AALBORG UNIVERSITY
DENMARK

LoRaWAN
Research instruments in remote regions

Last mile – remote regions
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Assoc. Prof. **Jimmy Jessen Nielsen**, Ph.D.,
Connectivity Section
Department of Electronic Systems
Aalborg University (AAU), Denmark

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LoRaWAN overview

- LoRa/LoRaWAN is a long-range wireless communication system promoted by the LoRa Alliance
- LoRaWAN is an open IoT standard
- Using unlicensed (free) ISM frequency bands
- High throughput (0.3 kbps – 50 kbps) for IoT
- Up to 15 km range in rural areas
- Small form factor
- Expansion boards

Transceiver

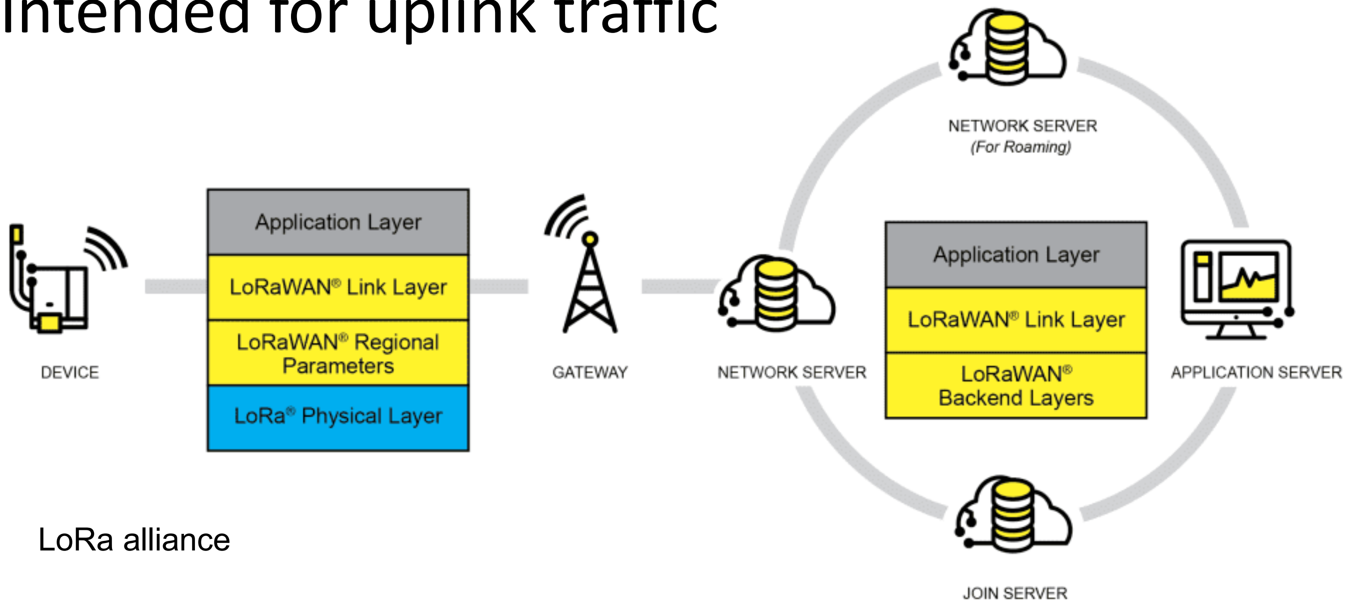
Connectivity Kit for Arduino, Waspmote, Raspberry Pi

- Seemingly ideal for remote deployments of sensor nodes, but

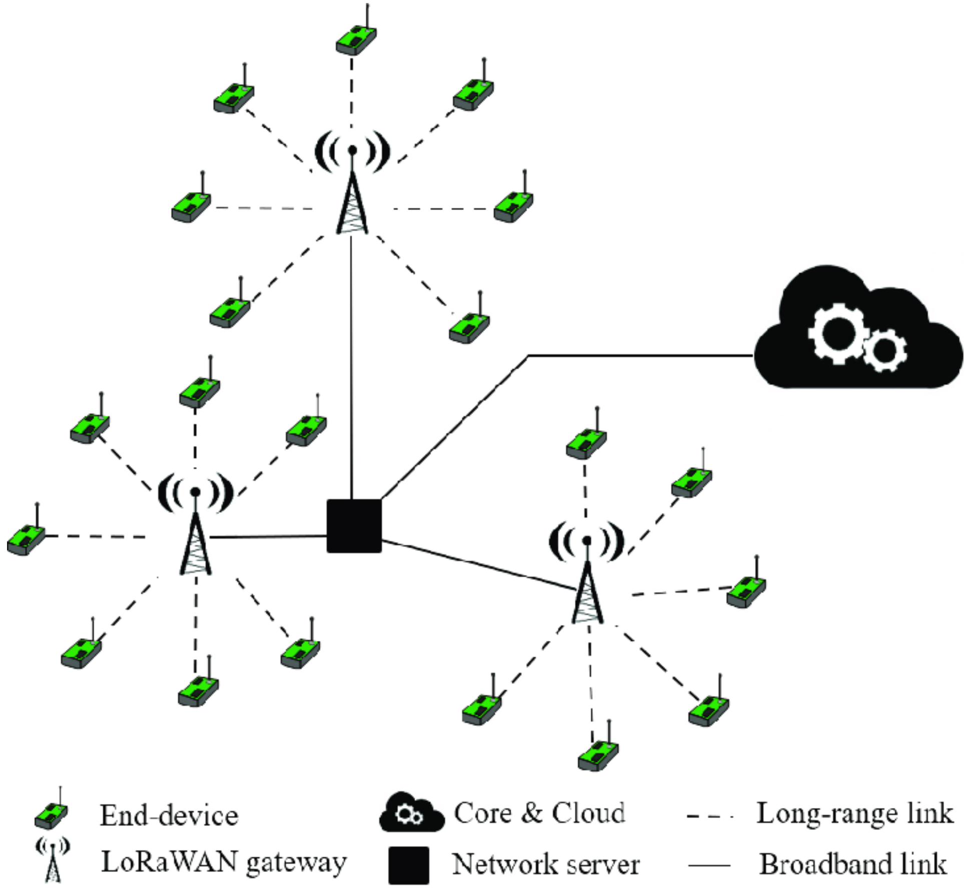
what are the limiting factors and what performance can be expected in different situations?

