Università degli Studi di Padova

Master's degree ICT Internet Multimedia Engineering

Department of Information Engineering (DEI)
Master degree on ICT for Internet and Multimedia Engineering (MIME)

Internet of Things and Smart Cities
L08 – Long Range (LoRa)

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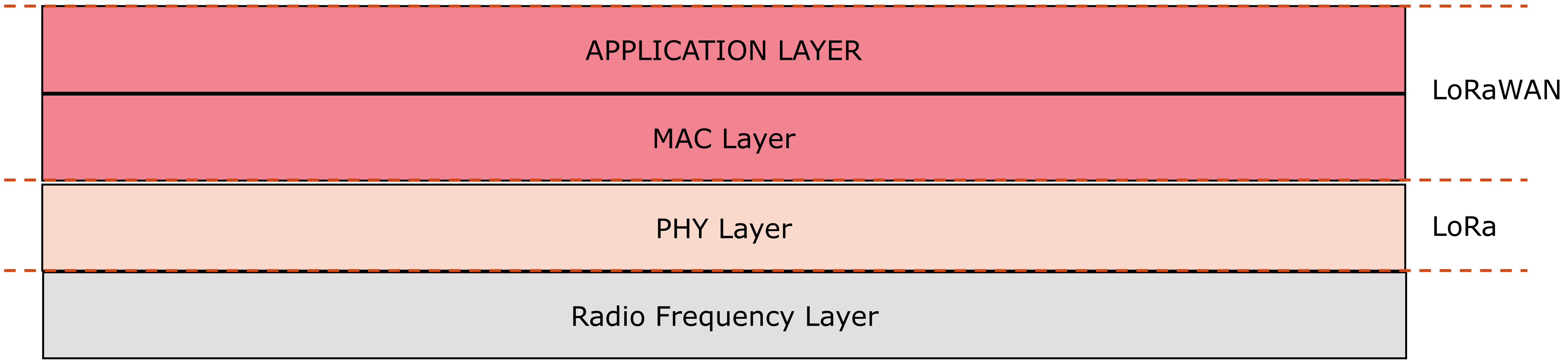
LoRa

Overview

- LoRa → <u>Lo</u>ng <u>Ra</u>nge
- **LoRa** was developed in France in 2009; **LoRa Alliance** was founded in 2015.
- LoRa: PHY layer implementation.
- LoRaWAN: the rest of the protocol stack (MAC + higher layers).



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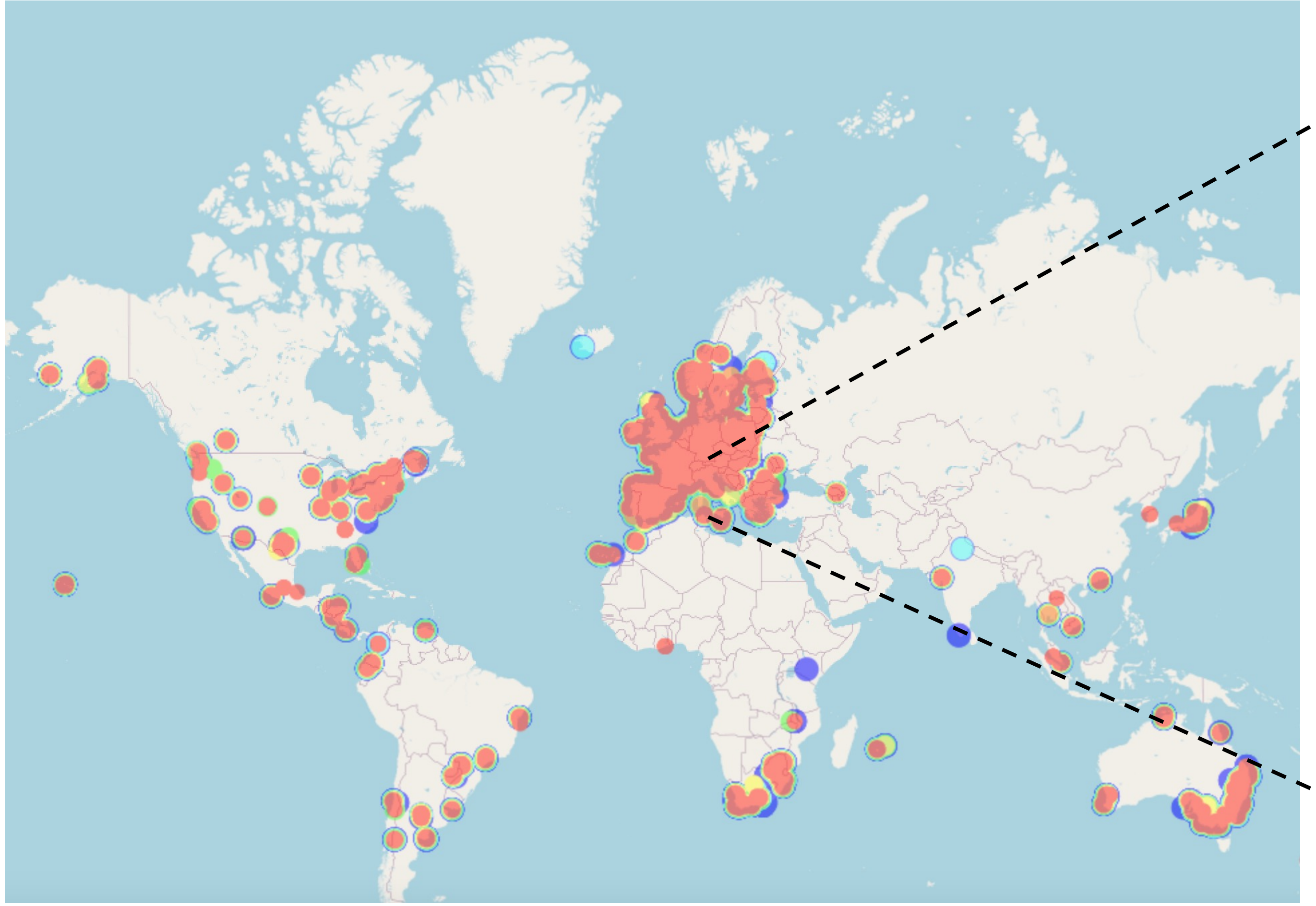
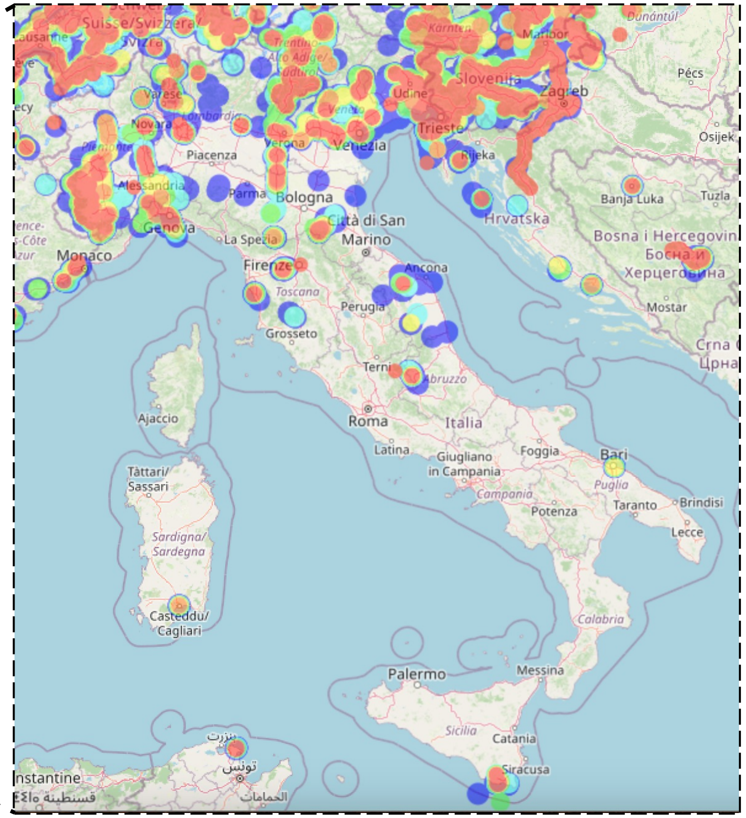
Coverage





