Scalability of LoRa Networks for Dense IoT Deployment Scenarios

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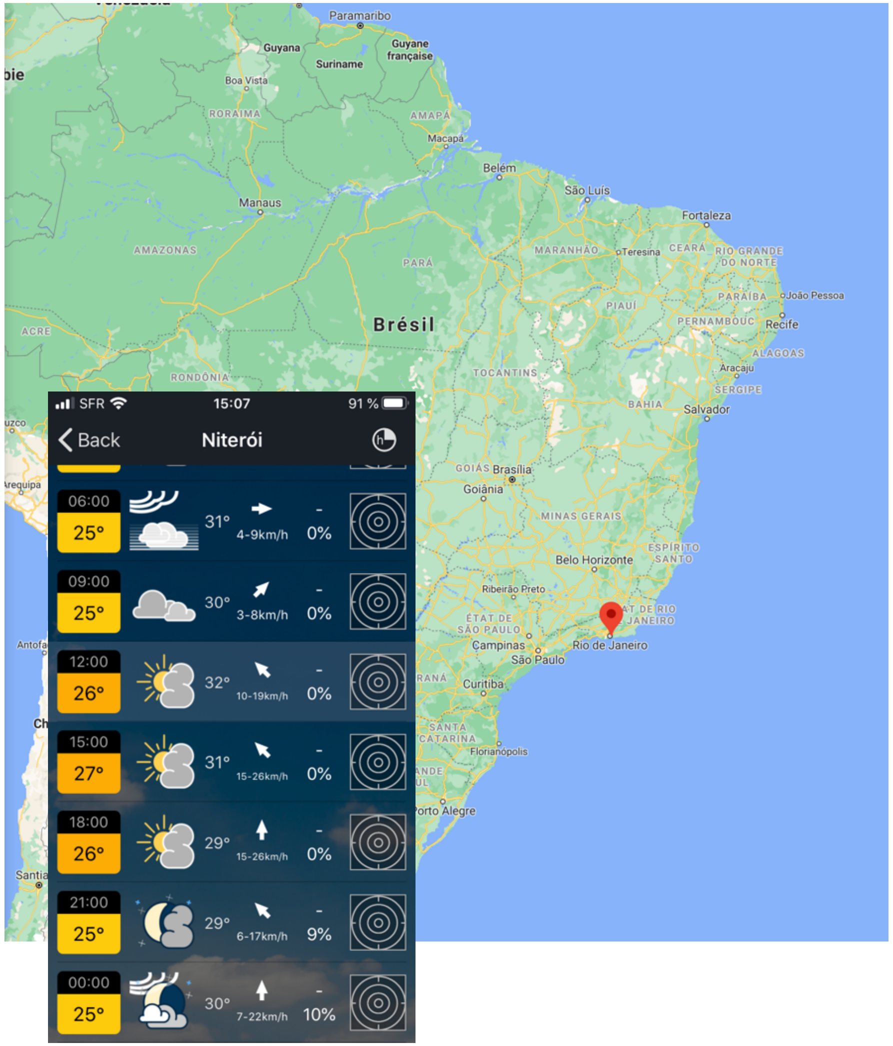
LIUPPA

HORIZON 2020

WAZIUP
IoT – from idea to reality
WAZIHUB

Where am I now?