LoRa and LoRaWAN

- LoRa is the PHY layer
- LoRa's MAC layer protocol is called LoRaWAN
- A typical LoRa network is a "star-of-stars" topology
- Gateways have fiber or 4G/5G connectivity
- Intended for uplink traffic



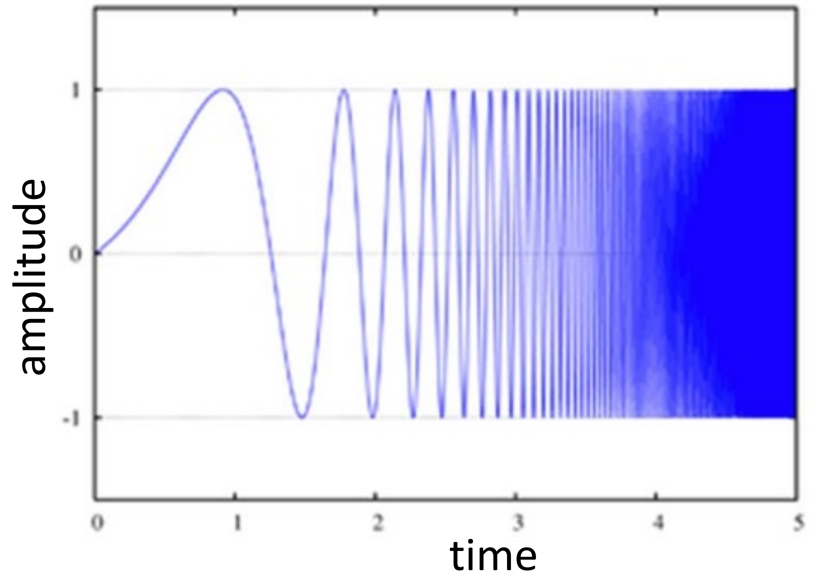
LoRa alliance

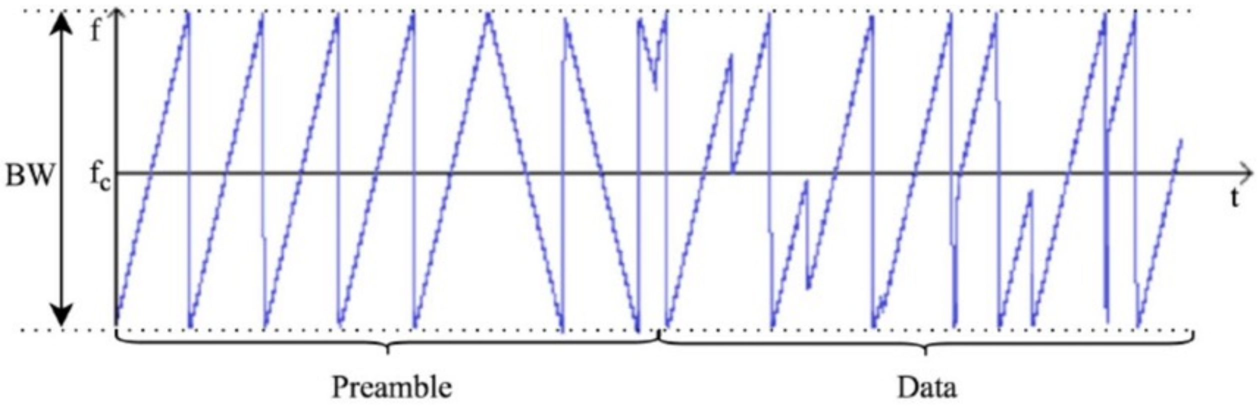


Santa, José & Sanchez-Iborra, Ramon & Skarmeta, Antonio. (2019). LPWAN-Based Vehicular Monitoring Platform with a Generic IP Network Interface. Sensors. 19. 1-17. 10.3390/s19020264.

Chirp Spread Spectrum (CSS)

- LoRa PHY is based on CSS
- Chirp
  - A signal with continuously increasing (or decreasing) frequency (Whale sound)
  - Up-chirp: vary from low to high frequency
  - Down-chirp: vary from high to low frequency
- LoRa data frames are encoded as a sequence of such phase-shifted chirps.





LoRa Modulation

- Key parameter is the spreading factor (SF)
  - Low SF means shorter chirps, high bitrate
  - high SF gives more robust transmission, but lower bitrate

Data rate [DR]	Spreading Factor [SF]	Bitrate [Bits/Sec]
0	12	290
1	11	440
2	10	980
3	9	1760
4	8	3125
5	7	5470

BW = 125 kHz, f_c = 868 MHz

time

frequency

Duty cycling

- Indicates the fraction of time a resource is busy
- Ex: Single channel with 20% DC:

1% DC constraint for device:

- transmit for 1 sec (time-on-air)
- stay silent for 99 sec
- transmit for 1 sec
- stay silent for 99 sec
- …
- → limit on Time on Air

Band	f^{-}-f^{+} [MHz]	Power [dBm]	Duty cycle	Channels
G	865-868	$\frac{6,2}{100}$ [/kHz]	1%	15 (125 kHz) 10 (250 kHz) 4 (500 kHz)
G1	868-868.6	14	1%	3 (125 kHz) 1 (250 kHz)
G2	868.7-869.2	14	0.1%	2 (125 kHz) 1 (250 kHz)
G3	869.4-869.65	27	10%	1 (125 kHz)
G4	869.7-870	7	100%	1 (125 kHz)
G4*	869.7-870	14	1%	1 (125 kHz)

EU863-870 ISM band available sub-bands

https://www.thethingsnetwork.org/docs/lorawan/duty-cycle/

Time on Air

- As duty cycle and fair-use limitations depend on time duration of transmission, time-on-air is a critical metric.

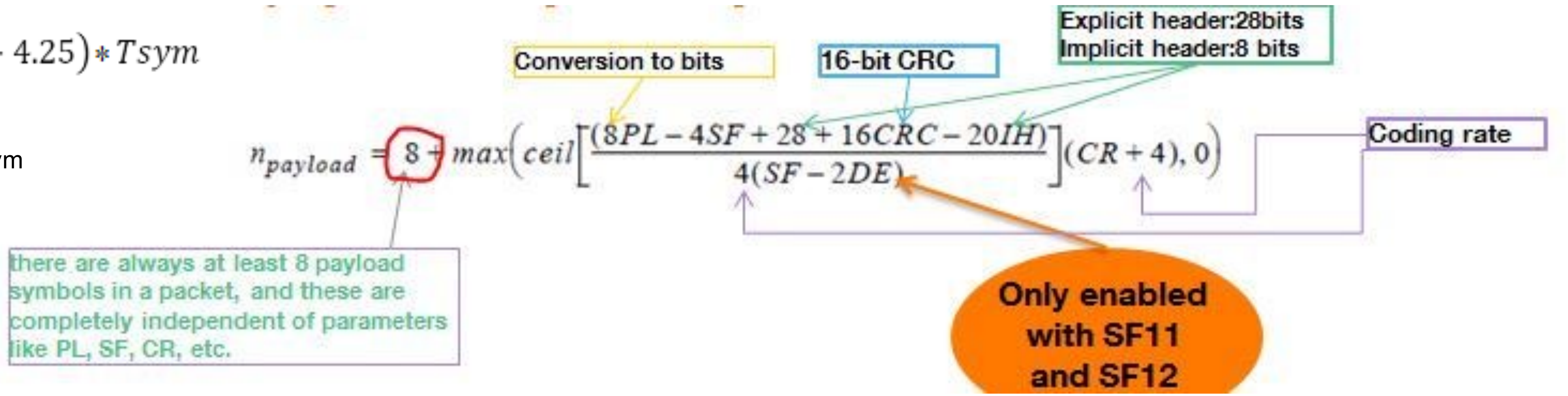
$$T_{packet} = T_{preamble} + T_{payload}$$