https://ttnmapper.org/heatmap/

Applications

More examples here: https://www.semtech.com/lora/lora-applications

- **Smart agriculture**
  - Cattle management: https://www.chipsafer.com
  - Health of soil monitoring: https://teralytic.com
- **Smart buildings**
  - Reading and collection of utility usage: https://circuitcellar.com/tech-news/product-news/utility-metering-solution-taps-semtechs-lora-technology/
- **Smart cities**
  - City network: https://www.smartcitiesworld.net/news/news/iot-boost-for-glasgow-2265
  - Bus Schedule: https://business.teliacompany.com/internet-of-things/smart-public-transport
- **Smart environment**
  - Fire monitoring: https://www.zdnet.com/article/sk-telecom-launches-lora-based-fire-detection-solution/

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Frequency range

- Regional specifications establish rules on (among other parameters):
  - preamble, channel frequencies, allowed spreading factors, maximum payload size, receive windows, join procedures, …
- **Regional Parameter** document: https://lora-alliance.org/wp-content/uploads/2020/11/RP_2-1.0.2.pdf

Region	Frequency (MHz)
EU	863-870
US	902-928
China	779-787 and 470-510

Complete set of frequencies:
https://www.lansitec.com/blogs/lorawan-frequency-plan-by-country-or-region/

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Frequency range (Europe)

- From 24 to 80 channels, of 125 KHz each.
- The network operator can decide how many channels are employed.
- Must implement at least **3 channels**: 868.10, 868.30, 868.50 MHz.
  - For sending join-requests, so all gateways should listen on these channels.
- The maximum MAC payload size is **230 bytes** (application: **222 bytes**)

Range	Power	Duty cycle	Bandwidth(*)
863 MHz - 865 MHz	25 mW (**14 dBm**)	0.1%	125 KHz
865 MHz - 868 MHz	25 mW	1%	125 KHz
868 MHz - 868.6 MHz	25 mW	1%	125 KHz
868.7 MHz - 869.2 MHz	25 mW	0.1%	125 KHz
869.4 MHz - 869.65 MHz	500 mW (27 dBm)	10%	125 KHz
869.7 MHz - 870 MHz	5 mW	No requirements	125 KHz
	25 mW	0.1%	125 KHz

https://www.thethingsnetwork.org/docs/lorawan/regional-parameters/eu868/

(*) 250 KHz only for DR6

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PHY layer

- **Chirp Spread Spectrum (CSS)**
  - Symbols are encoded by modulating a carrier that changes frequency **linearly in time**.
  - Spreads signal power on a wide region of the spectrum to resist frequency-selective noise.
  - **Up-chirps** and **down-chirps**.

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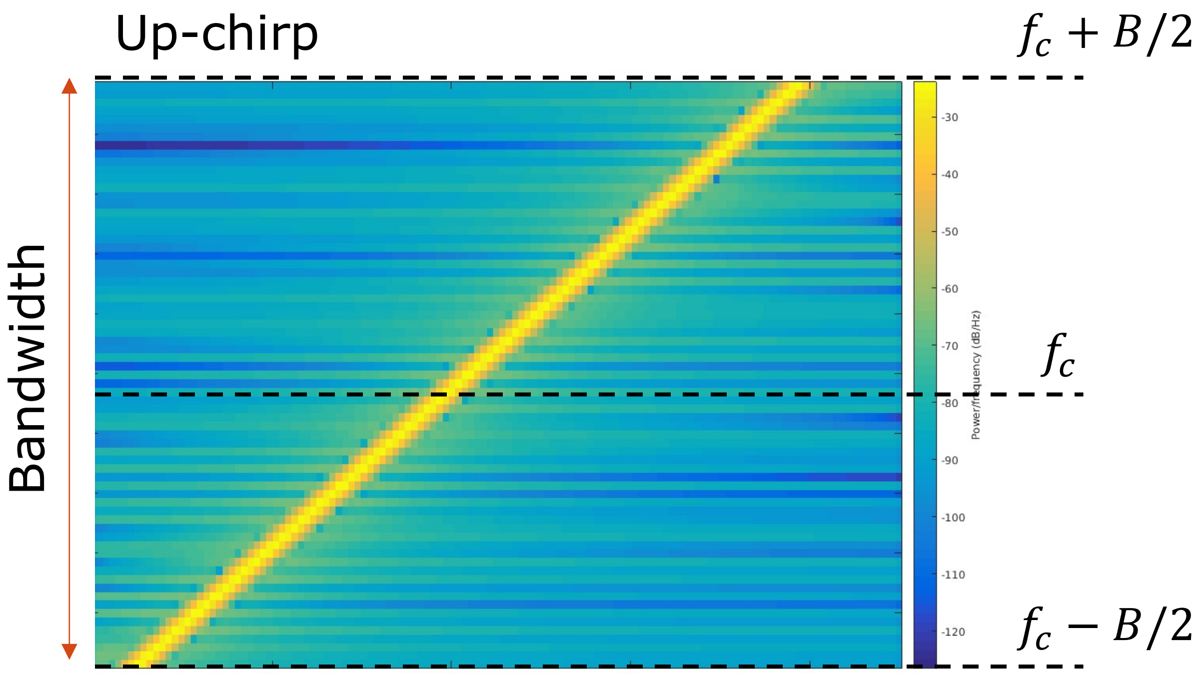
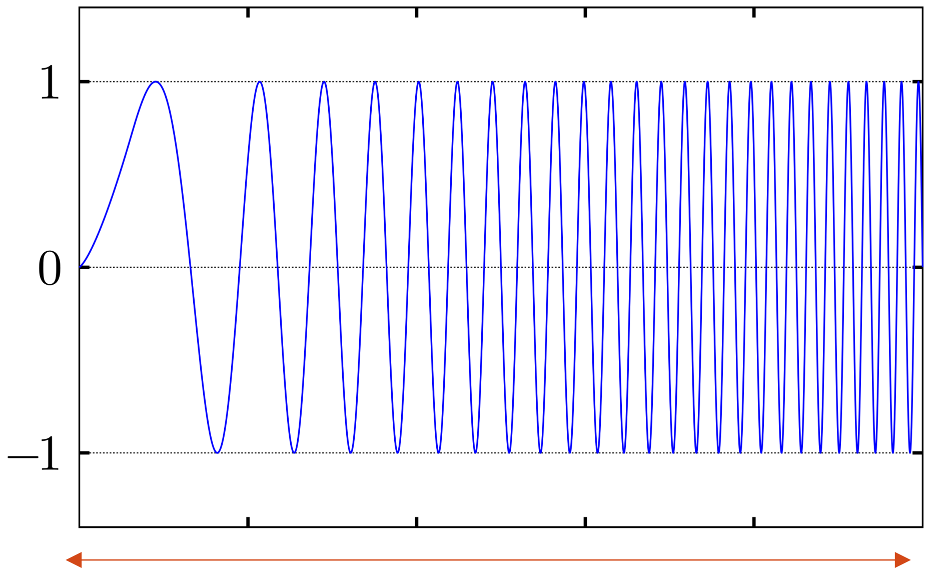
PHY layer