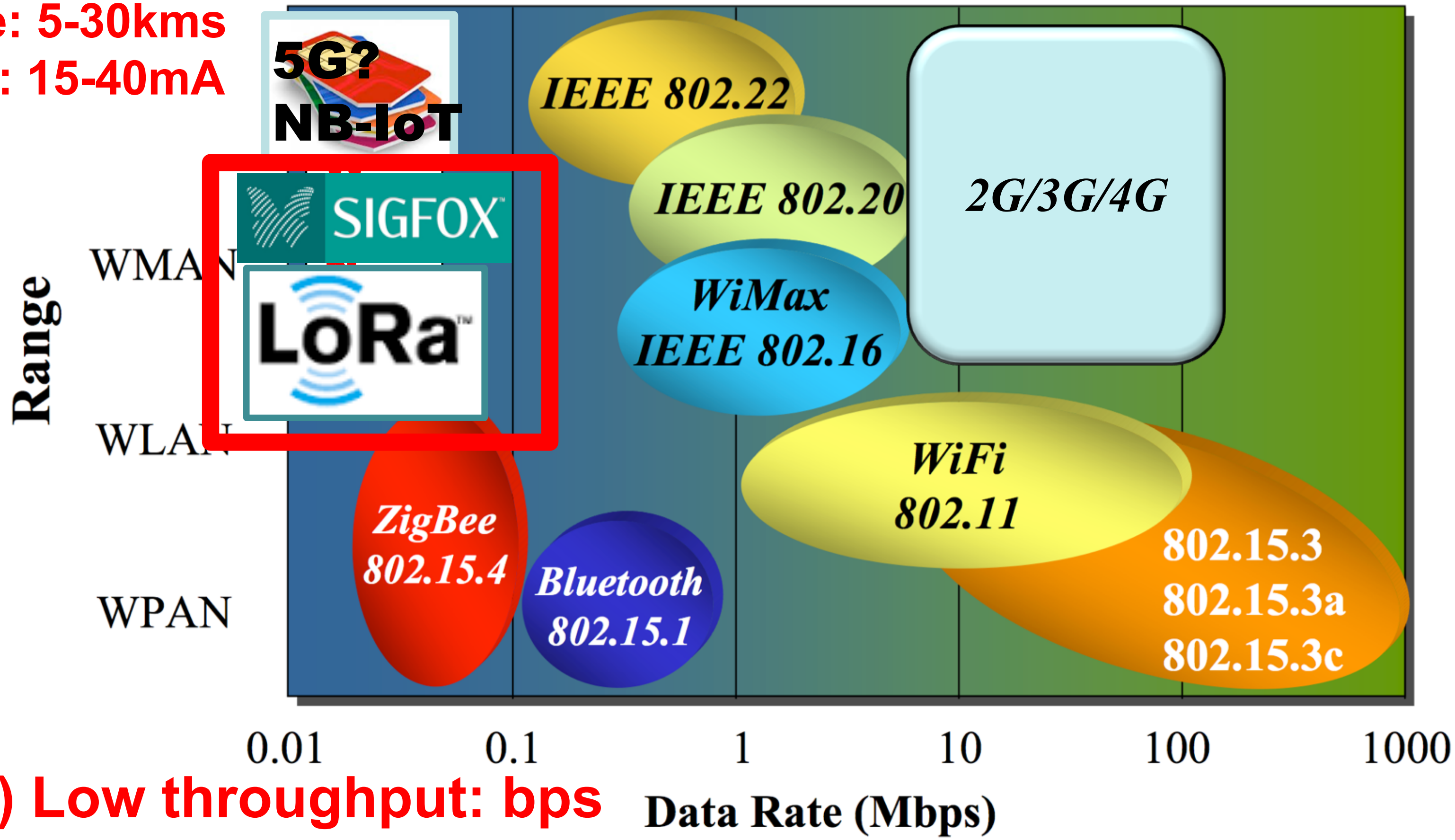


Low-power & long-range radios

Energy-Range dilemma

Long-range: 5-30kms
Low-power: 15-40mA

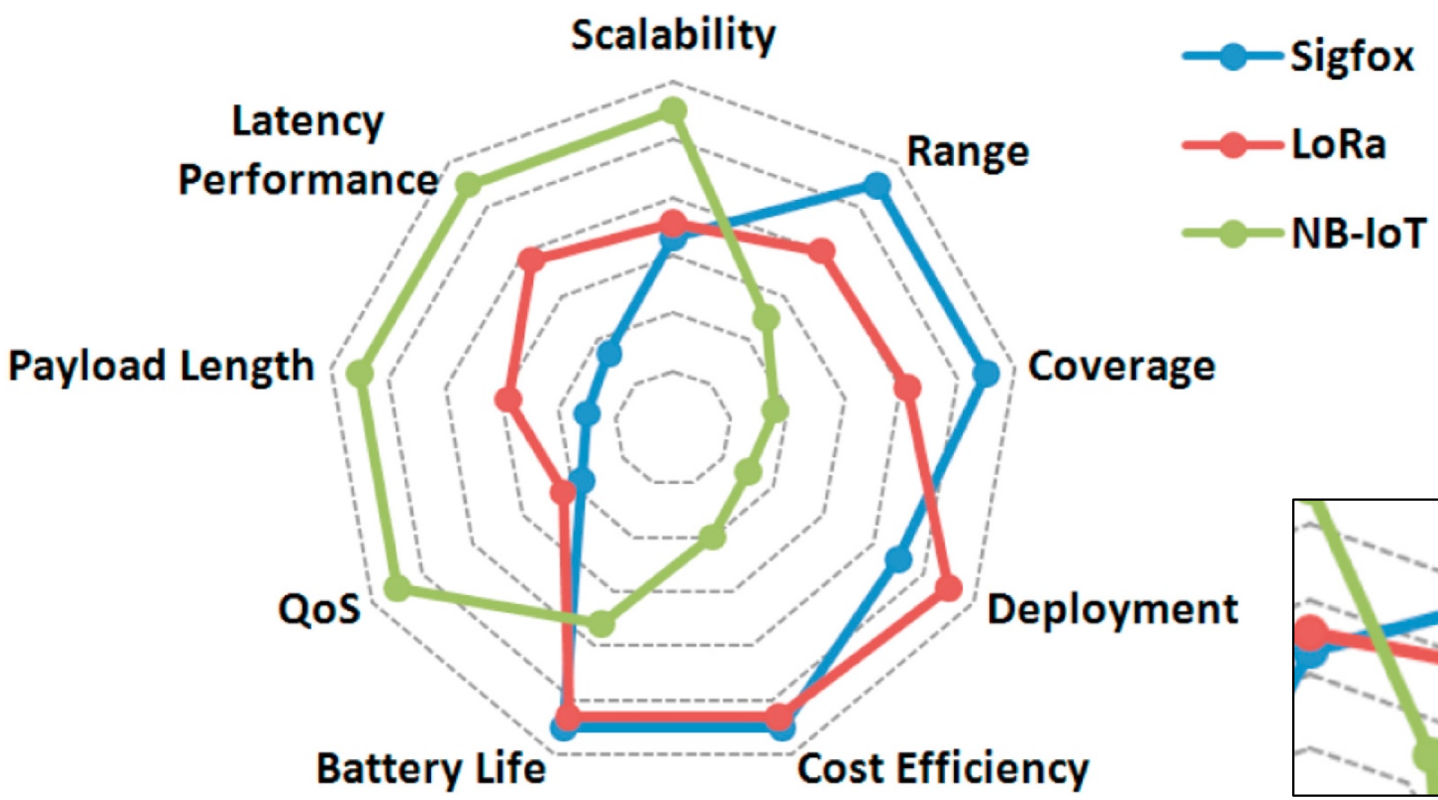
Energy



(Very) Low throughput: bps

Transmitting: `TC/22.5/HUM/67.7` ; about 20 bytes with packet header
Time on air can be 1.44s with LoRa

Expected range?



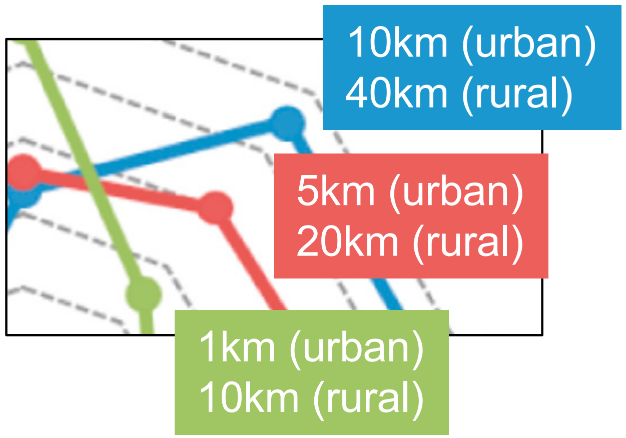


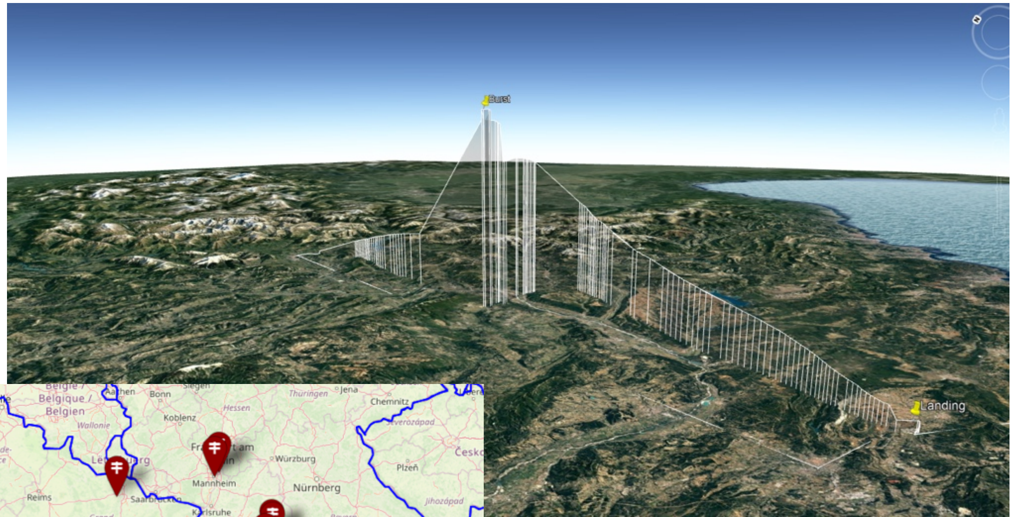
Figure from Kais Mekki, Eddy Bajic, Frederic Chaxel, Fernand Meyer,
A comparative study of LPWAN technologies for large-scale IoT deployment,
ICT Express, Volume 5, Issue 1, 2019.

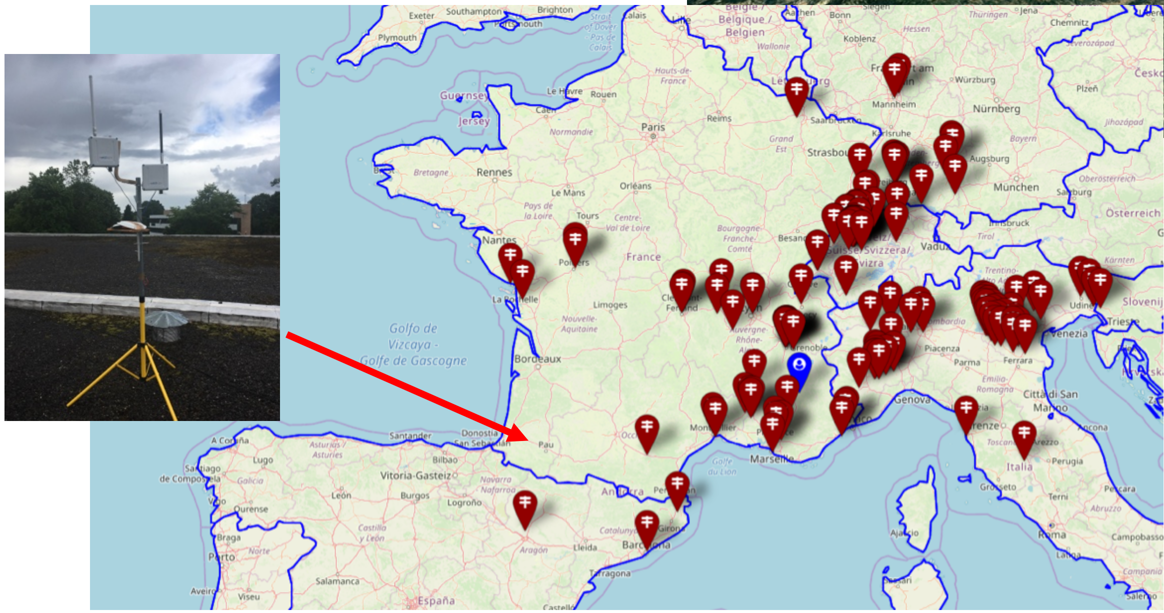
LoRa coverage test by Fabien Ferrero on March 21-22, 2019

- LoRa gateway on top of Danang's DSP building by Fabien, U. Danang and DSP team. Almost 26kms! Congrats Fabien!