$$T_{preamble} = (n_{preamble} + 4.25) * Tsym$$

$$T_{payload} = n_{payload} \cdot T_{sym}$$

$$T_{sym} = \frac{2^{SF}}{BW}$$

$$n_{payload} = 8 + max\left(ceil\left[\frac{(8PL - 4SF + 28 + 16CRC - 20IH)}{4(SF - 2DE)}\right](CR + 4), 0\right)$$



- Example: 20 bytes, 125 kHz BW

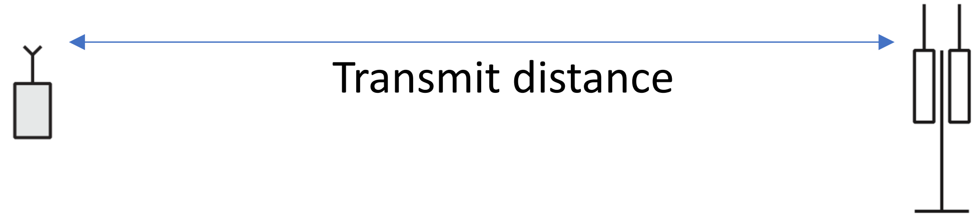
SF7	SF8	SF9	SF10	SF11	SF12
71.9 ms	133.6 ms	246.8 ms	452.6 ms	987.1 ms	1810.4 ms

Roughly doubling ToA when increasing SF by 1.

https://www.thethingsnetwork.org/airtime-calculator

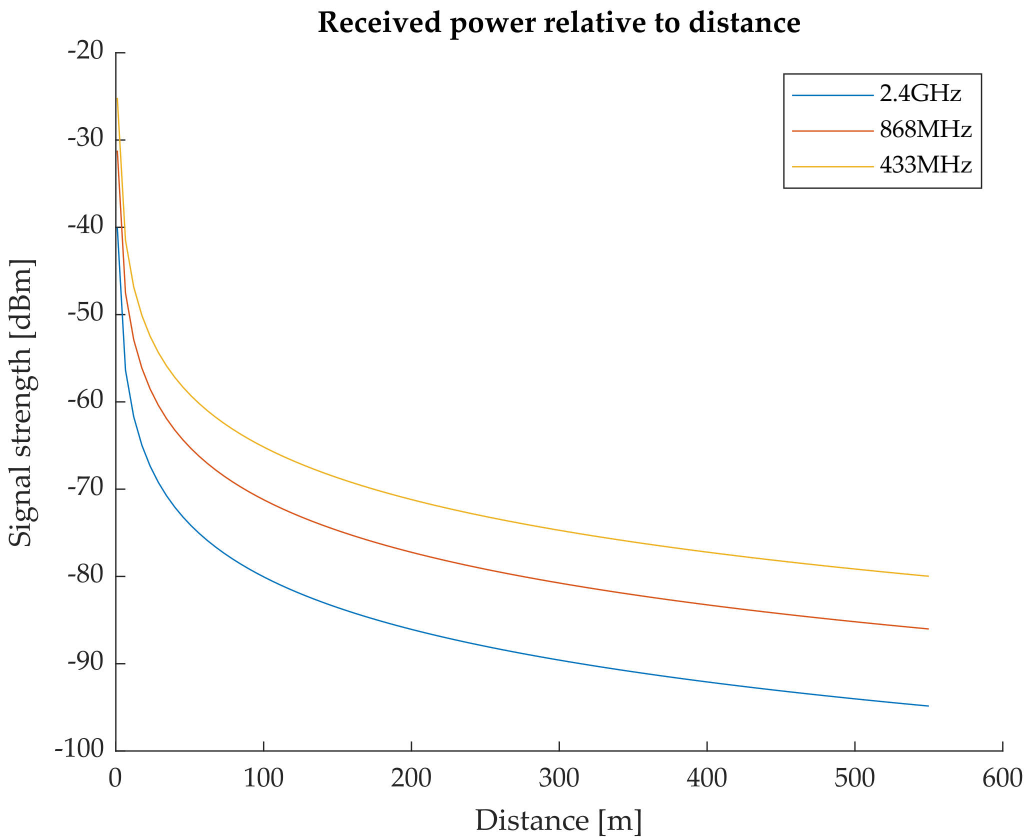
Path loss

- Received signal strength decays exponentially with distance
- We can increase transmit power, but only to a limit, and it costs energy



Spreading Factor [SF]	Bitrate [Bits/Sec]	Range [Km]	Rx Sensitivity [dBm]
12	290	12+	-136
11	440	10	-133
10	980	8	-132
9	1760	6	-129
8	3125	4	-126
7	5470	2	-123

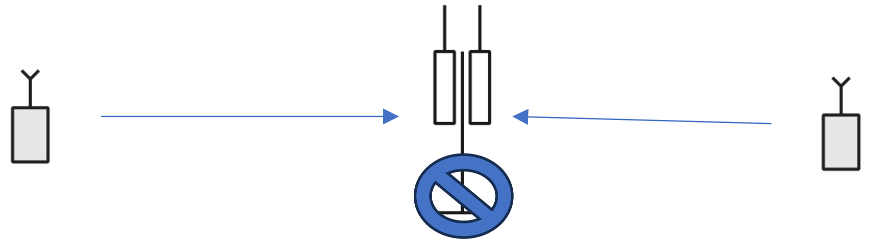
Typical Wi-Fi chipset have appr. -105 dBm sensitivity.