Up-chirp



Symbol duration

Within the symbol duration, the frequency increases linearly, so "peaks" in amplitude get **closer and closer.**



Symbol duration

PHY layer

- **Spreading Factor (SF)**: Number of bits per symbol.
  - 2^{SF} possible combinations of symbols (**chips**).
    - Example: SF = 2 → 2 bits to represent symbols → 2^2=4 possible symbols: {00,01,10,11}.
    - Example: SF = 3 → 3 bits to represent symbols → 2^4=8 possible symbols: {000,001,010,…111}.
  - In LoRa, SF can assume values between 7 and 12.
  - SFs influence data rate, time-on-air, battery life, and receiver sensitivity.

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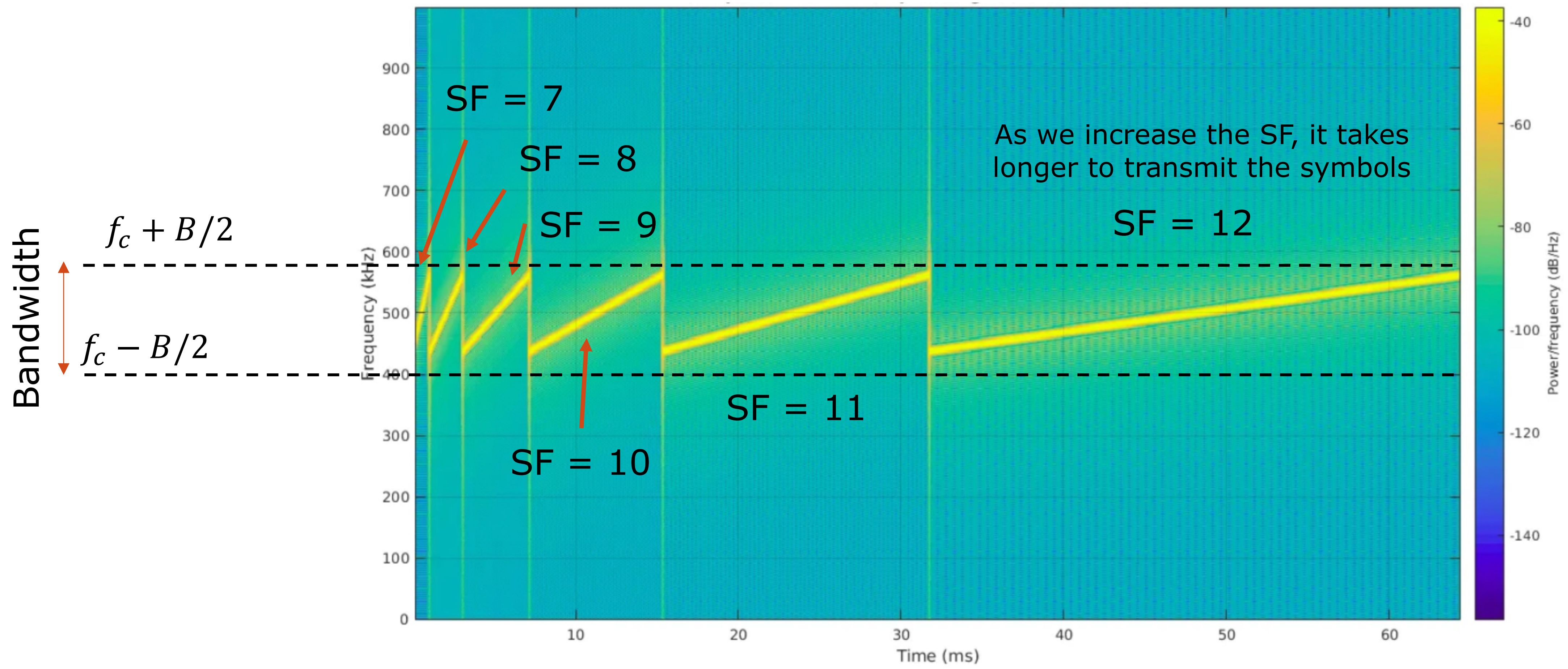
PHY layer: spreading factor



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PHY layer: spreading factor

- **Symbol rate**: Number of symbols/s → $R_S = B/2^{SF}$.
  - Since there are 2^{SF} possible symbols, the whole bandwidht is split into 2^{SF} parts.
  - If we increase the SF, we have more combinations of symbols.
- **Symbol duration**: how much time it takes to tx a symbol → $T_S = 1/R_S = 2^{SF}/B$.
  - If we increase the SF, it takes longer to transmit a (longer) symbol.
- **Bit rate**: Number of bits/s → $R = SF \cdot R_S = SF \cdot B/2^{SF}$
  - Each symbol is represented by SF bits.
  - Increasing the SF means to increase linearly the number of bits per symbol, but also increase exponentially the symbol duration.
  - The increase of symbol duration is dominant → **The bit rate decreases by increasing SF.**
- **Energy consumption**: It increases as $SF/2^{SF}$ increases (more ToA = more energy).