LoRa coverage test by Fabien Ferrero on June 11th, 2019

- High Altitude Ballon





- 31kms high
- Reception at 642km (Udine, Italy)!
- Current record at 702km with balloon at 38kms

https://github.com/FabienFerrero/HAB_Relay_STM32Contest

LPWAN = star topology, gw centric
forget about multi-hop routing!

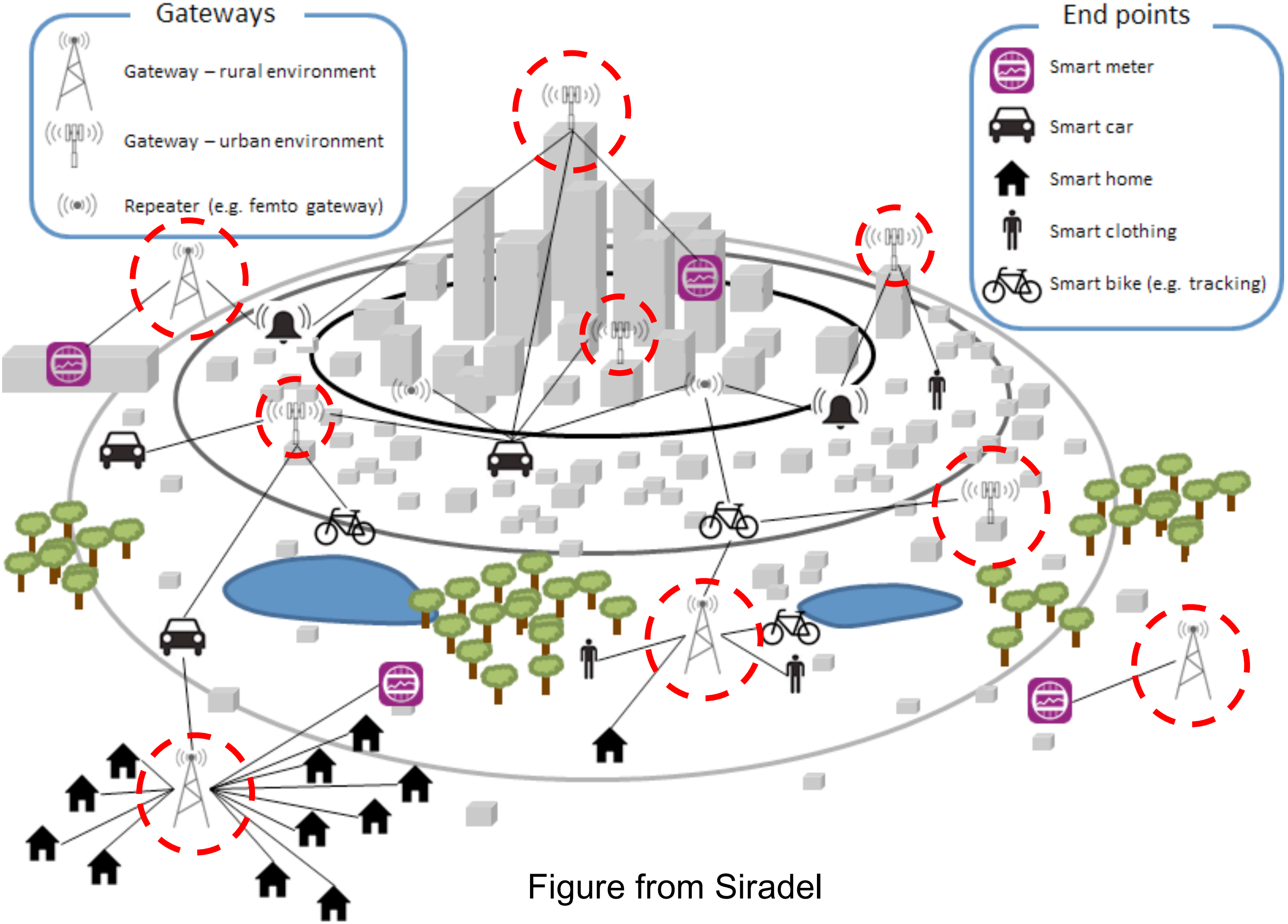
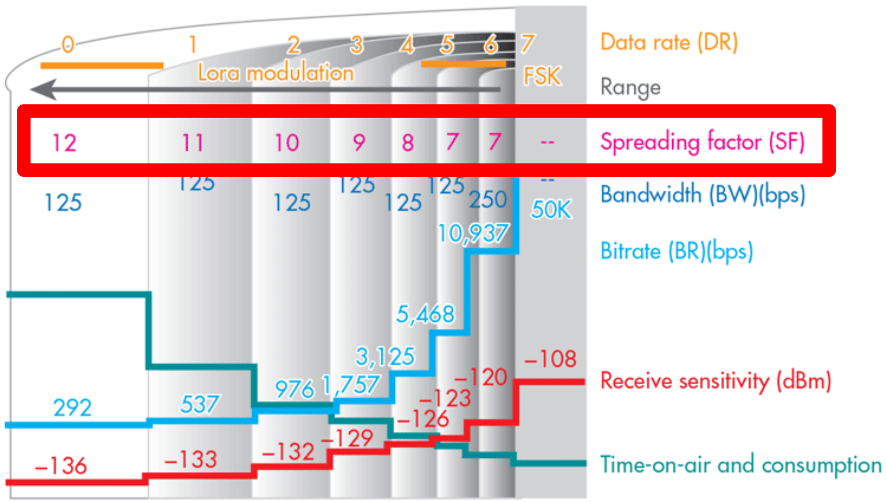


Figure from Siradel

How can we increase range?

- Increase TX power and/or improve RX sensitivity

- Generally, RX sensitivity (~robustness) can be increased when transmitting (much) slower (like speaking slower!)
- LoRa uses spread spectrum approach to increase RX sensitivity
  - a Spreading Factor defines how many chips will be used to code a symbol: more chip/symbol=longer time-on-air=more robustness
  - LoRa is long-range but low throughput: 200bps-37.5kbps



SpreadingFactor (RegModulationCfg)	Spreading Factor (Chips / symbol)	LoRa Demodulator SNR
6	64	-5 dB
7	128	-7.5 dB
8	256	-10 dB
9	512	-12.5 dB
10	1024	-15 dB
11	2048	-17.5 dB
12	4096	-20 dB

Spreading factor in image

- Higher spreading factor means lower data rate but increased receiver sensitivity -> speaking slower!

