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

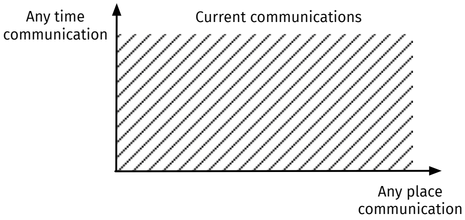
- How do LPWAN complement traditional cellular and short-range wireless technologies?
- What are the fundamental mechanisms that enable to meet the LPWAN requirements?
- What are the major design choices made in the LoRaWAN and NB-IoT specifications?
- How do we evaluate the performance of a LoRaWAN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

Feedback and Material

- Feedback form
- Presentation slides are available

Outline

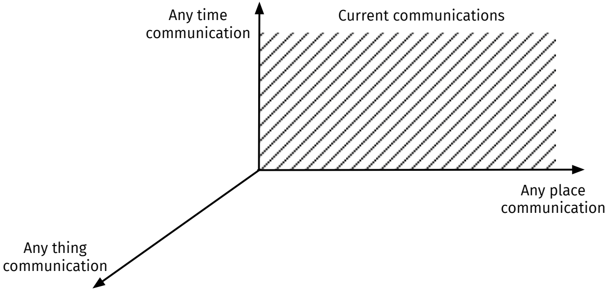
A New Dimension in Communications



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

A New Dimension in Communications



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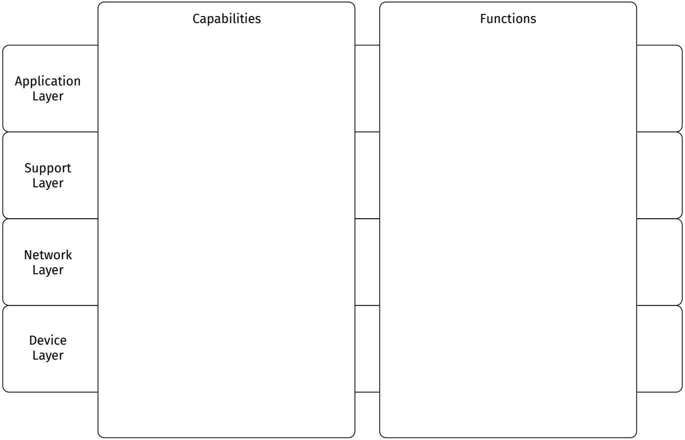
IoT Scenarios

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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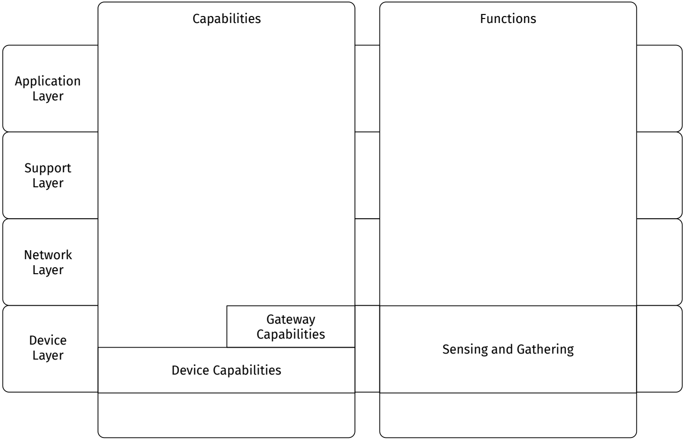

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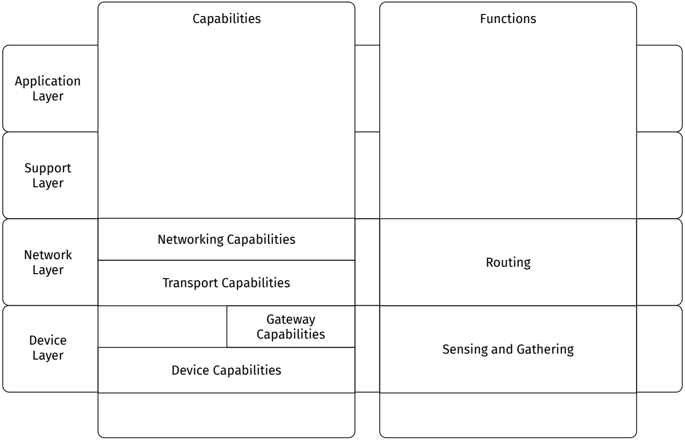

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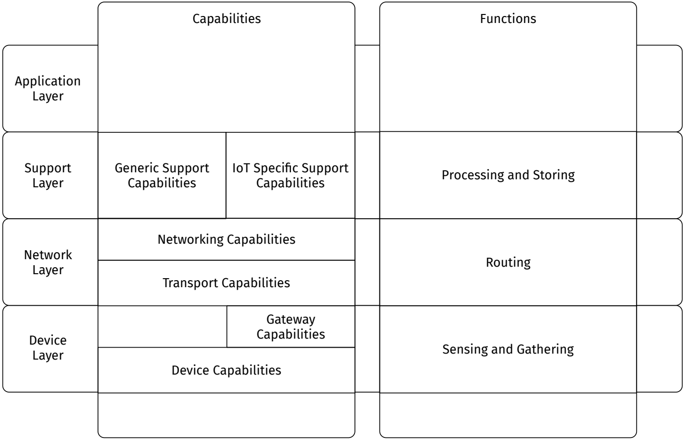