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PHY layer: spreading factor

- SFs are **pseudo-orthogonal.**
  - Multiple signals at different data rates (e.g., using different SFs) on the same channel (i.e., using the same time/frequency resources) can be received simultaneously.
  - Signals can arrive concurrently with **no collision**, as long as they have a different SF.
  - In practice, no collision even with the same SF if the power difference is **≥6 dB.**

- **Code rate (CR)**: LoRa applyies **Forward Error Correction** by adding a number of CR extra bits every 4 bits, with CR = {1,2,3,4}.
  - The actual bit rate can be computed as:

$$R = SF \cdot \frac{B}{2^{SF}} \cdot \left(\frac{4}{4 + CR}\right)$$

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PHY layer: spreading factor

- Higher SF have a longer transmission duration (”**time on air**”).
- We can accumulate energy for a longer time.
  - **Better sensitivity**: the receiver is able to effectively receive more corrupted signals.
  - **Longer range:** the receiver can receive on a more attenuated (i.e., longer) link.
  - The sensitivity (S) depends on the bandwidth, the min. SNR, and the circuitry noise:

SF (bits/symbol)	SNR_m
7	-7.5 dB
8	-10 dB
9	-12.5 dB
10	-15 dB
11	-17.5 dB
12	-20 dB

$$S = -174 + 10\log(B) + NF + SNR_m$$

PHY layer: spreading factor

- Lower SF → Higher rate → Lower range.
- Higher SF → Lower rate → Higher ToA → Higher range.

We'll see...

SF	Bandwidht (KHz)	Bit rate (Kbit/s) (CR = 1)	Range (km)	ToA (ms) (10-Byte)	Sensitivity (dBm)	Max. payload (B)
7	250	10.9	2	28	-120.5	222
	125	5.5	2	56	-123	222
8	125	3.125	4	103	-126	222
9	125	1.758	6	205	-129	115
10	125	0.977	8	371	-132	51
11	125	0.537	10	741	-134.5	51
12	125	0.293	12+	1483	-137	51

Adaptive data rate

- How to select the optimal SF?
  - It must be large enough to reach the end device, but not too large to avoid energy waste.
  - **Adaptive data rate**: mechanism to adapt the SF based on the link conditions.
  - The objective is to jointly optimize the quality of the communication, the network capacity, and the power consumption.
- Rule: If the link margin is high, the data rate can be increased (i.e., the SF can be reduced); on the other hand, if the link budget is low, the data rate should be reduced (i.e., the SF should be increased).
- In other words, **as the distance of the end device from the gateway increases, the SF increases** to cope with the progressively worse SNR. Correspondingly, the ToA increases, together with the power consumption.

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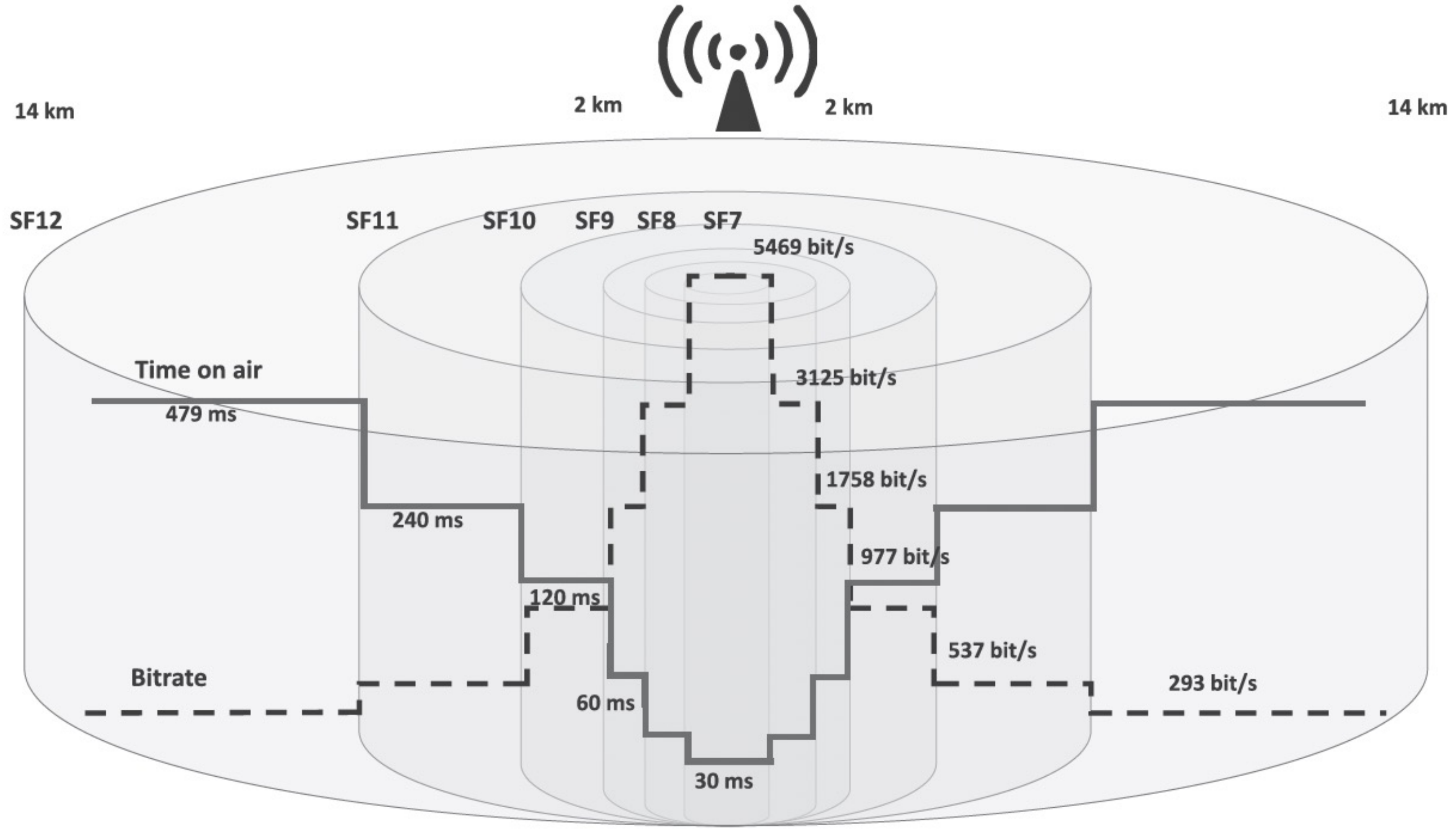
Adaptive data rate