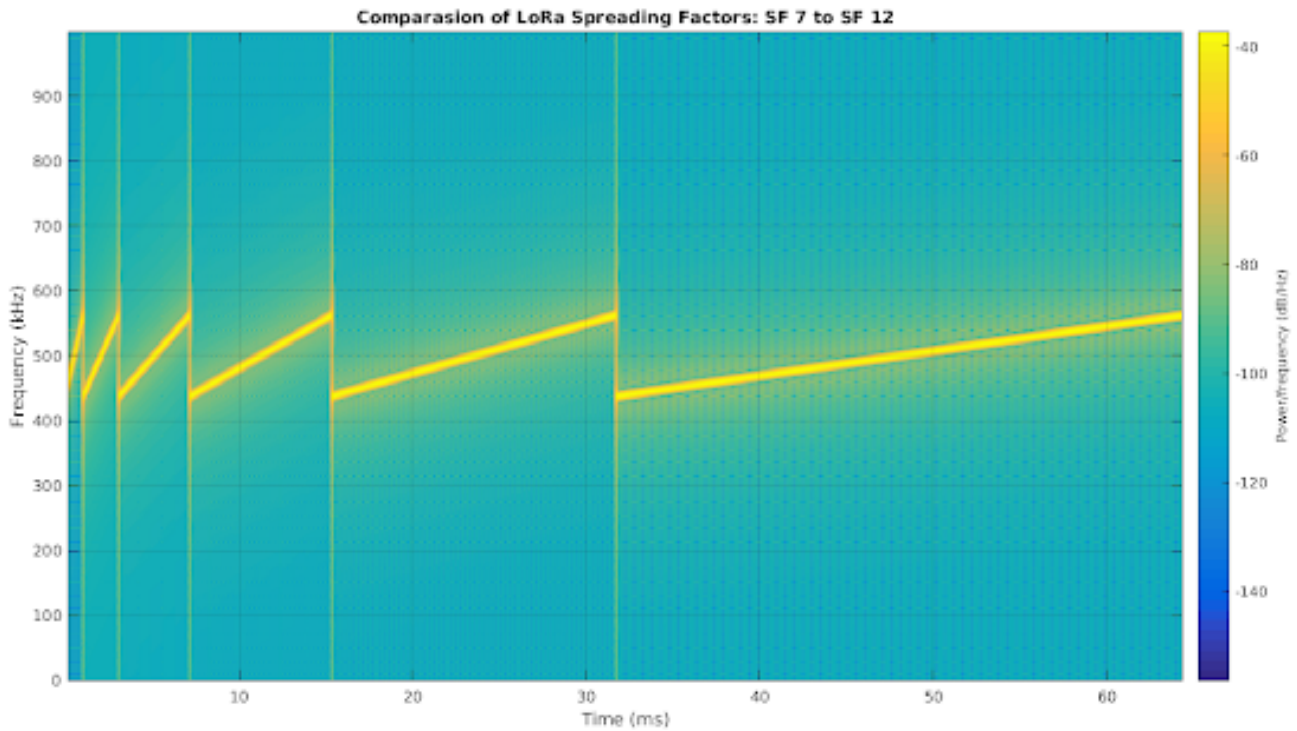
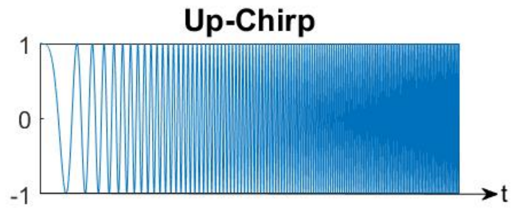


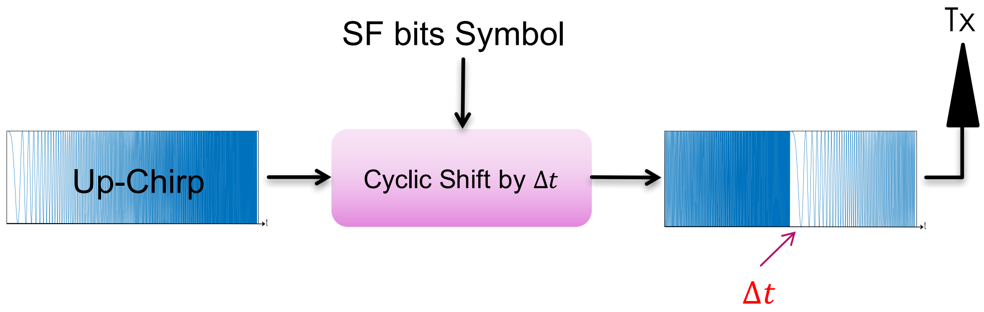
Figure from "All About LoRa and LoRaWAN", https://www.sghoslya.com

Chirp Spread Spectrum Modulation



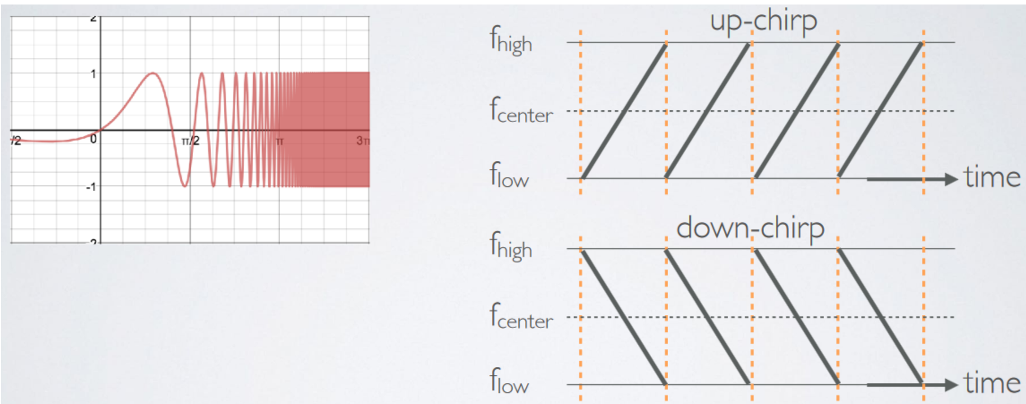
$$C(t) = \begin{cases} \exp(2\pi j(at+b)t) & -\frac{T_s}{2} \le t \le \frac{T_s}{2} \\ 0, & otherwise \end{cases}$$

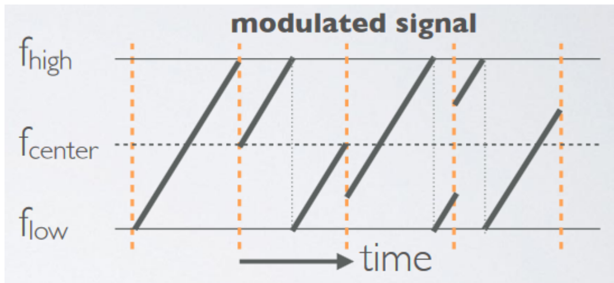
CSS Modulation



Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

$$x_i(t) = \begin{cases} \exp\big(2\pi j(a(T_s - t - \Delta t) + b)(T_s - t - \Delta t)\big), & -\frac{T_s}{2} \le t \le -\frac{T_s}{2} + \Delta t \\ \exp\big(2\pi j(a(t-\Delta t) + b)(t - \Delta t)\big), & -\frac{T_s}{2} + \Delta t \le t \le \frac{T_s}{2} \\ 0, & Otherwise \end{cases}$$