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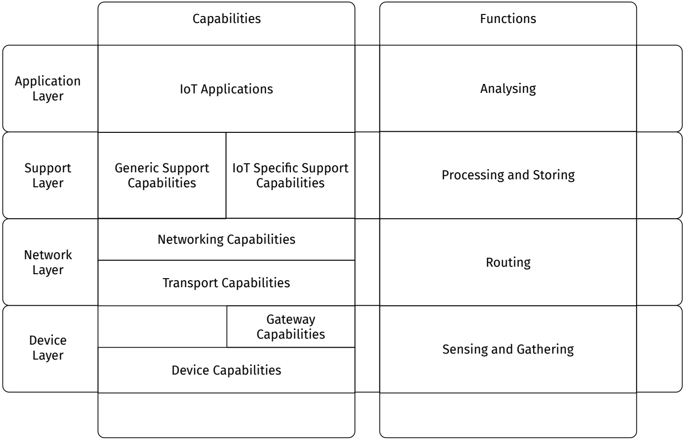

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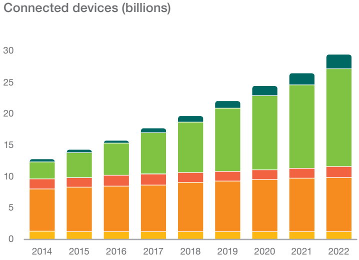
Evolution of IoT Devices

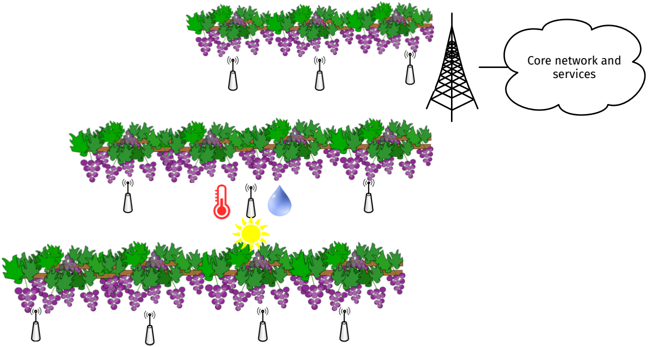
- The largest growth is expected for devices connected to a wide-area network



	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

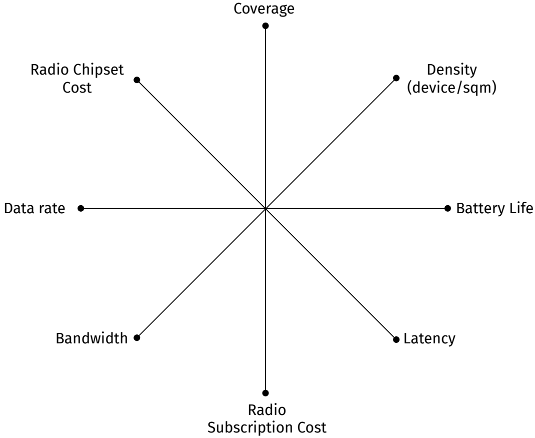
Constraints on the Device and Network Layers

- 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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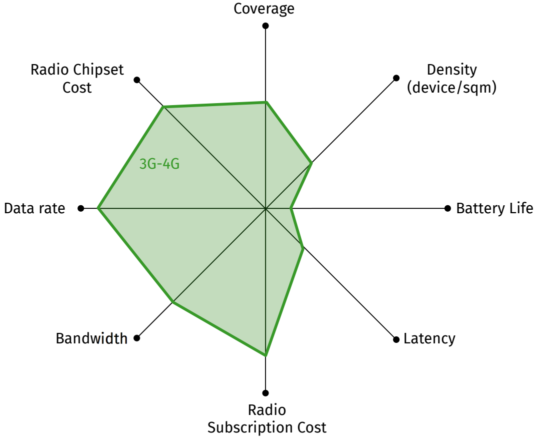
LPWAN Sweet Spot



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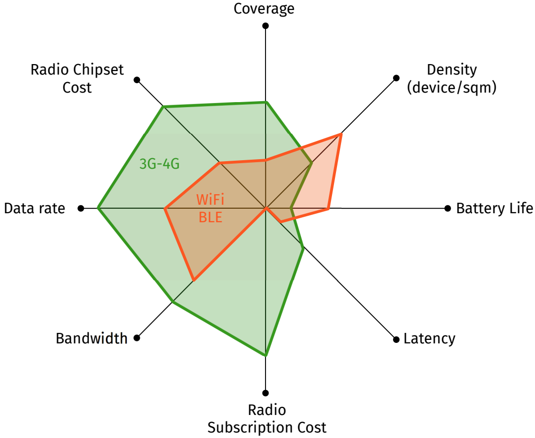

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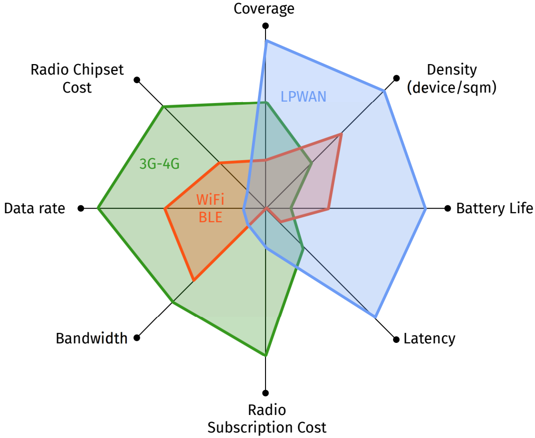

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LPWAN Scenarios

Low Power Wide Area Networks

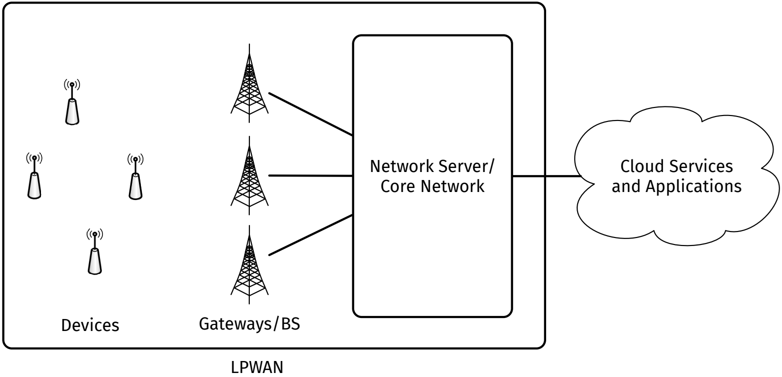
Low power refers to the ability of an IoT device to function for many years on a single battery charge, while at the same time it is able to communicate from locations where shadowing and path loss would limit the usefulness of more traditional cellular technologies (3GPP Low Power Wide Area Technologies,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