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Frame structure

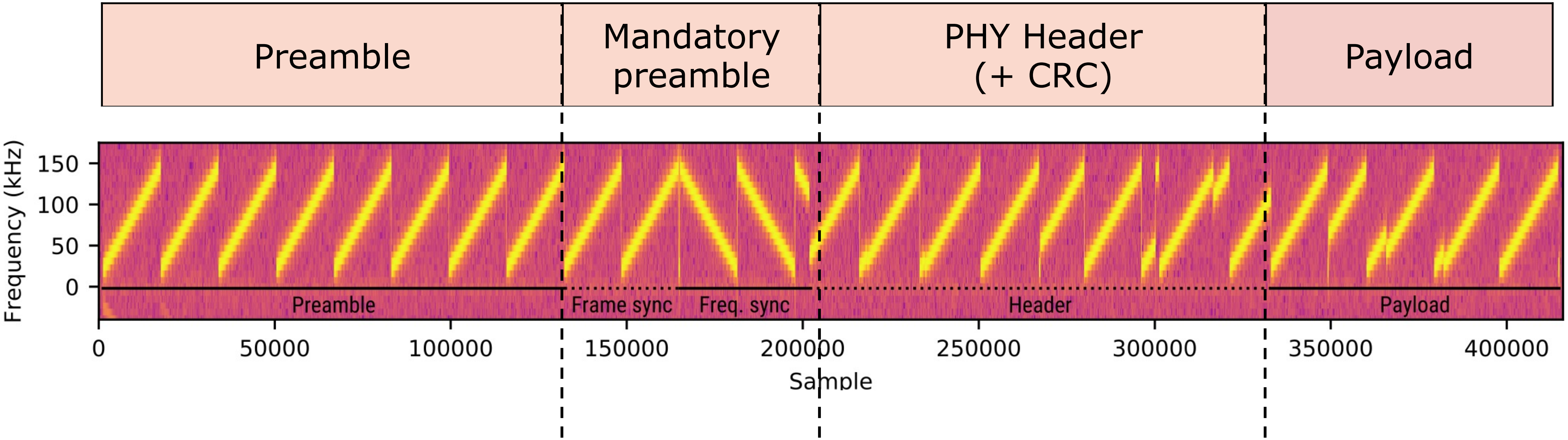
- **Preamble**: Well-knonw sequence of up-chirps and down-chirps.
  - The longer, the more likely the detection of the packets by the receiver.
  - Typically, 8 symbols.
- **Mandatory preamble**: for synchronization.
- **PHY Header**: Payload length, data rate configuration, …
- **Header CRC**: indication of the CRC in the payload.

Preamble	Mandatory preamble	PHY Header (+ CRC)	Payload	CRC
6-65535 symbols	4.25 symbols	8 symbols (explicit mode)	0-255 bytes	0-2 bytes