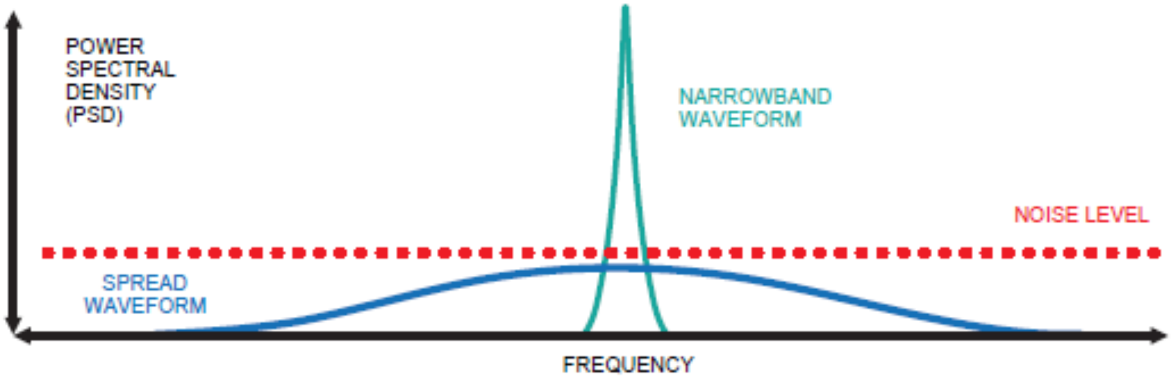


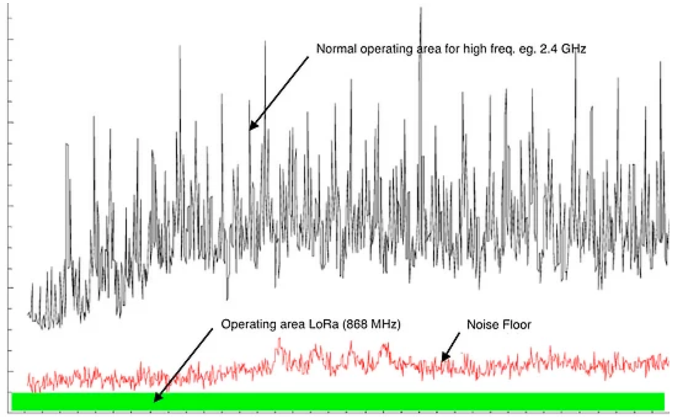


https://lora.readthedocs.io/en/latest/

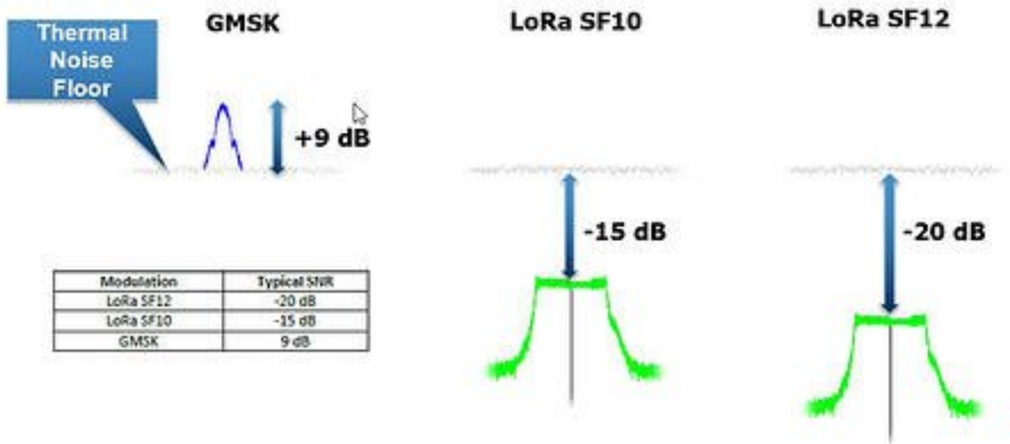
Advantage of Spread Spectrum

- Spread Spectrum techniques are usually more robust to noise





- LoRa signals can be decoded below noise floor

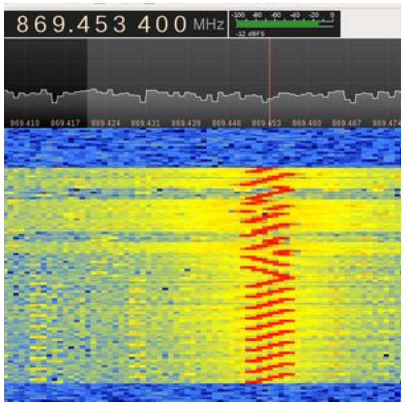


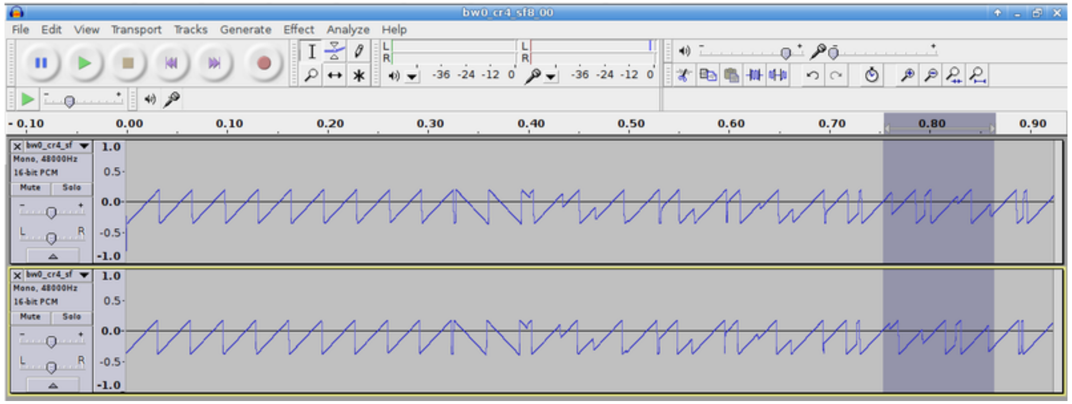
Modulation	Typical SNR
LoRa SF12	-20 dB
LoRa SF10	-15 dB
GMSK	9 dB

SpreadingFactor (RegModulationCfg)	LoRa Demodulator SNR
6	-5 dB
7	-7.5 dB
8	-10 dB
9	-12.5 dB
10	-15 dB
11	-17.5 dB
12	-20 dB

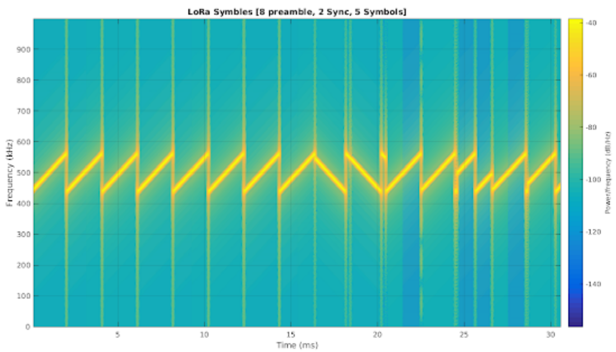
Want to know more on LoRa PHY?

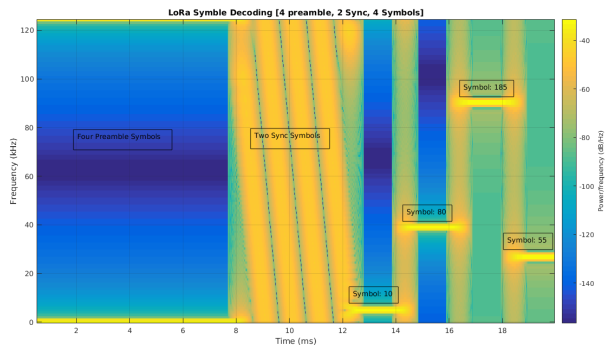
- https://revspace.nl/DecodingLora





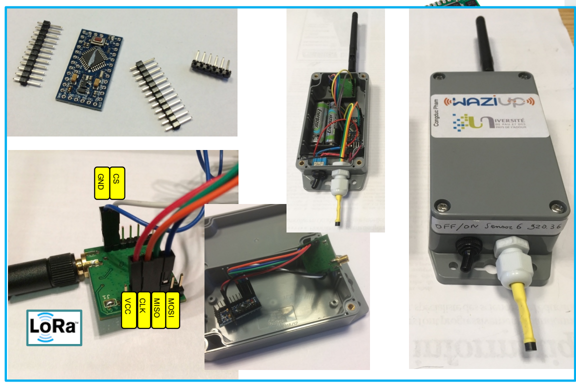
- "All about LoRa and LoRaWAN"
  https://www.sghoslya.com/p/lora-is-chirp-spread-spectrum.html

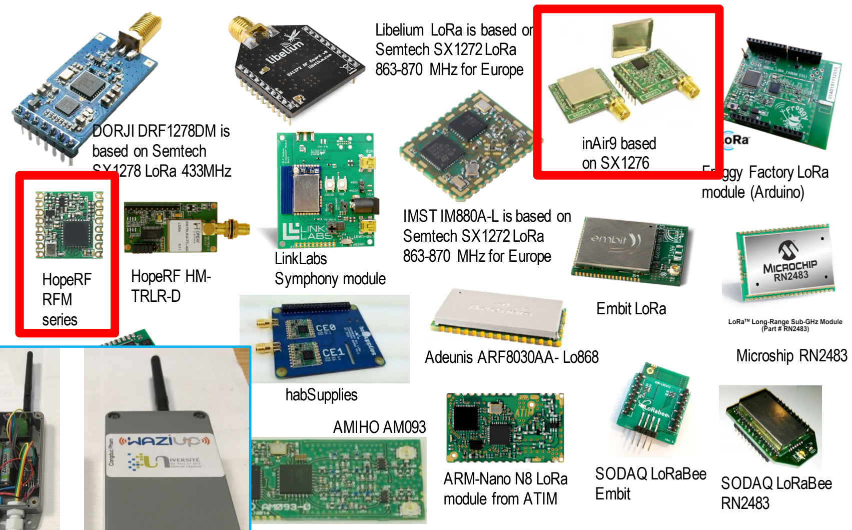




Explaining the success of LoRa

- Long-range, low-power – 5-10 years on battery possible
- Ad-hoc deployment of devices and gws, no need for operators – many LoRa deployments are currently private including companies
- Large availability of very low-cost radio modules making DIY IoT almost as efficient as commercial products
- Large choice of commercial products





