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

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

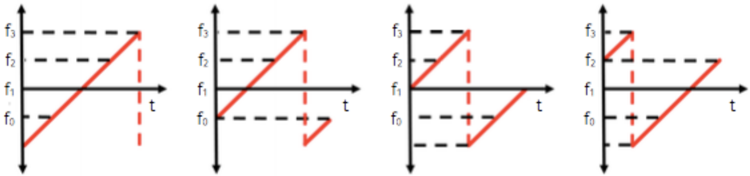
$$R_b = \frac{log_2(g_p)}{T} = log_2(g_p) \cdot \frac{B}{g_p}$$

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

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

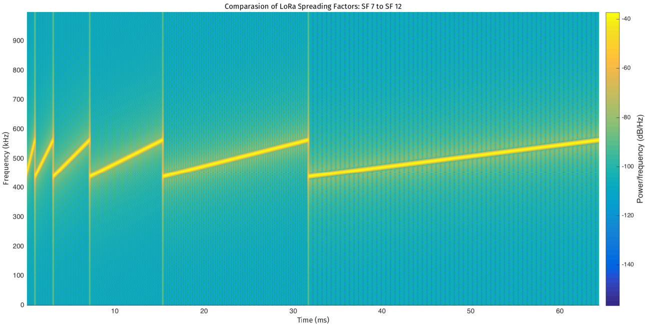
LoRa Symbols

- $log_2(g_p)$ 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 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	868.10 868.30 868.50	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:

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

  - 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

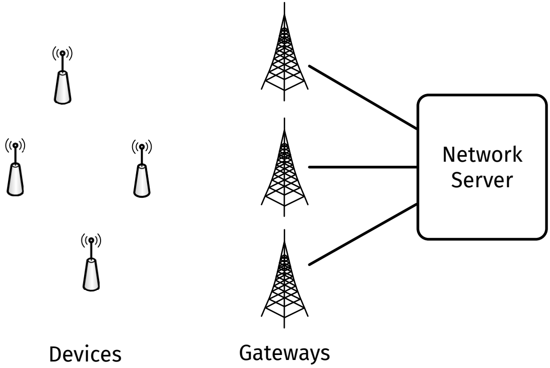
- LoRa
  - Modulation technique for LPWAN
- LoRaWAN
  - Uses LoRa modulation on physical layer
  - Proposes a MAC layer for access control
  - Specified by LoRa Alliance

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

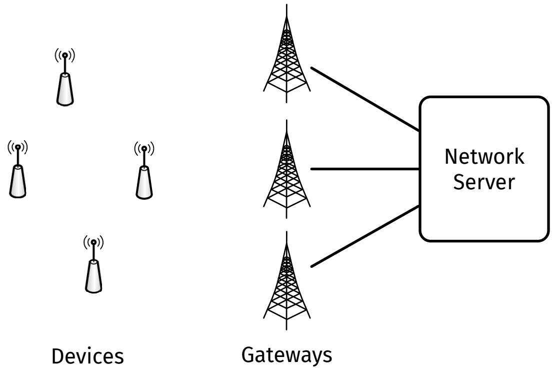
LoRaWAN Physical Architecture

End-Devices



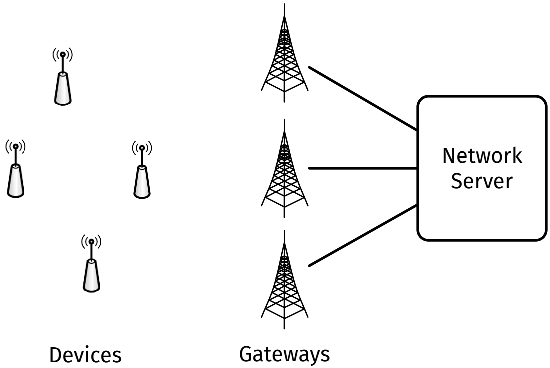
- End-devices are also called motes or devices
- Communicate to one or more gateways via a wireless interface using single hop LoRa or FSK

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

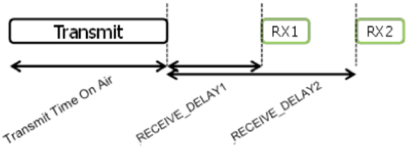
- Class A
  - Each uplink transmission is followed by two short downlink receive windows
  - Adapted for applications that only require downlink communication from the server shortly after the end-device has sent an uplink transmission
- Class B
  - In addition to class A, receive windows are opened 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

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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