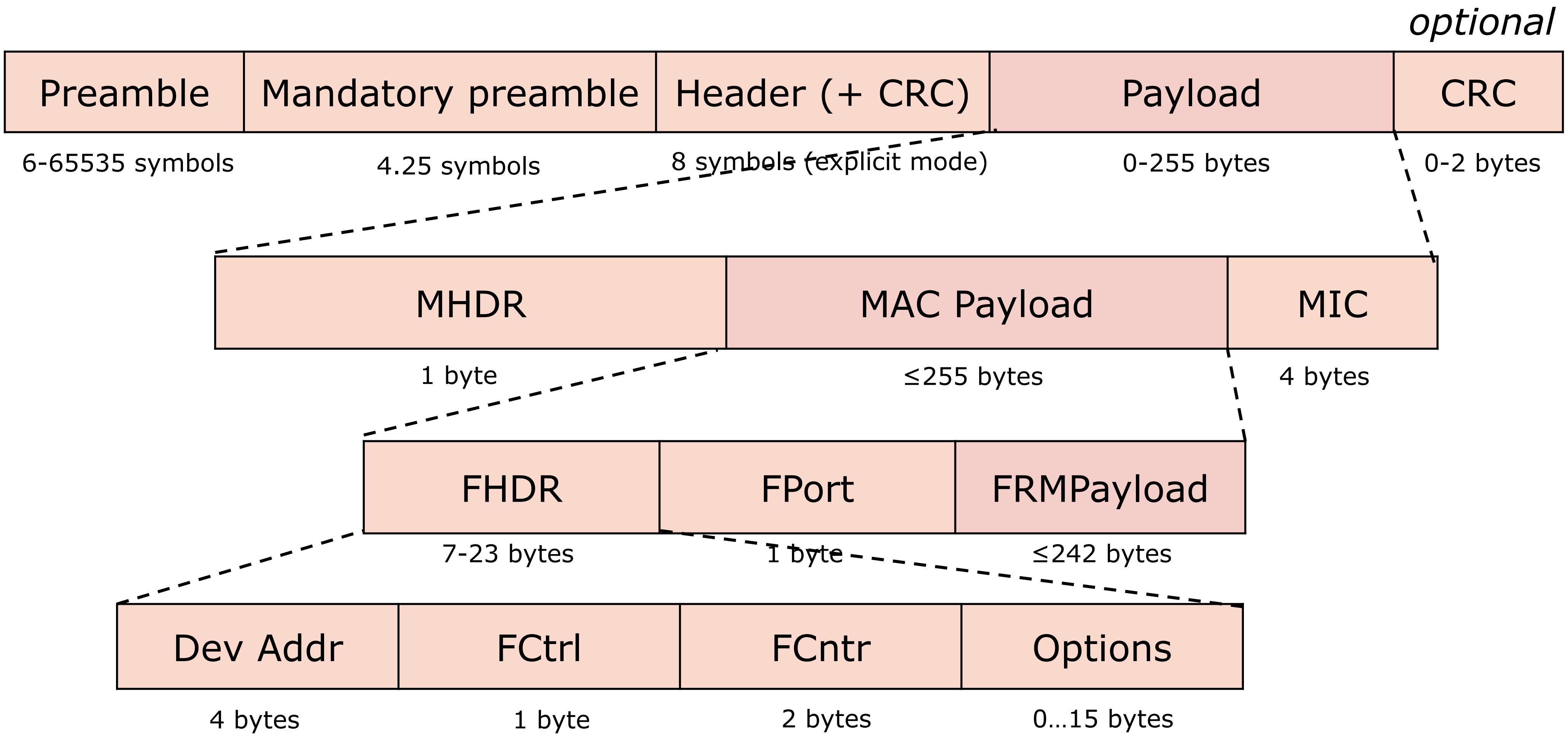
LoRa

Frame structure

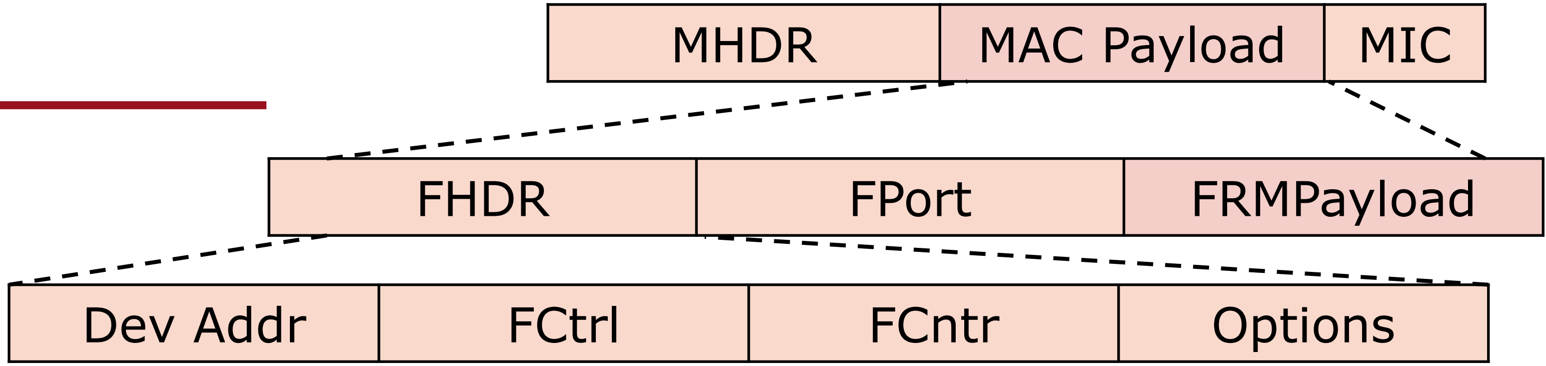
- Spectrogram of an example LoRa signal transmitted with the RN2483 LoRa transceiver using **SF 11** and **CR 5**, and received with a USRP B210 SDR.
  Robyns, Pieter, et al. "A Multi-Channel Software Decoder for the LoRa Modulation Scheme." IoTBDS. 2018.



Frame structure



LoRa



Frame structure

- **MHDR** (MAC Header): Specify the message type.
- **MIC** (Message Intregrity Code): Digital signature (for security).
- **FPort** (Frame Port): if the payload has some app data, then Fport = 1.
- **FHDR** (Frame Header): contains several subfields:
  - Dev Addr (32 bits).
  - Frame Control (FCtrl): Network control information, such as whether to use the data rate specified by the gateway for uplink transmission, whether this message acknowledges the reception of the previous message, whether the gateway has more data for the mote.
  - Frame Counter (FCntr): sequence numbering.
  - Frame Options: commands used to change data rate, power transmission, etc.

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Time on Air

- The “**Time on Air**” is the time to transmit a frame, which depends on the number of symbols in the preamble and in the payload:

$$ToA = t_{preamble} + t_{payload}$$

- $t_{preamble} = \left(n_{preamble} + 4.25\right)T_S$.
- $t_{payload} = \left(n_{payload}\right)T_S$ → The computation of $n_{payload}$ depends on many parameters:
  - The Spreading Factor (SF).
  - Number of payload bytes (PL).
  - Whether the PHY Header is enabled (H).
  - Whether low data rate optimization is enabled (DE). This mode consist in deleting the top two rows of the interleaving matrix, because they are more prone to errors.
  - The number of CRC bits (CR).

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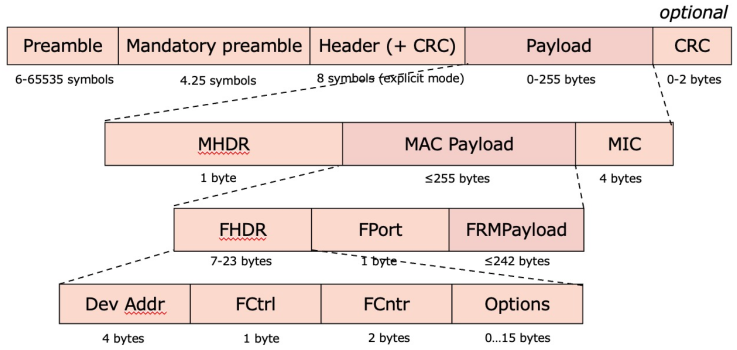


Time on Air

- We have that:

*Min. payload overhead is **12 (+1) bytes**: MHDR (1)+Dev Addr (4) + FCtrl (1) +FCnt (2) + MIC (4) (+ FPort (1) if app data).*

$$n_{payload} = 8 + max\left(\left\lceil\frac{8PL - 4SF + 28 + 16 - 20H}{4(SF - 2DE)}\right\rceil (CR+4), 0\right)$$

Formula based on SX1276 Semtech datasheet: https://www.mouser.com/datasheet/2/761/sx1276-1278113.pdf

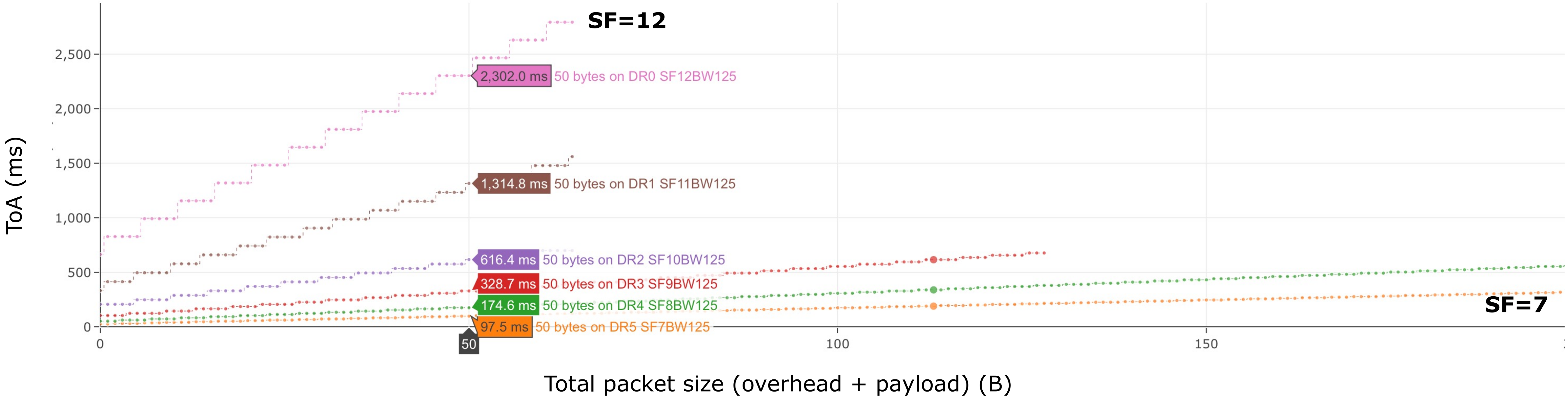
- Given that $T_S = 1/R_S = 2^{SF}/B$, we have that:

$$ToA = \frac{2^{SF}}{B}\left((n_{preamble} + 4.25) + 8 + max\left(\left\lceil\frac{8PL - 4SF + 28 + 16 - 20H}{4(SF - 2DE)}\right\rceil (CR+4), 0\right)\right)$$