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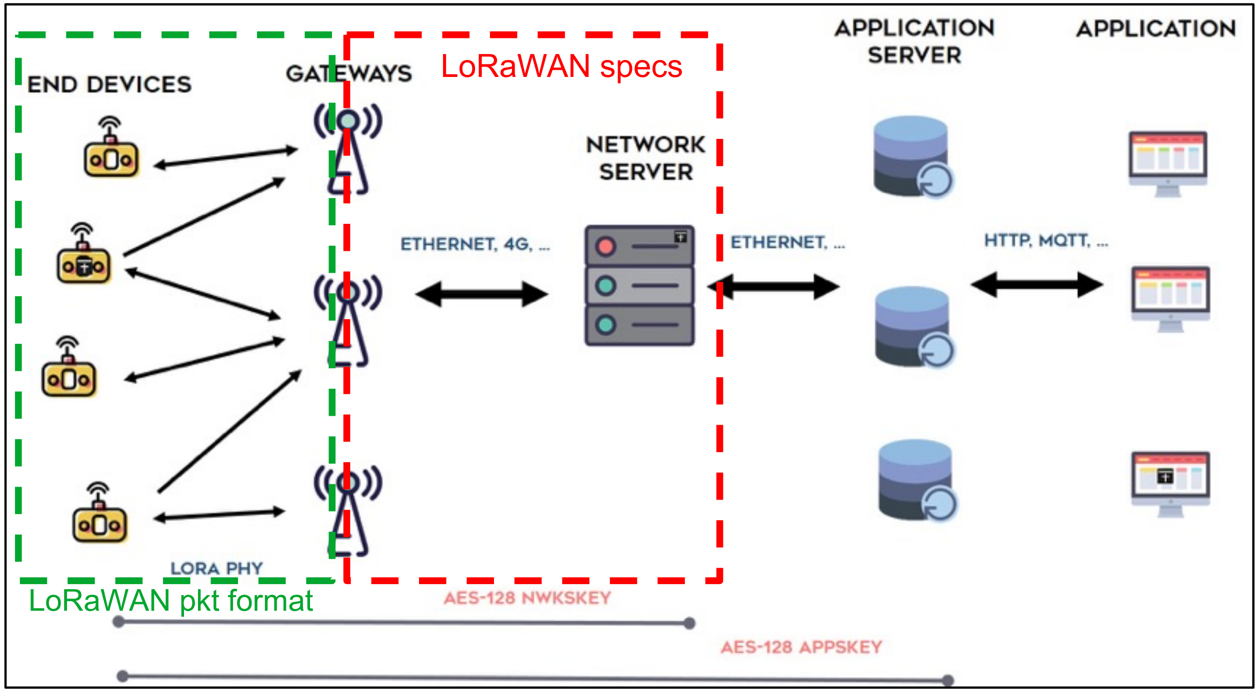
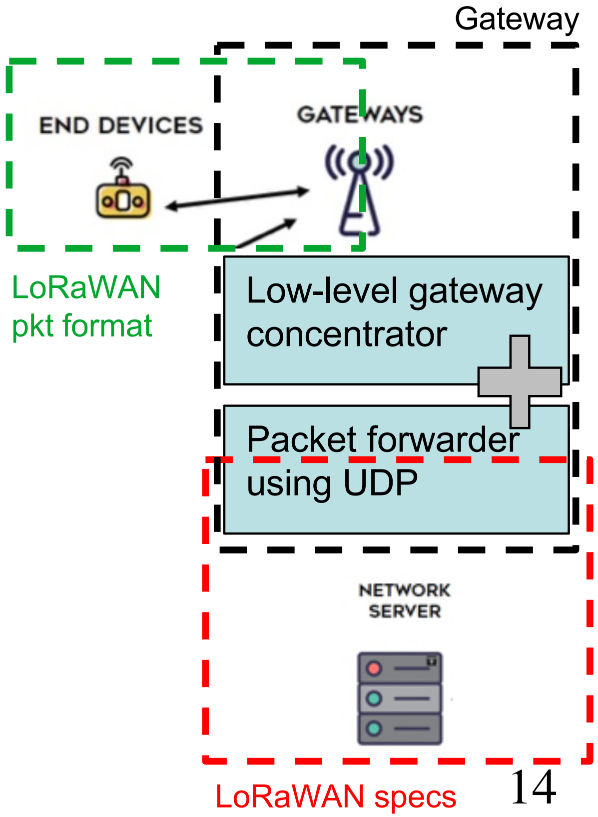
LoRaWAN

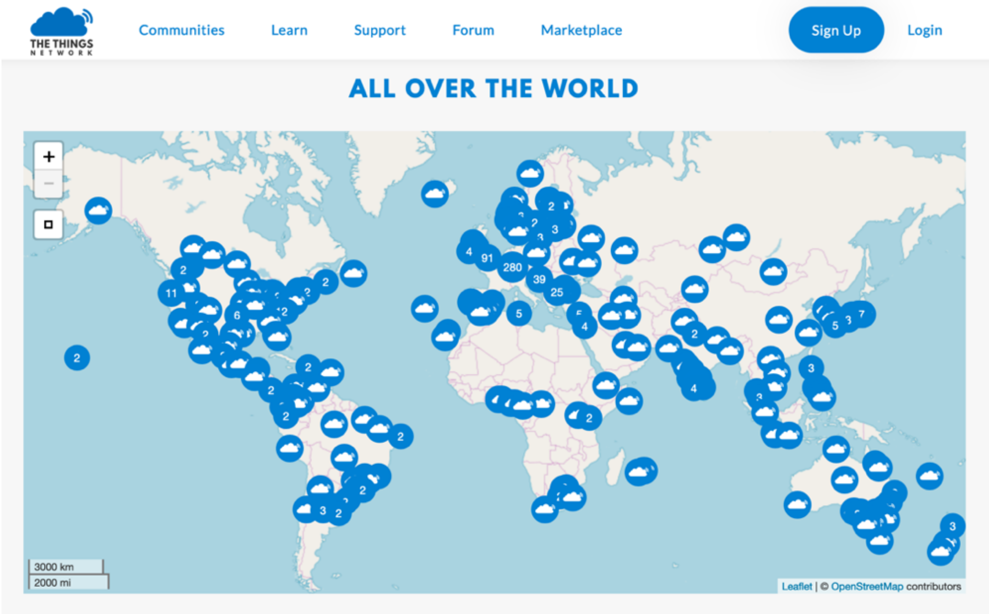
- LoRaWAN protocols run on top of LoRa physical networks. It is defined and managed by the LoRa Alliance
- It specifies protocols to run large-scale, public LoRa networks

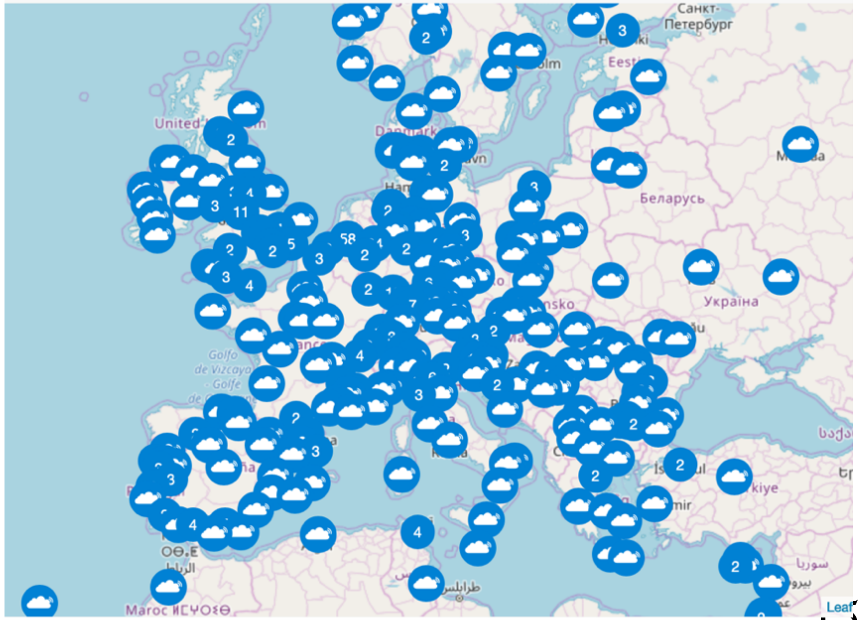




LoRa networks boosted by community-based deployments

- e.g. TheThingNetwork (TTN)
- Community-based deployment of LoRa gateways (using LoRaWAN stack)
  - User A can buy a LoRa gateway, register it and deploy it
  - User B then creates an account on TTN to register its devices
  - Messages from registered devices received by a TTN gateway will be made available for users on the TTN console