LPWAN Architecture



Common Characteristics of LPWAN Technologies

- Optimised radio modulation
- Star topology
- Frame sizes in the order of tens of bytes
- Frames transmitted a few times per day at ultra-low speeds
- Mostly upstream transmission pattern
- Devices spend most of their time in low-energy deep-sleep mode

LPWAN Technologies

Various technologies are currently candidating for LPWA: LoRaWAN, NB-IoT, Sigfox, Wi-SUN, Ingenu, etc.

Comparison of LPWAN Technologies

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

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:
    - 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

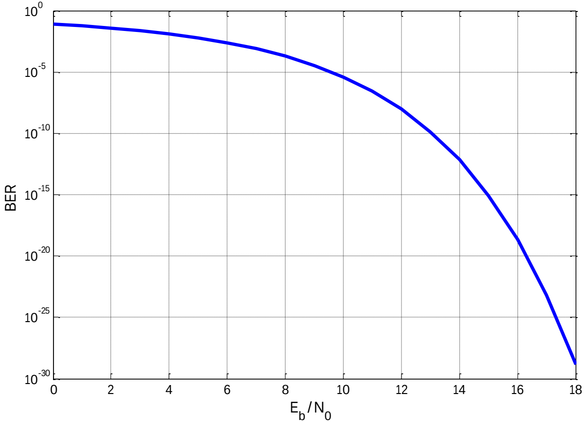
RF Processing

- 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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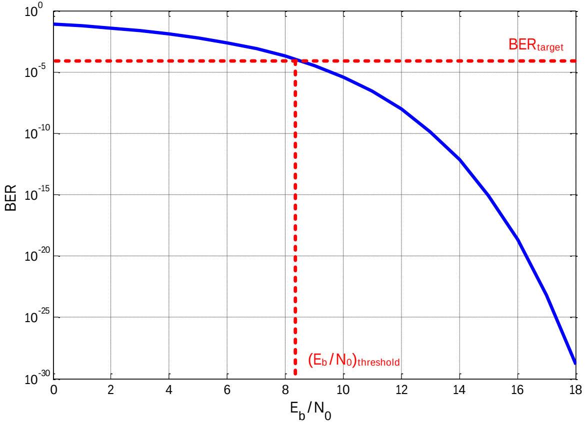


Radio Quality

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

- $(E_b/N_0)_{threshold}$ 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

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

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

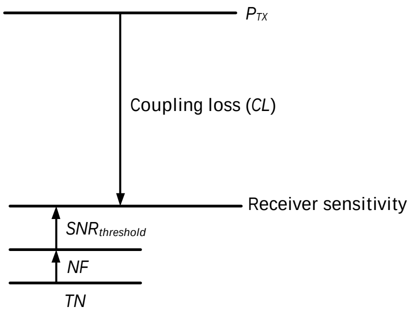
- N (dBm) is the background noise power at the receiver $=$ TN (dBm) $+NF$ (dB)
    - TN is the thermal noise caused by thermal agitation of charge carriers: $-174 + 10\log_{10}(B)$
    - NF is the noise figure caused by RF components

Maximum Coupling Loss

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

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

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



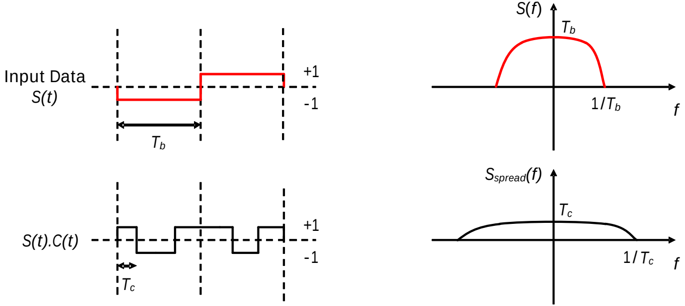
How to Improve Coverage?

- 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 $SNR_{threshold}$
  - LoRaWAN: optimised radio modulation that uses spread spectrum $\Rightarrow$ LoRa
  - NB-IoT: repetitions and efficient HARQ retransmissions

Chirp Spread Spectrum in LoRaWAN

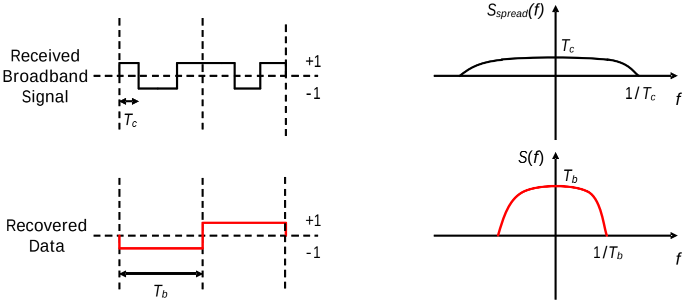
What is Spread Spectrum?

