rate

- 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 Packet Reception



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

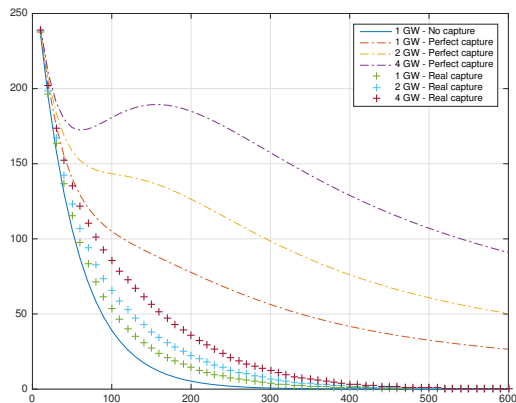
- For 50 end-devices, the average number of received packets per end-device per hour increases from 6 to 106 when SF decreases from 12 to 7



Use Case Conclusion

- Conclude for use case

Multiple Gateways and Capture Effect



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

- The total number of received packets starts decreasing after 50 end-devices

Old remove

- ALOHA with duty cycle

$$\frac{\delta}{\tau} N \exp\left(-2N \frac{\delta}{\tau}\right)$$

- ALOHA with multiple receivers and perfect packet capture

$$\frac{\delta}{\tau} N \exp\left(-2N \frac{\delta}{\tau}\right) \left(1 + \sum_{n=2}^N \frac{(2N \frac{\delta}{\tau})^n}{n!} \left(1 - \left(1 - \frac{1}{n}\right)^r\right)\right)$$

- ALOHA with multiple receivers and realistic packet capture

$$\frac{\delta}{\tau} N \exp\left(-2N \frac{\delta}{\tau}\right) \left(1 + \sum_{n=2}^N \frac{(2N \frac{\delta}{\tau})^n}{n!} \left(1 - \left(1 - \frac{K^{n-1}}{n}\right)^r\right)\right)$$

with

$$K = \frac{1}{2} 10^{-\frac{\Delta}{10\alpha}}$$



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Test



Test