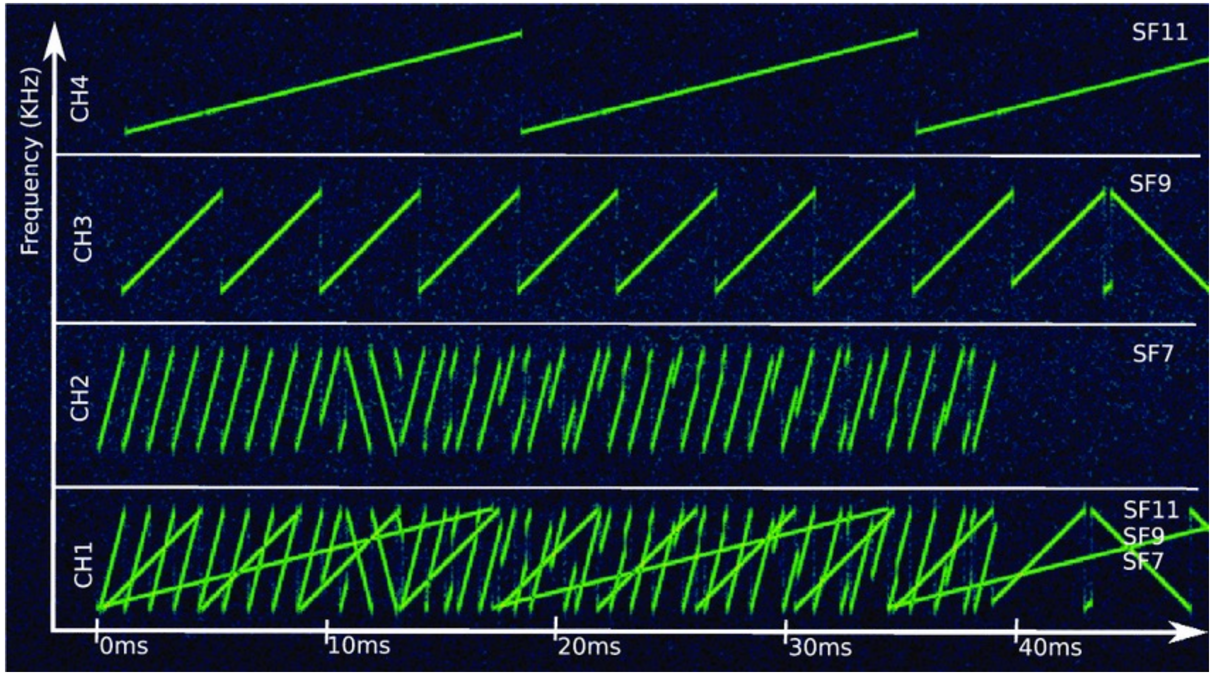


(For transmit power 0 dBm)

Collisions/quasi-orthogonality

- Typically, in wireless systems, overlapping transmission from two devices will cause a collision in the receiver.
- LoRa gateway can separate and receive multiple simultaneous transmissions due to:
  - Chirp modulation
  - spreading factors are quasi-orthogonal
- Typically, gateway supports up to 8 simultaneous receptions





Sorensen, R.B., Razmi, N., Nielsen, J.J. and Popovski, P., 2019, May. Analysis of LoRaWAN uplink with multiple demodulating paths and capture effect. In *ICC 2019-2019 IEEE International Conference on Communications (ICC)* (pp. 1-6). IEEE.

Putting it together

- Example:
  - Periodic transmission of 20 bytes measurement packet.
  - Assuming 1% duty cycle, using 1 channel
  - For 1 sensor device:

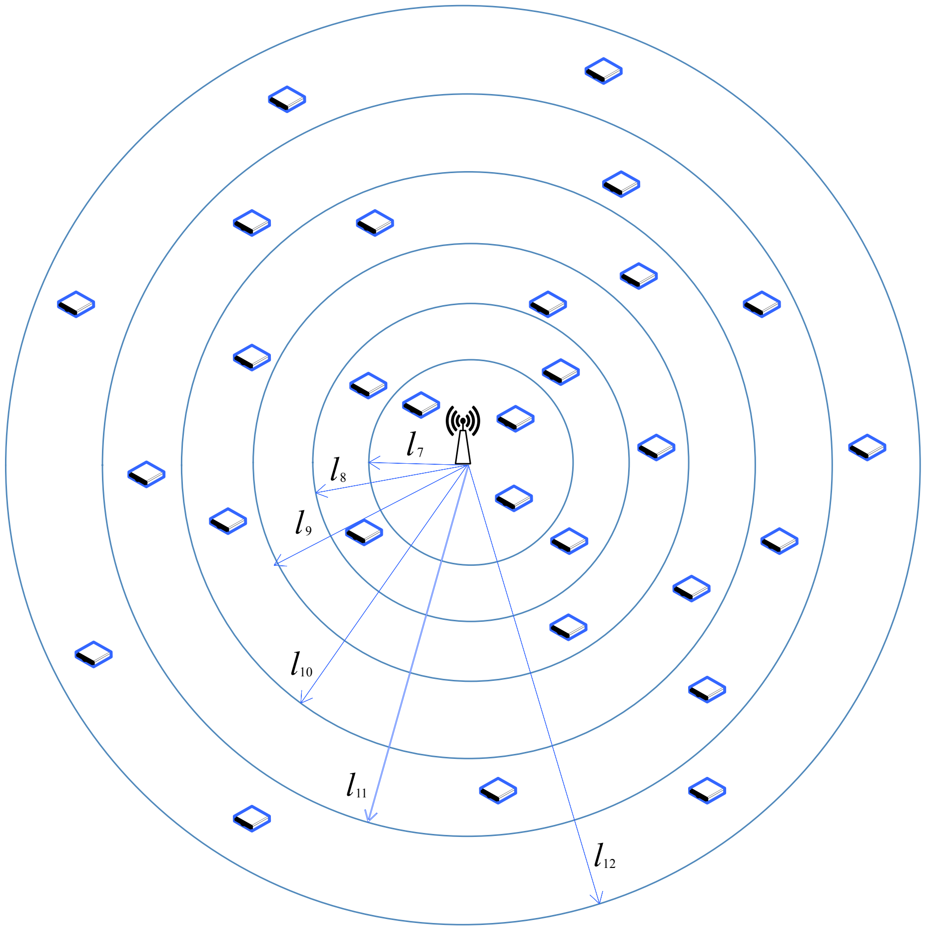
Short range (< 2km) – SF7	Long range (~12 km) – SF12
1 transmission: 71.9 ms (followed by 99x silence) Shortest transmit interval: 7.19 sec Data rate: 22 bit/sec	1 transmision 1810.4 ms (followed by 99x silence) Shortest transmit interval: ~3 min Data rate: ~1 bit/sec

- Luckily, in LoRaWAN, many devices can be active at the same time, by distributing:
  - in time (x 100),
  - across channels (x 1-15), and
  - across spreading factors (x 6)

⇒ Hundreds of devices

SF allocation

- The task of assigning the SF for each device in the system.
  - Or rather, defining the limits of the annuli (regions between rings)
- Challenging because annuli further away from the gateway will:
  - have larger area and thus more devices for a given width (assuming uniform device distribution)
  - use higher SF which has longer time-on-air → higher risk of collision