- 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

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

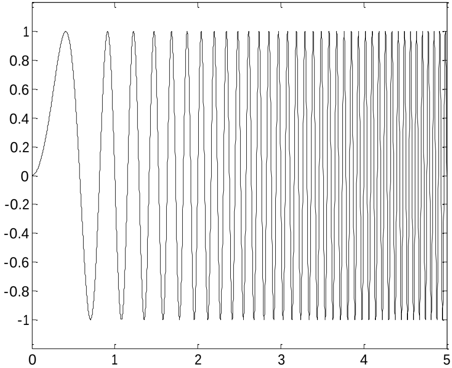
where G_p is the processing gain given by: $G_p = 10\log_{10}(T_b B)$

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

- 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:

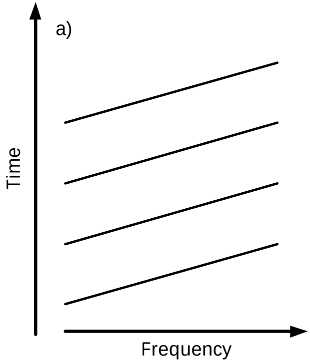
$$f(t) = \frac{1}{2\pi} \frac{d(2\pi f_0 t + \pi \mu t^2 + \phi_0)}{dt} = f_0 + \mu t$$

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

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

Spectrograms of Linear Chirps

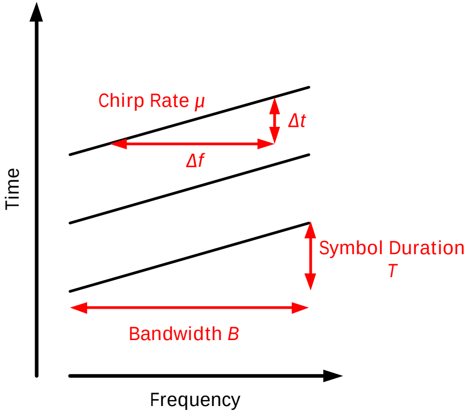
- $\mu > 0 \Rightarrow$ *up-chirps*, $\mu < 0 \Rightarrow$ *down-chirps*



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

Bandwidth Spreading

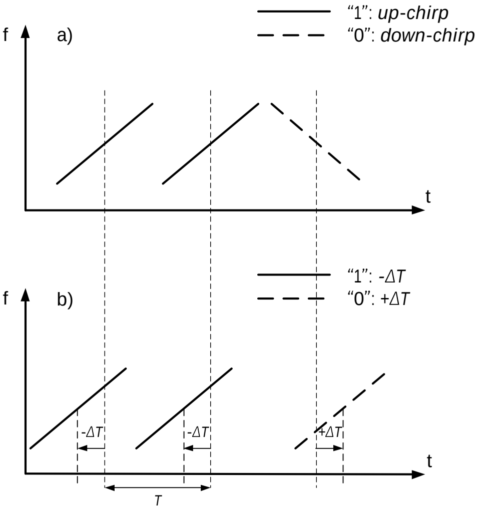
- The bandwidth B is defined as the range of the instantaneous frequency: $B = |\mu| T$
- The processing gain is given by the time-bandwidth product TB



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 degradation

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.
      Class C devices extend Class A by keeping the receive windows open unless they are transmitting.
    - 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.

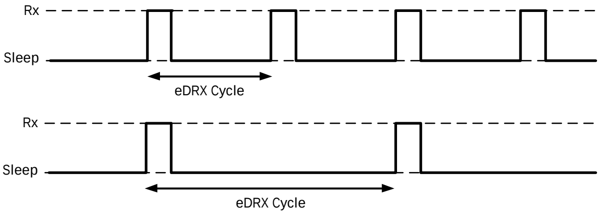
Battery Lifetime

- 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

extended Discontinuous Reception (eDRX)

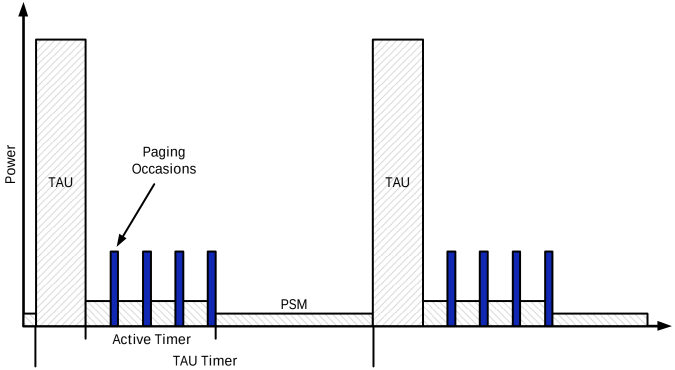
- How often an idle device monitors paging channels?
- An eDRX cycle is the time period between two paging occasions the device needs to monitor (up to 2 h, 54 min, and 46 s)
- In between these two occasions, the device is assumed to be in deep sleep mode
- eDRX cycle is negotiated on a per device basis



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)

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:

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

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

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

C no longer depends on B

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

Outline

LoRa Radio Interface

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 $g_p = BT$
- Variable number of bits encoded in a symbol

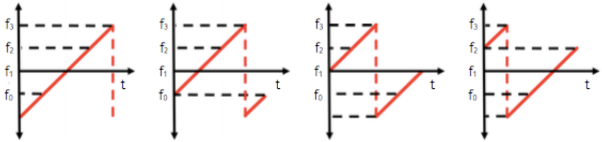
$$R_b = \frac{log_2(g_p)}{T} = log_2(g_p) \cdot \frac{B}{g_p}$$

- Spreading factor SF given by $log_2(g_p)$

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

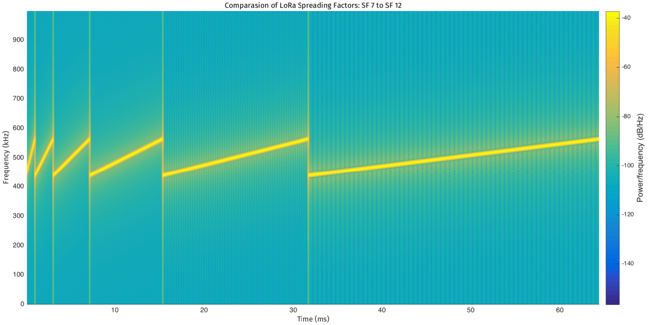
LoRa Symbols

- $log_2(g_p)$ 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 Bit-Rate

- LoRa includes a variable error correction scheme that improves the robustness of the transmitted signal at the expense of redundancy
- Given a coding rate CR, the bit-rate is given by:

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

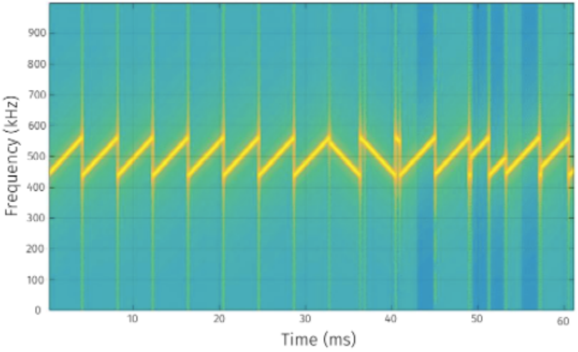
- R_b can also be written as:

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

with $1 \leq CR \leq 4$, and $7 \leq SF \leq 12$

LoRa Physical Layer

- LoRa transmission consists of:
  - 8 preamble (*up-chirp*) symbols
  - 2 synchronization (*down-chirp*) symbols
  - 5 modulated symbols (payload)



LoRa Characteristics

- Operates in license-free bands all around the world
  - 433, 868 (EU), 915 MHz
- Spectrum regulation for EU
  - Transmit power (EIRP) is limited to 14 dBm (25 mW)
  - 1% per sub-band duty-cycle limitation
- Receiver sensitivity: -142 dBm
- Link budget: 156 dB
- Uses spreading factors and channel coding rates to set the modulation rate

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

Channels

- 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	868.10 868.30 868.50	DR0 to DR5 0.3-5 kbps	3	<1%

ETSI Limitations

- Restrictions on the maximum time the transmitter can be on or the maximum time a transmitter can transmit per hour
- Choice between
  - Duty-cycle limitation
  - Listen Before Talk Adaptive Frequency Agility (LBT AFA) transmissions management
- The current LoRaWAN specification exclusively uses duty-cycled limited transmissions to comply with the ETSI regulations

Duty Cycle Limitation

- The LoRaWAN enforces a per sub-band duty-cycle limitation
  - 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

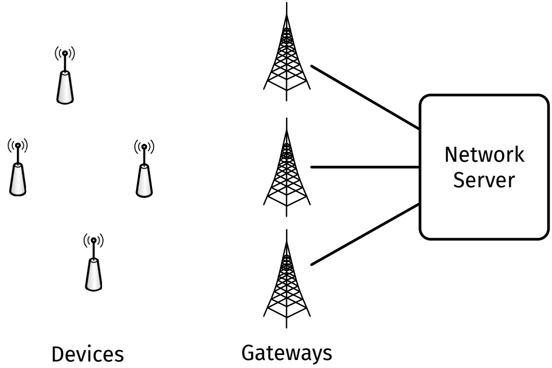
- LoRa
  - Modulation technique for LPWAN
- LoRaWAN
  - Uses LoRa modulation on physical layer
  - Proposes a MAC layer for access control
  - Specified by LoRa Alliance

LoRaWAN Timeline

- Cycleo first introduced LoRa in 2009
  - M2M communications
  - Large coverage
- Semtech acquired Cycleo in 2012 for 5 M$!
  - Patents filed in 2014
- LoRa Alliance initiated in 2014
  - Actility, Cisco, Bouygues, IBM, Orange, SK Telecom, KPN, ZTE, Semtech, La Poste, SoftBank, Swisscom, etc.
  - LoRaWAN 1.0 specification in 2015

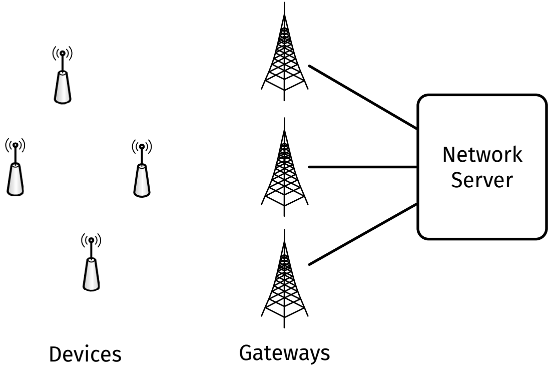
LoRaWAN Physical Architecture

End-Devices



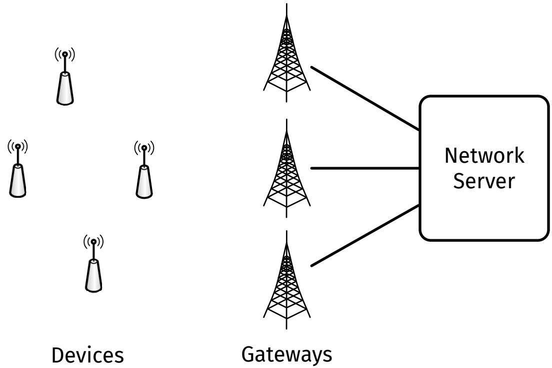
- End-devices are also called motes or devices
- Communicate to one or more gateways via a wireless interface using single hop LoRa or FSK

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

LoRaWAN Protocol Architecture

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

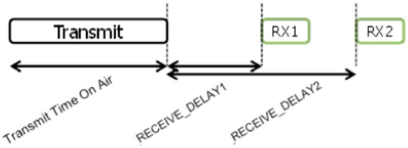
- Class A
  - Each uplink transmission is followed by two short downlink receive windows
  - Adapted for applications that only require downlink communication from the server shortly after the end-device has sent an uplink transmission
- Class B
  - In addition to class A, receive windows are opened at scheduled times
  - A time synchronized Beacon is sent by the gateway
- Class C
  - Nearly always open receive windows (unless transmitting)