Transmission times (example)

https://avbentem.github.io/airtime-calculator/ttn/eu868/100

- B = 125 KHz.
- $n_{preamble} = 8$ (default).
- Min. possible overhead (H=0, DE=0, CR = 1) → 12 B.



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Transmission times (example)

https://avbentem.github.io/airtime-calculator/ttn/eu868/100

	DR6 SF7 BW 250	DR5 SF7 BW 125	DR4 SF8 BW 125	DR3 SF9 BW 125	DR2 SF10 BW 125	DR1 SF11 BW 125	DR0 SF12 BW 125
airtime	28.3 ms	56.6 ms	102.9 ms	205.8 ms	370.7 ms	741.4 ms	1,482.8 ms
1% max duty cycle	2.8 sec 1,272 msg/hour	5.7 sec 636 msg/hour	10.3 sec 349 msg/hour	20.6 sec 174 msg/hour	37.1 sec 97 msg/hour	74.1 sec 48 msg/hour	148.3 sec 24 msg/hour
fair access policy	81.5 sec (avg) 44.2 avg/hour 1,060 msg/24h						

We'll see...

SF	Bandwidht (KHz)	Bit rate (Kbit/s) (CR = 1)	Range (km)	ToA (ms) (10-Byte)	Sensitivity (dBm)	Max. payload (B)
7	250	10.9	2	28	-120.5	222
	125	5.5	2	56	-123	222
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12	125	0.293	12+	1483	-137	51

Transmission times (example)

Duty cycle: 1% → **Transmitter must be silent for 99% of time after transmisssion**.

- Previous example: ToA (100 B, SF = 7) = 189.7 ms.
  - Transmitter can transmit only 36 s/h → It must be silent for 189.7 * 99 = 18.78 s.
  - Total cycle is 18.78 s + 189.7 ms = 18.97 s.
  - In 1 hour, there are ~(60*60)/(18.97) = 190 cycles → I can send ~190 packets (of 100 B) / h.

- Previous example: ToA (100 B, SF = 12) = 4431.9 ms.
  - Transmitter must be silent for 4431.9 * 99 = 443.2 s = **<u>7.3 min.</u>**
  - Total cycle is 4.43 + 443.2 ms = 447.63 s.
  - In 1 hour, there are ~ (60*60)/(447.63) ~ 8 cycles → I can send ~8 packets/h.

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Transmission times (example)

- Further constraint: Fair Access Policy.
  - An average of **30 seconds uplink time on air, per 24 hours, per device**.
    - Therefore, 1.25 s/h.
  - At most 10 downlink messages per 24 hours, including the ACKs for confirmed uplinks.

- Previous example: ToA (100 B, SF = 7) = 189.7 ms.
  - With fair access policy: 1.25/0.1897 = 6.6 packets/s = <u>158 packets/day.</u>

  - Previous example: ToA (100 B, SF = 12) = 4431.9 ms.
  - With fair access policy: 1.25/4.4319 = 0.28 packets/s = <u>6 packets/day.</u>

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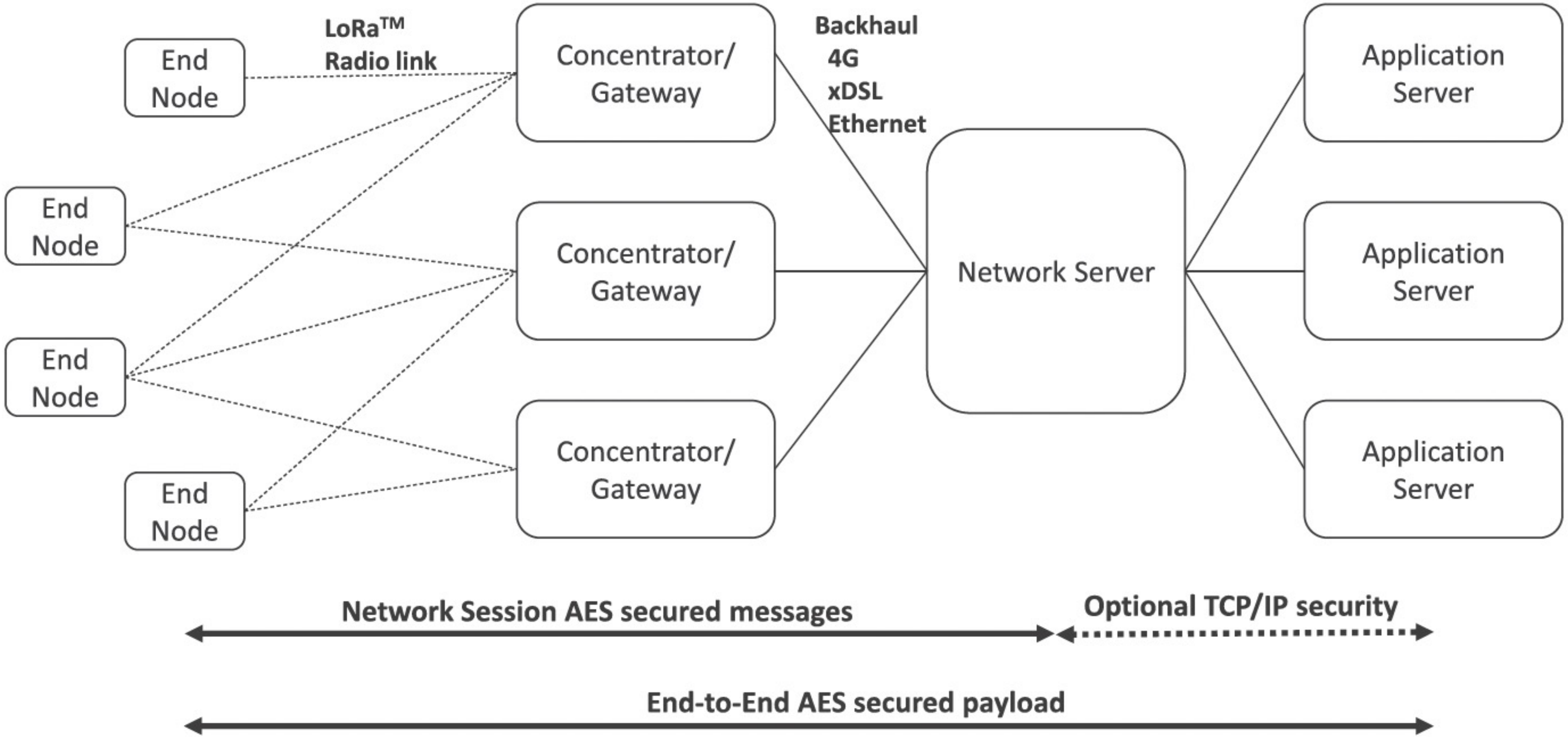
LoRaWAN architecture



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LoRaWAN architecture

LoRaWAN: It defines the components and the recommended protocols.