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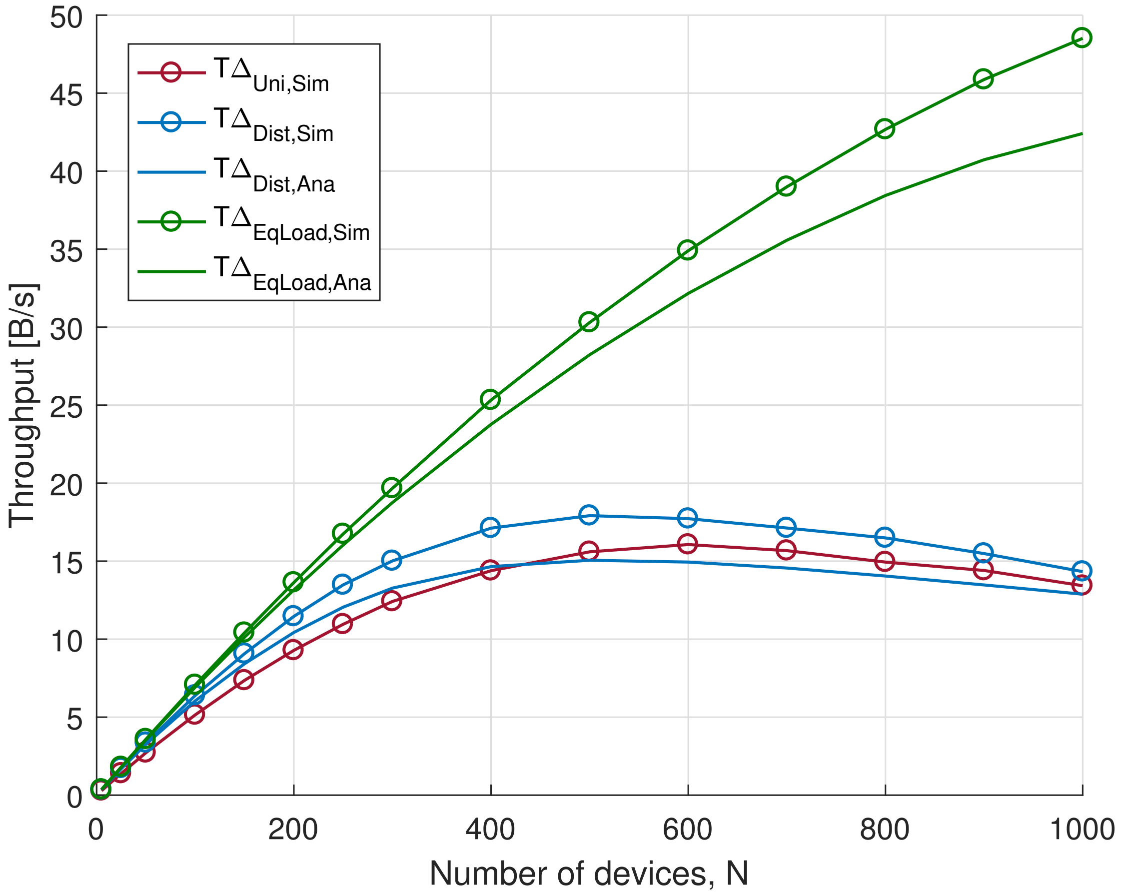
SF allocation

- Comparison:
  - Equal length annuli (Dist)
  - Equal time-on-air annuli (EqLoad)
    - Offloading high SF to lower SF

- Smart SF allocation can increase average throughput in the system



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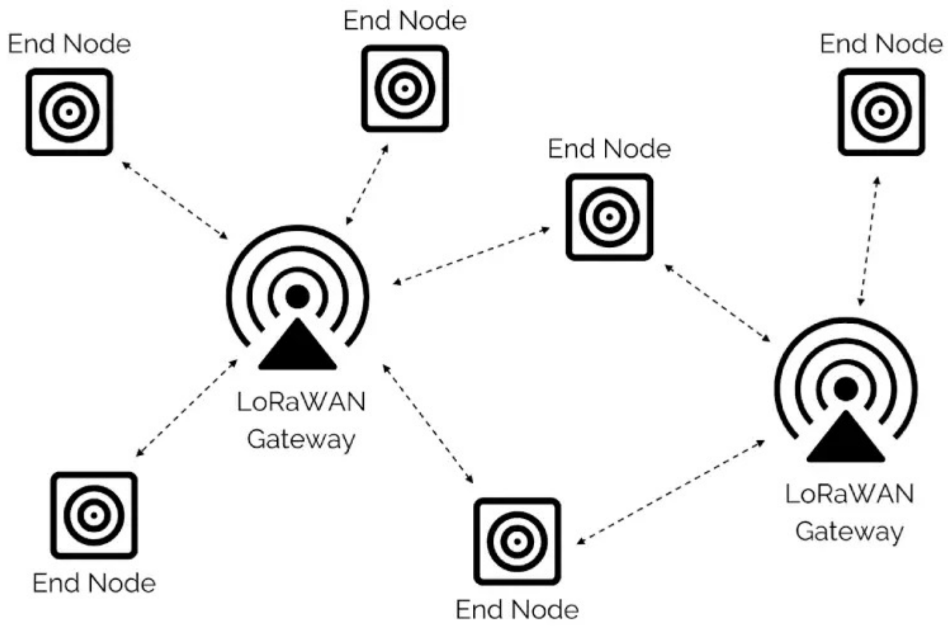
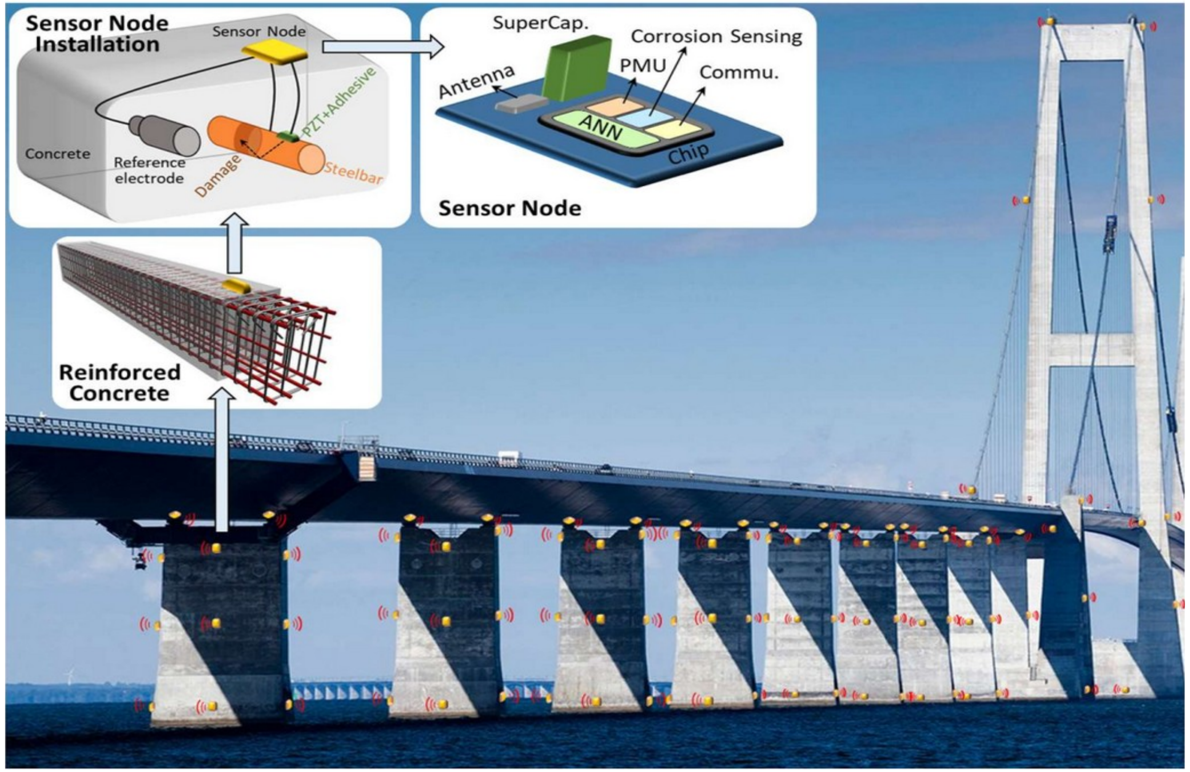
Relability improvement