Messages

- Uplink messages
  - Sent by devices to the NS
  - Relayed by one or multiple gateways
  - [Preamble, PHDR, PHDR_CRC, Payload, CRC]
- Downlink messages
  - Sent by the NS to only one device and is relayed by a single gateway
  - [Preamble, PHDR, PHDR_CRC, Payload]

Receive Windows for Class A Devices

- First receive window
  - Same channel (and data rate) as the uplink
- Second receive window
  - Predefined channel and data rate, and possibility to modify it by MAC commands



MAC Header

- Format
  - [MAC type, ..., Device Address, Frame Control, Frame Counter, Frame Options, Frame Port, Payload]
- Message Types
  - Join Request
  - Join Accept
  - Unconfirmed Data Up
  - Unconfirmed Data Down
  - Confirmed Data Up
  - Confirmed Data Down
  - RFU
  - Proprietary

ACK in Frame Control

- If the ACK (demanding acknowledge) sender is an end-device, the network will send the acknowledgement using one of the receive windows opened by the end-device after the send operation
- If the sender is a NS, the end-device transmits an acknowledgment at its own discretion, possibly piggybacked with the next Data message
- A message is retransmitted (predefined number of times) if an ACK is not received

Frame Counter

- Each device has two frame counters
  - Uplink frames, incremented by the device
  - Downlink frames, incremented by the NS

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

Data Stored in Each device

- Device address
  - 7 bit network identifier
  - 25 bit network address arbitrarily assigned by the admin
- Application Identifier
  - 64 bits that uniquely identify the owner of the device (EUI-64)
- Session key
  - Used for integrity check and encryption/decryption of MAC only messages
- Application Session key
  - Used for integrity check and encryption/decryption of application data messages

Two Ways of Activation

- Over the air activation
  - Necessitates a globally unique end-device identifier (DevEUI), the application identifier (AppEUI), and an AES-128 key (AppKey)
  - Two MAC messages between NS and devices: Join and Accept
- Activation by Personalization
  - No MAC messages
  - The DevAddr and the two session keys NwkSKey and AppSKey are directly stored into the end-device

LoRa Radio Optimization

Spreading Factor	Bit Rate (kb/s)	Sensitivity (dBm)
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

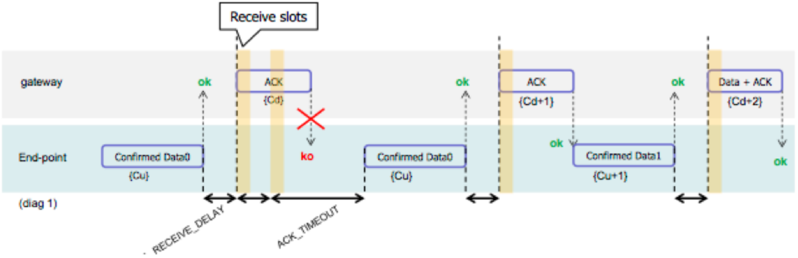
(RC = 1 and B = 125 kHz)

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

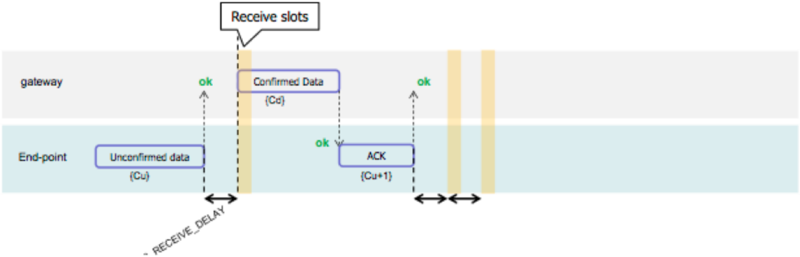
Adaptive Data Rate

- 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

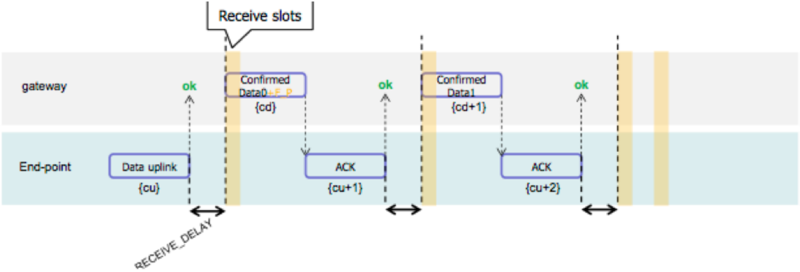
Wrap-up Example (1/3)



Wrap-up Example (2/3)



Wrap-up Example (3/3)



Outline

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:

$$SF12 + SF11 + SF10 + SF9 + SF8 + SF7 + SF6$$

$$= 293 + 537 + 976 + 1757 + 3125 + 5468 + 9375$$

$$= 21531 \text{ b/s} = 21.321 \text{ kb/s}$$

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

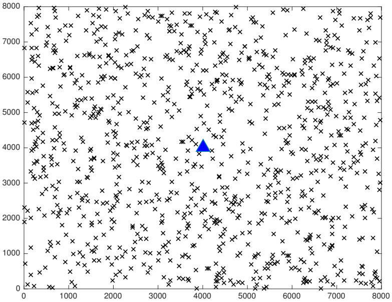
$L_{Channel}$ = losses due to the propagation channel

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

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

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

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 $\mathrm{SNR}(i)$ for end-device i:

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

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

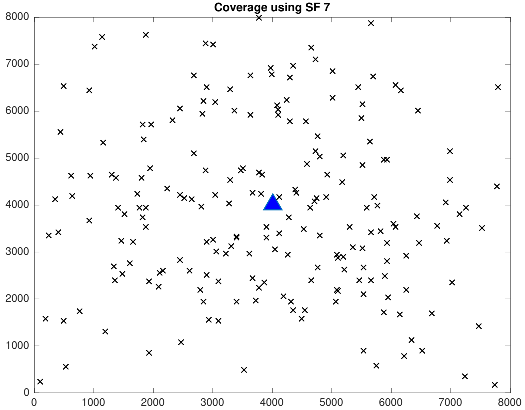
Spreading Factor Selection

- 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

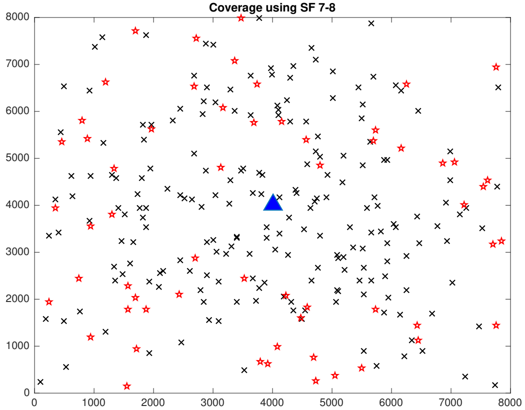
- Note that for SNR values lower that -20 dB, the end-device is considered out of coverage of the gateway

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



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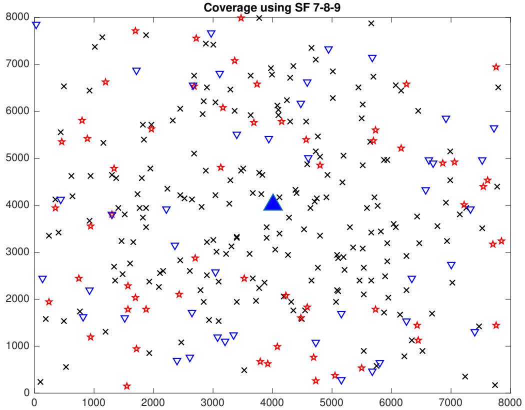

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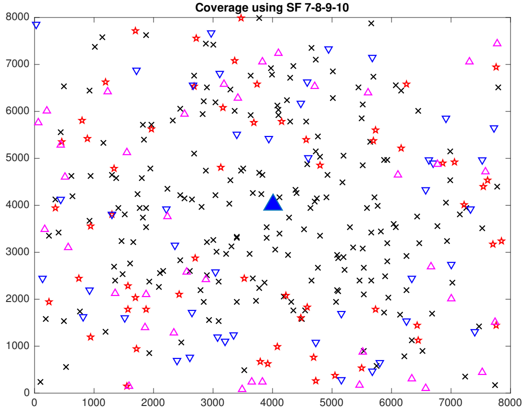

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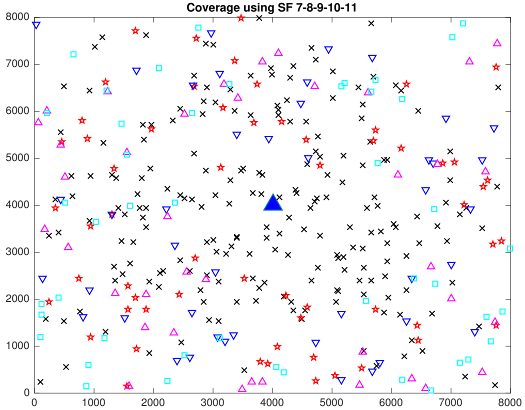

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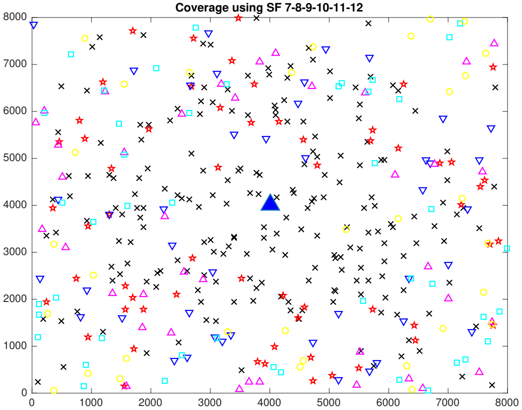

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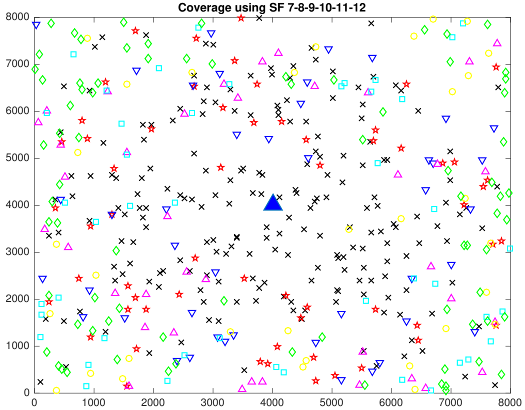
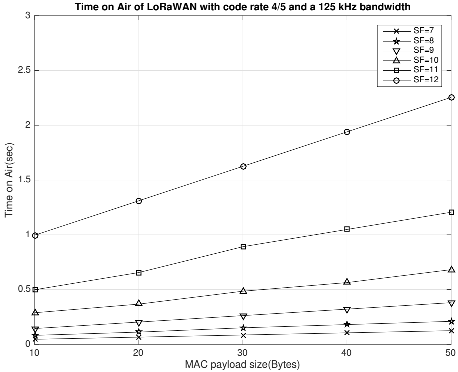


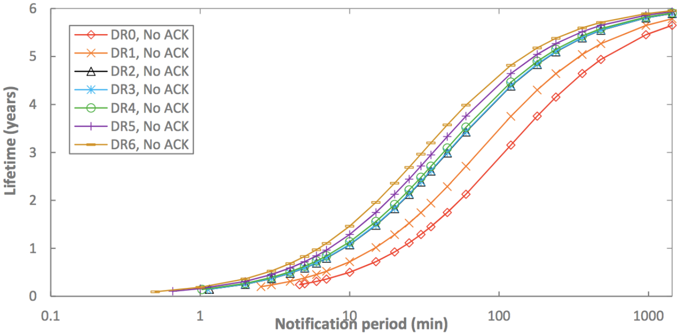
Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	40.50	51.60	61.60	70.40	77.70	86.10