LoRaWAN gateway

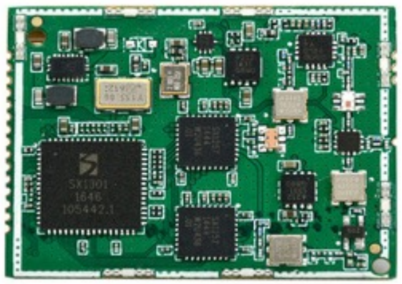
- A full LoRaWAN gateway should be able to listen on multiple channels and spreading factors

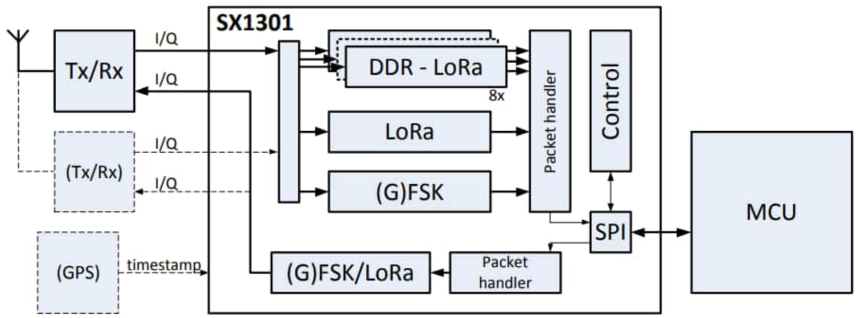
EU863-870

Uplink:

1. 868.1 - SF7BW125 to SF12BW125
2. 868.3 - SF7BW125 to SF12BW125
3. 868.5 - SF7BW125 to SF12BW125
4. 867.1 - SF7BW125 to SF12BW125
5. 867.3 - SF7BW125 to SF12BW125
6. 867.5 - SF7BW125 to SF12BW125
7. 867.7 - SF7BW125 to SF12BW125
8. 867.9 - SF7BW125 to SF12BW125
9. 868.8 - FSK

- They are mostly based on the Semtech SX1301 radio concentrator



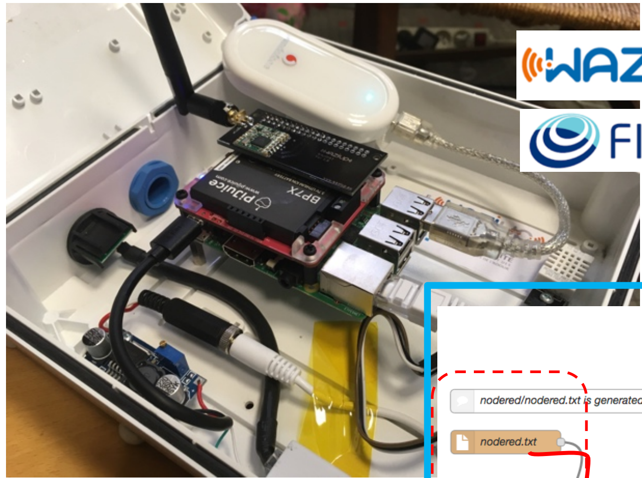


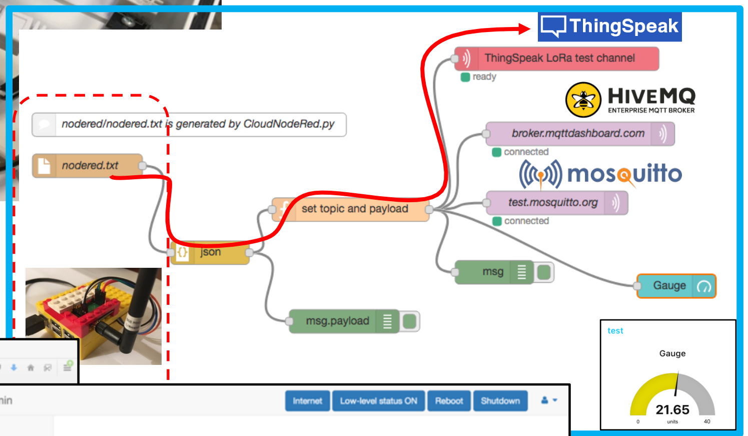
Open, DIY, versatile IoT gateway

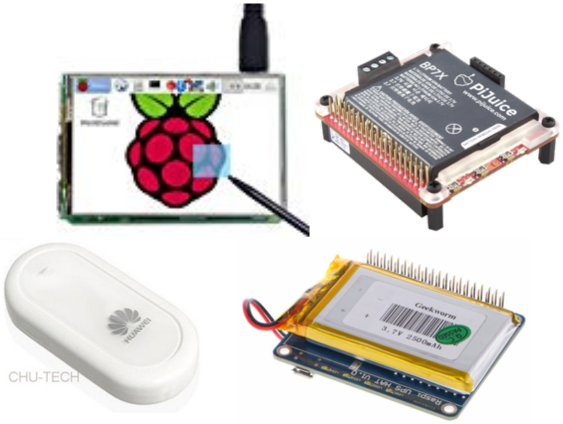
Large customization features

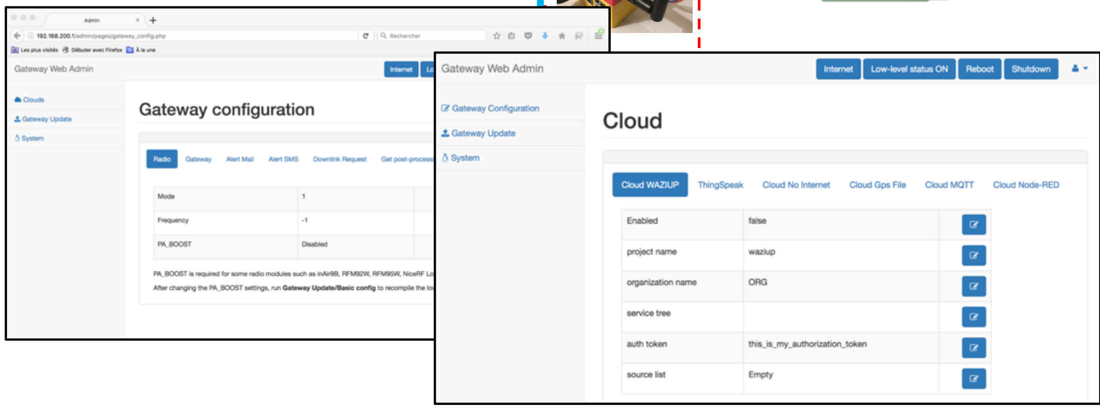
Raspberry PI: lots of libraries, lots of software, lots of hardware, lots of shields,…