- Multiple GWs can overhear transmission from end device
- Increases reliability of packet reception:
  - $p_{\mathrm{suc}} = 1 - (1 - p_{\mathrm{s}})^n$
  - E.g. 2 GWs, each with $p_{\mathrm{s}} = 0.8$:
  - $p_{\mathrm{suc}} = 1 - (1 - 0.8)^2 = 0.96$
- Or similarly, repeated transmissions can increase success rate.



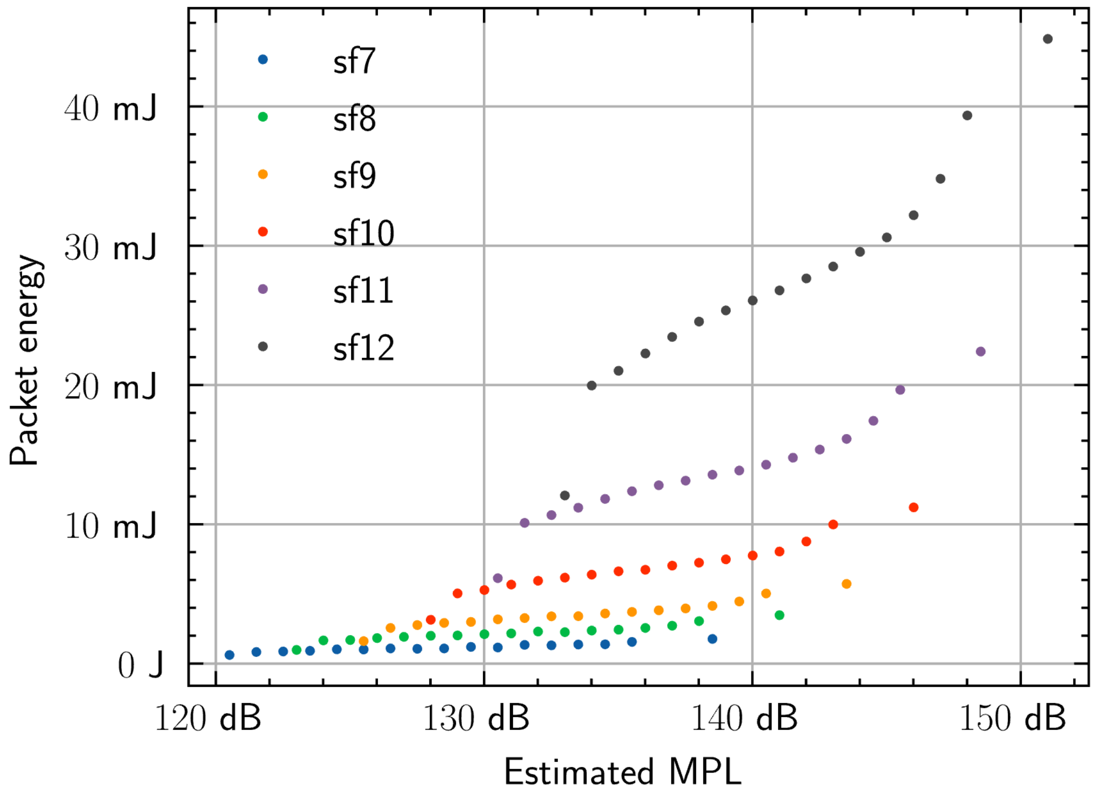
Ongoing work – Structural health monitoring

- Monitoring corrosion level of reinforcement (steel rebar)
- Sensor solution:
  - Lightweight sensor devices
  - Expected life-time – tens of years
  - Battery-less operation
- How should LoRaWAN devices communicate?



Energy measurements in lab

- Energy required to transmit packet with different spreading factors
  - for different mean path loss (MPL):
- SF7 is cheapest until below RX sensitivity
- Guideline: Always choose lowest possible SF.

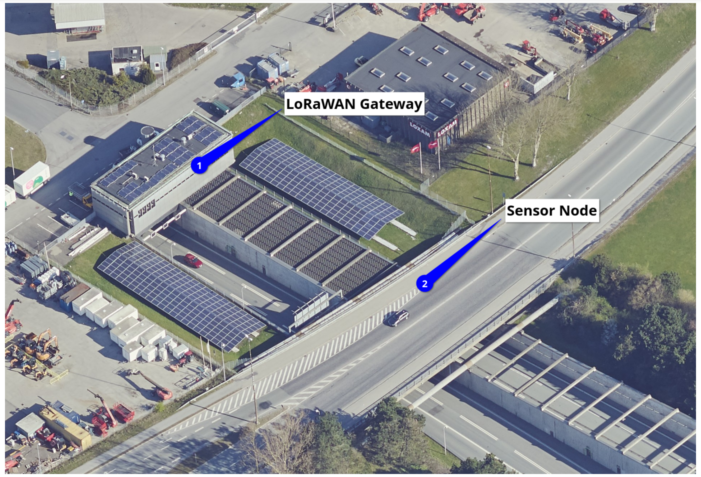


Field measurements

GW inside building, sensor on underside of bridge

Plots: "How much success per energy"

- Left: Good channel, lowest transmit power is best.
- Middle: Bad channel, higher TX power needed.
- Right: Bad channel, and allowing repetitions to reach 95% success rate: best to do few strong transmissions.