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



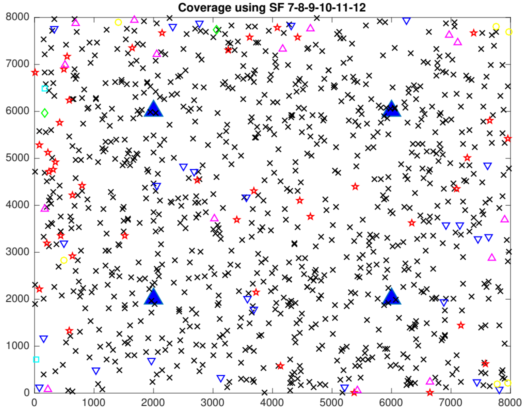
Spreading Factor and Energy Consumption



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

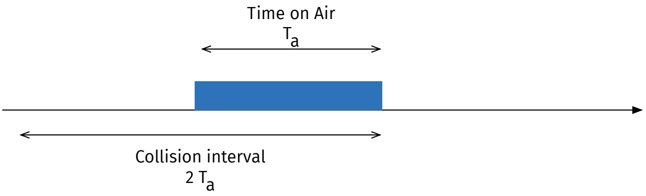


Spreading Factor	7	8	9	10	11	12
Cumulative coverage (%)	88.70	94.50	97.60	99.20	99.60	100.00

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:

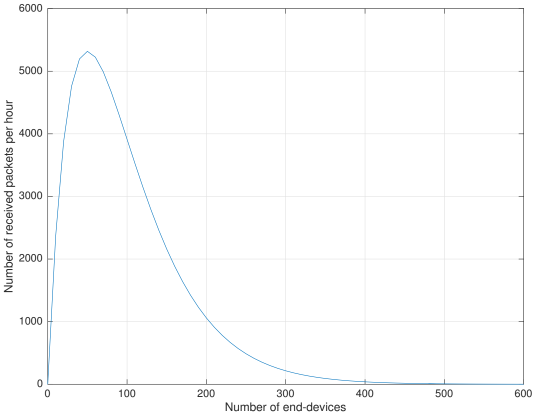
$$S = G \exp(-2G) = N\lambda(s)T_a(l,s) \exp(-2N\lambda(s)T_a(l,s))$$

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

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

Received Packets per Hour

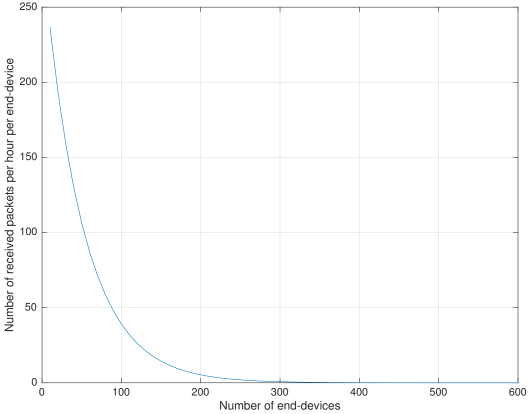
- The number of received packets per hour decreases after 50 end-devices



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

Received Packets per End-Device per Hour

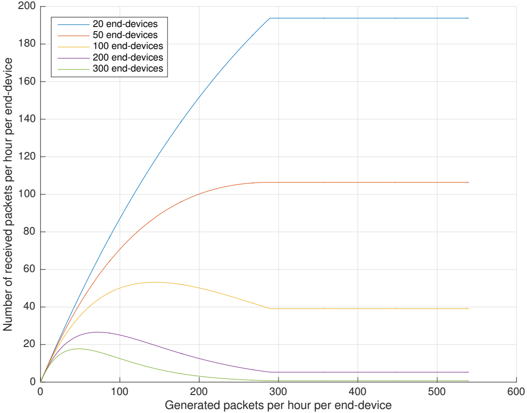
- For 100 end-devices generating 289 packets per hour, the average number of received packets per end-device equals 40 per hour



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

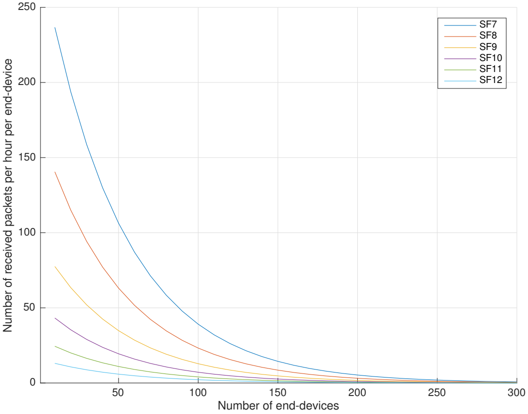
Packet Generation Rate

- 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



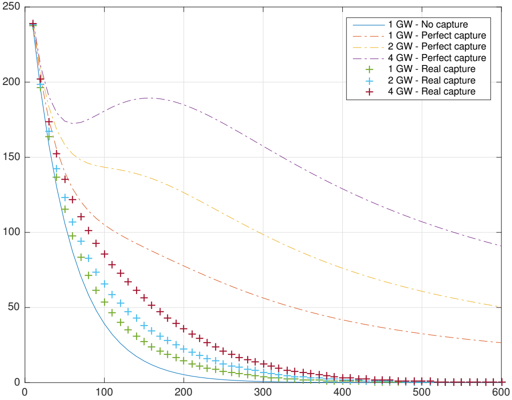
l=50 bytes, $\lambda(s) = \frac{d}{T_a(l,s)}$

- 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 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

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

- ALOHA with multiple receivers and perfect packet capture

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

- ALOHA with multiple receivers and realistic packet capture

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

with

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

Outline

Test

Test