- **End Nodes**: end devices carrying sensing and actuating tasks.
  - DevEUI: End Node identifier (64 bits).
- **Gateway**: wireless base stations, to which End Nodes communicate based on the LoRa physical layer. Star-of-stars topology.
  - Dev Addr: Gateway identifier (32 bits).
- **Network Server**: eliminates duplicate messages, routes data to the relevant **Application Server**, and selects the best Gateway to reach the End Node in DL (based on the link quality)
  - End Nodes transmit messages that can be received by **all gateways** within reach.
  - The gateways relay the message at the Network Server.

MAC layer

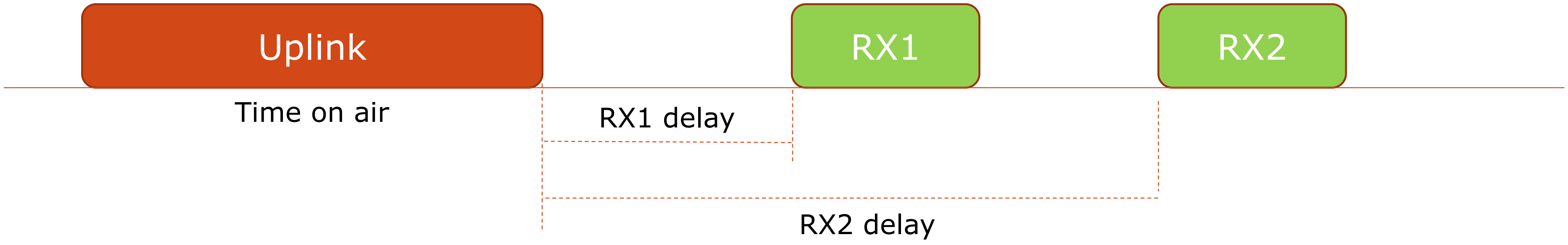
Three different classes of End Nodes.

- **Class A: communication is always initiated by the End Node.**
  - End Node sends an UL message at any unspecified time.
  - Completely unsolicited and asynchronous.
  - After a certain delay, the End Node opens two short received windows (**RX1** and **RX2**), that can be used to implement DL communication (e.g., commands or ACK).
  - Very low energy consumption (End Node is most of the time in sleep mode).
  - Very large DL latency (DL communication is only triggered after UL transmissions).
  - Use case: periodic sensor measurements.

MAC layer

Three different classes of End Nodes.

- **Class A: communication is always initiated by the End Node.**
  - RX2 is opened only if the network server does not respond during RX1.
  - If the network server does not respond during both RX1 and RX2, the next DL opportunity will be scheduled immediately after the next uplink transmission → long delay due to DC.



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MAC layer

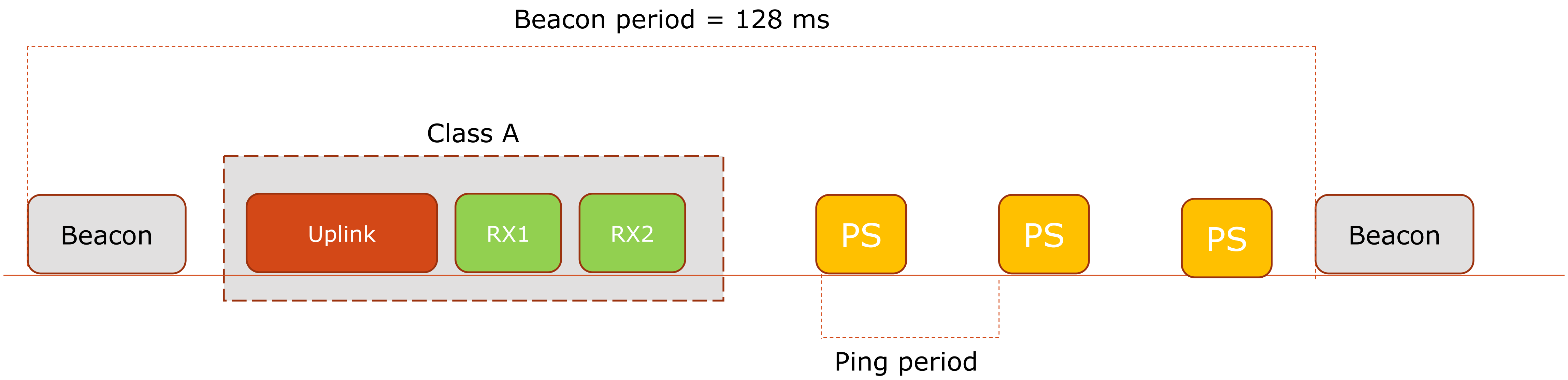
Three different classes of End Nodes.

- **Class B: bi-directional communication.**
  - It operates as Class A, with RX1 and RX2.
  - In addition, it uses time-synchronized beacons, sent by the Gateway, to open **ping slot**, i.e., extra receive windows opened by the Gateway itself to initiate DL transmissions.
  - Beacons are sent every 128 s, for 160 ms. The duration of the ping slot is 30 ms.
  - The interval between two beacons is divided evenly into 4096 ping slots.
  - Lower (bounded) DL latency (DL communication does not necessarily depend on UL).
  - Higher energy consumption than Class A (due to ping slots).
  - Use case: utility meters (electrical meters, water meters, etc.), street light, …

MAC layer

Three different classes of End Nodes.

- **Class B: bi-directional communication.**



MAC layer

Three different classes of End Nodes.

- **Class C: continuous receive mode.**
  - RX2 stays open until the next uplink transmission, unless there is activity on RX1.
  - Very low DL latency (End Nodes can receive DL messages at almost any time via RX2).
  - Very high energy consumption (since RX2 is always on).
  - Class C devices shall be connected to the mains (no battery power).
  - Use case: beacon lights, alarms, …