Device id	Data rate	Transmit power
D1	DR2	20
D2	DR3	20
D3	DR4	20
D4	DR5	20
D5	DR5	17
D6	DR5	14
D7	DR5	11
D8	DR5	8
D9	DR5	5
D10	DR5	2

DR0	SF12	BW125
DR1	SF11	BW125
DR2	SF10	BW125
DR3	SF9	BW125
DR4	SF8	BW125
DR5	SF7	BW125

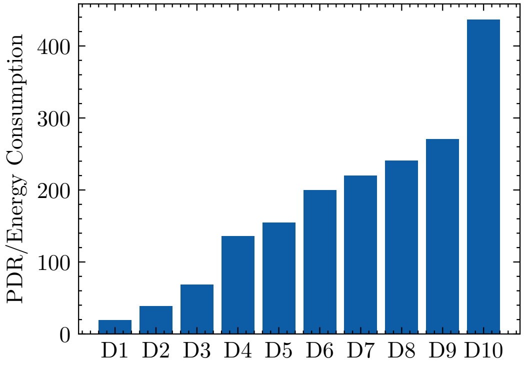


Figure 4.7. Packet delivery rate normalized with energy consumption, without attenuation for each device

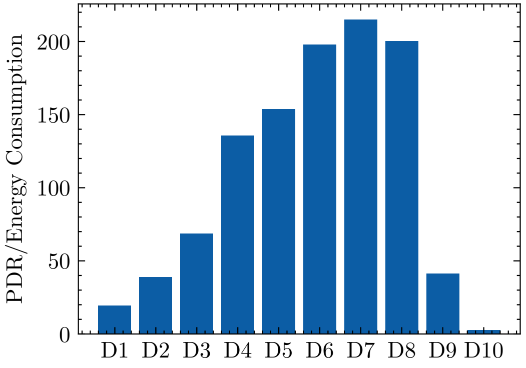
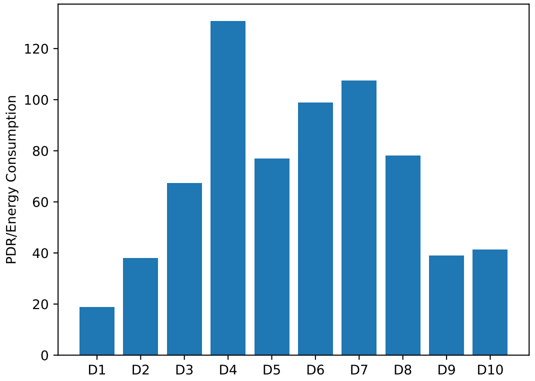


Figure 4.8. Packet delivery rate normalized with energy consumption, with attenuation for each device



Conclusion

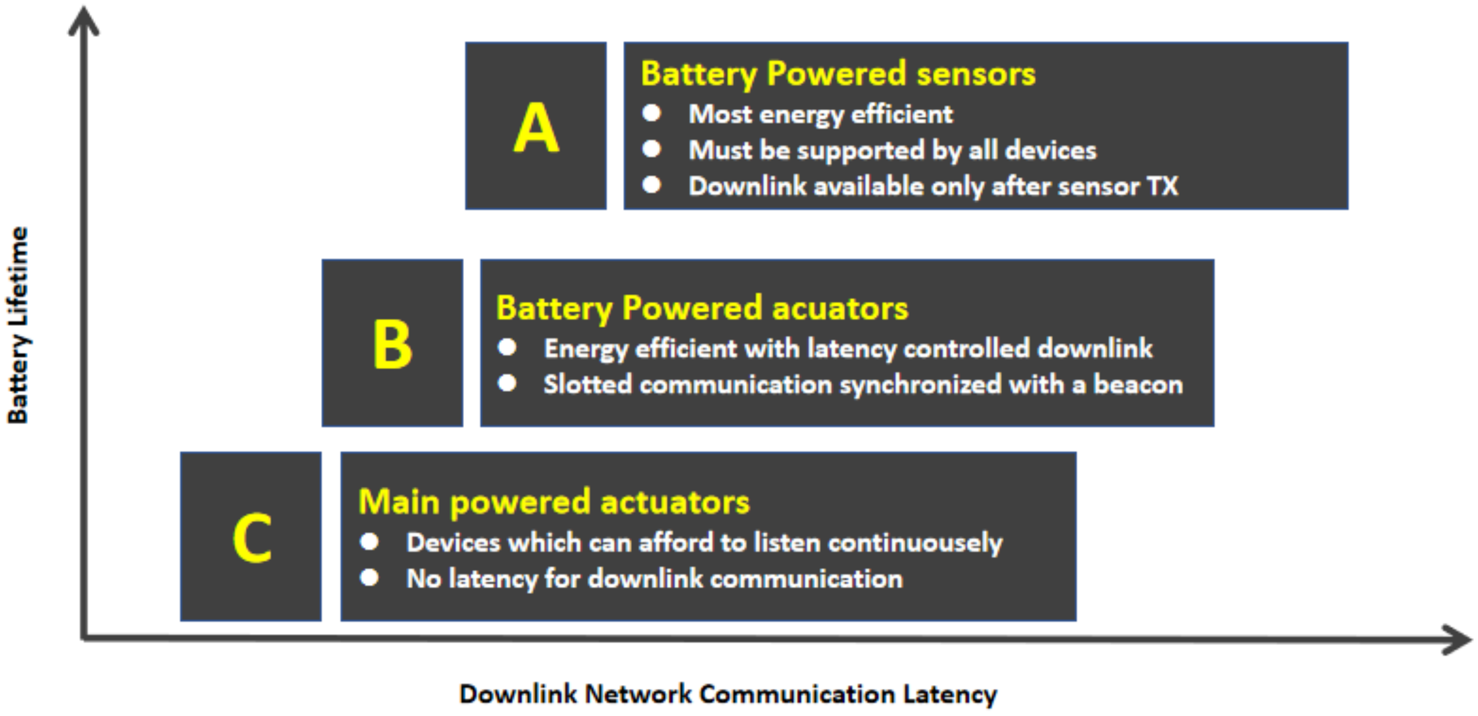
- LoRaWAN is well suited to connect sensor devices that only need to send data seldomly.
- A large number of devices can be supported

- To get highest data rate from 1 device:
  - Good channel/short distance → dense GW deployment
  - Use of channel with 10% or 100% duty cycle, and largest bandwidth (250 kHz in EU)
  - → ~10 kbit/sec
  - But not many devices like this can be supported simultaneously – consider alternative.

Backup slides

LoRaWAN device classes (A, B and C)

- Listening for downlink is expensive for power-limited devices.
- Three different classes ~ modes of operation



LoRaWAN Class A

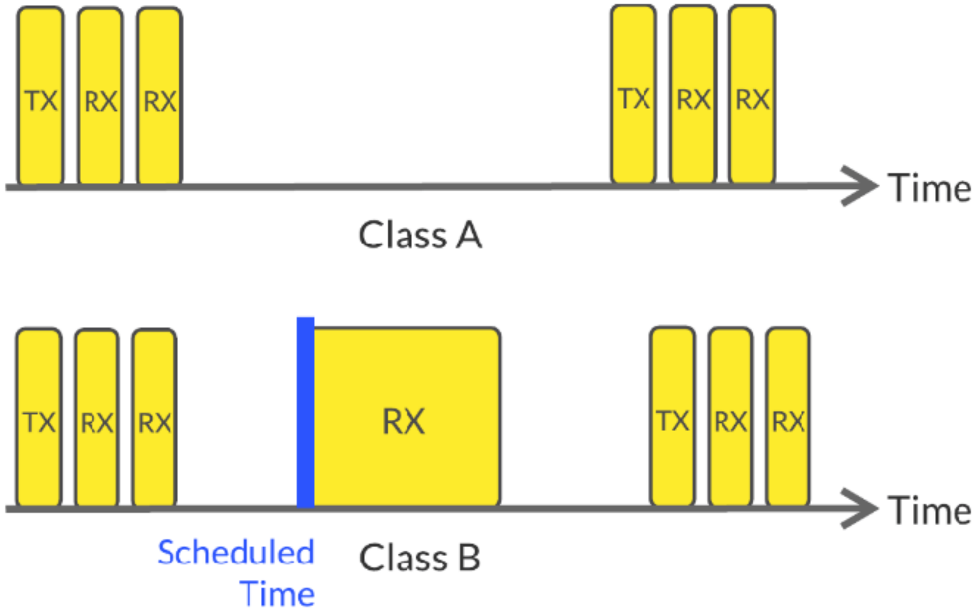
Class A:
Uplink transmission followed by 2 short downlink

- Schedule determined by the end point
  → Simple devices
- Pure Aloha → 18.4% efficiency under heavy load (half of slotted ALOHA)
- Gateways listen to multiple transmissions on multiple channels
- All gateways listen to all transmissions
  → Antenna Diversity
- Server selects one gateway for downlink/ack to device → Mobility

LoRaWAN Class B

Class B: Class A + extra receive window at scheduled time

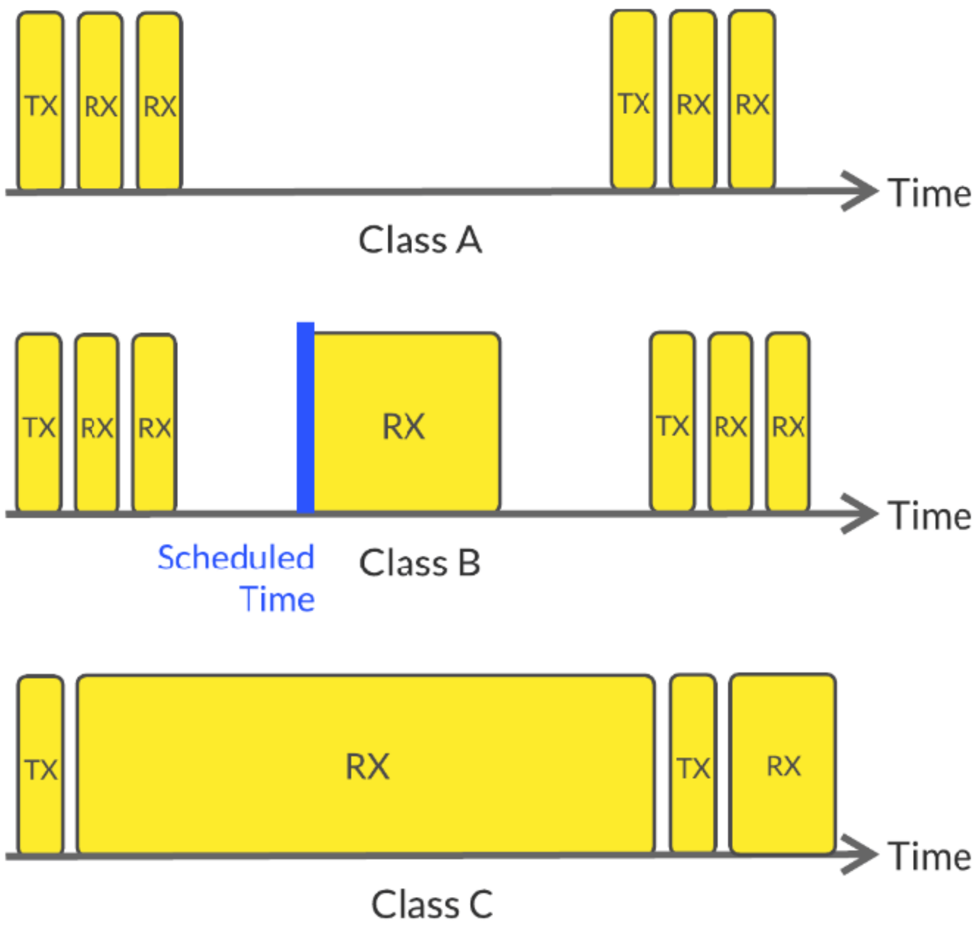
- Controlled by beacon from Gateway
- All gateways transmit beacons every 2*n* seconds (*n*=0..7)
- All gateways are synchronized using GPS
- Device is told receive slot



LoRaWAN Class C

Class C:

- Can receive anytime (unless in TX)
- Generally only mains-powered devices



LoRa Modulation

- Key parameter is the spreading factor (SF) – higher SF gives more robust transmission, but lower bitrate

Data rate [DR]	Spreading Factor [SF]	Bitrate [Bits/Sec]	Range [Km]	Rx Sensitivity [dBm]	Max Pay-load [Bytes]
0	12	290	12+	-136	51
1	11	440	10	-133	51
2	10	980	8	-132	51
3	9	1760	6	-129	115
4	8	3125	4	-126	222
5	7	5470	2	-123	222

BW = 125 kHz, f_c = 868 MHz

Frame format

- Max payload size *p* depends on SF.
  - *c.f. previous slide*