https://github.com/CongducPham/LowCostLoRaGw



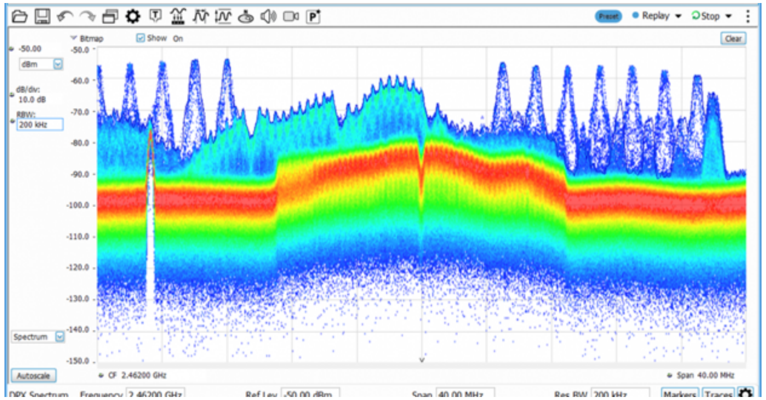






Deploying in dense environment

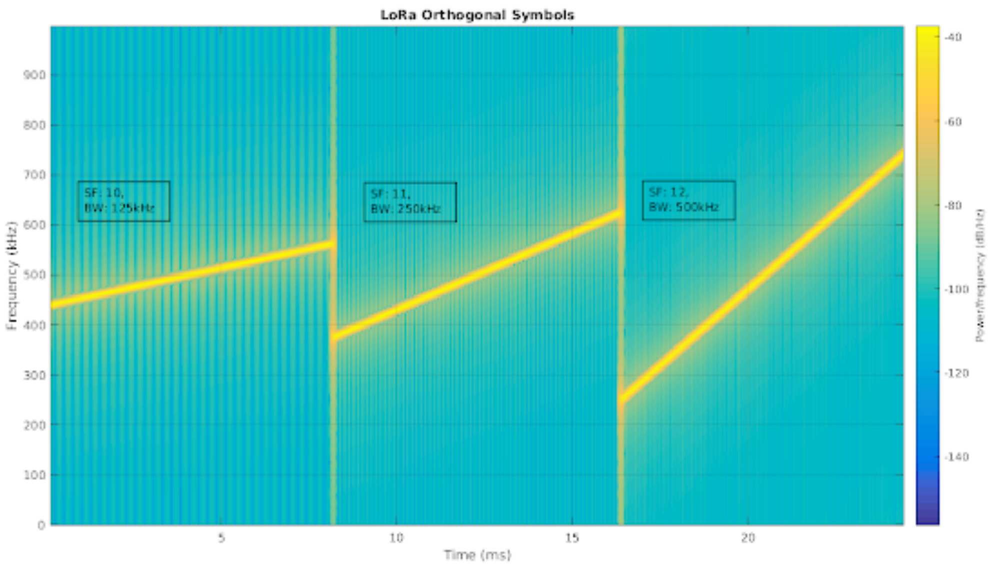
- LoRa currently works in unlicensed (ISM) band (sub-GHz & 2.4GHz)
- More devices: more traffic, more interferences & collisions



- More gateways: increased packet reception rate but LPWAN roaming is needed for E2E operation

Low-level LoRa interference mitigation techniques

- Orthogonal "chirpyness"
- Different chirp rate can be achieved by different spreading factors and/or by different bandwidths
- LoRa symbols can by simultaneously transmitted and received on a same channel without interference
- LoRa has 7 spreading factors (SF6 - SF12) and 10 different bandwidths in kHz (7.8, 10.4, 15.6, 20.8, 31.2, 41.7, 62.5, 125, 250, 500). 125kHz, 250kHz & 500kHz most used



SF=10 BW=125kHz | SF=11 BW=250kHz | SF=12 BW=500kHz

Figure from "All About LoRa and LoRaWAN", https://www.sghoslya.com

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http://www.univ-pau.fr/~cpham

Not always orthogonal!

- Symbol rate Rs = $BW/2^{SF}$ and Symbol period Ts = 1/Rs
- Chirp rate = BW*(Symbol rate)
- So Chirp rate = $BW^2/2^{SF}$
- i.e. slope = $(f_{max}-f_{min})/Ts = BW/(2^{SF}/BW)= BW^2/2^{SF}$

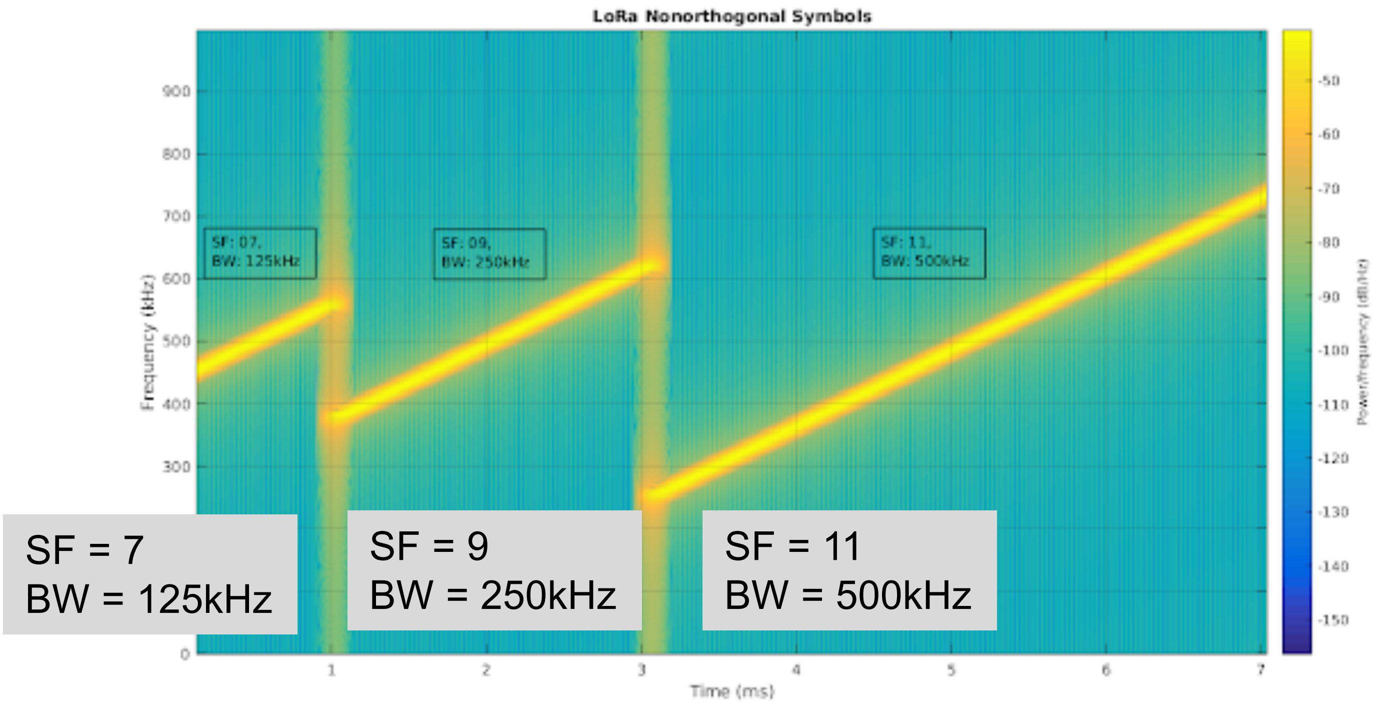


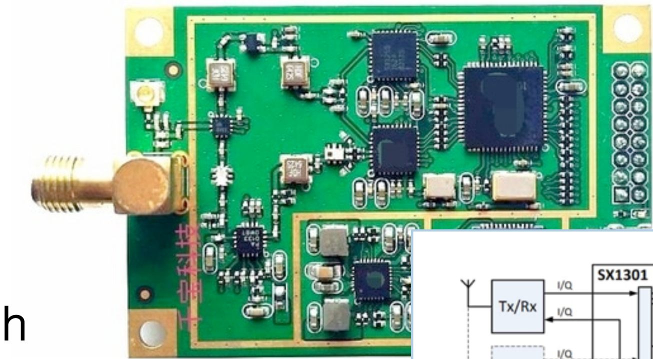
Figure from "All About LoRa and LoRaWAN", https://www.sghoslya.com

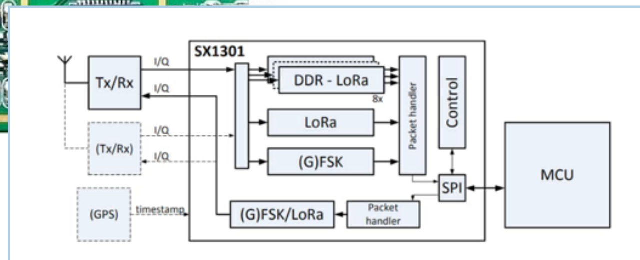
Orthogonal combinations

SF		7	8	9	10	11	12	7	8	9	10	11	12	7	8	9	10	11	12
	BW	125	125	125	125	125	125	250	250	250	250	250	250	500	500	500	500	500	500
7	125	x								x								x	
8	125		x								x								x
9	125			x								x							
10	125				x								x						
11	125					x													
12	125						x												
7	250							x								x			
8	250								x								x		
9	250	x								x								x	
10	250		x								x								x
11	250			x								x							
12	250				x								x						
7	500													x					
8	500														x				
9	500							x								x			
10	500								x								x		
11	500	x								x								x	
12	500		x								x								x

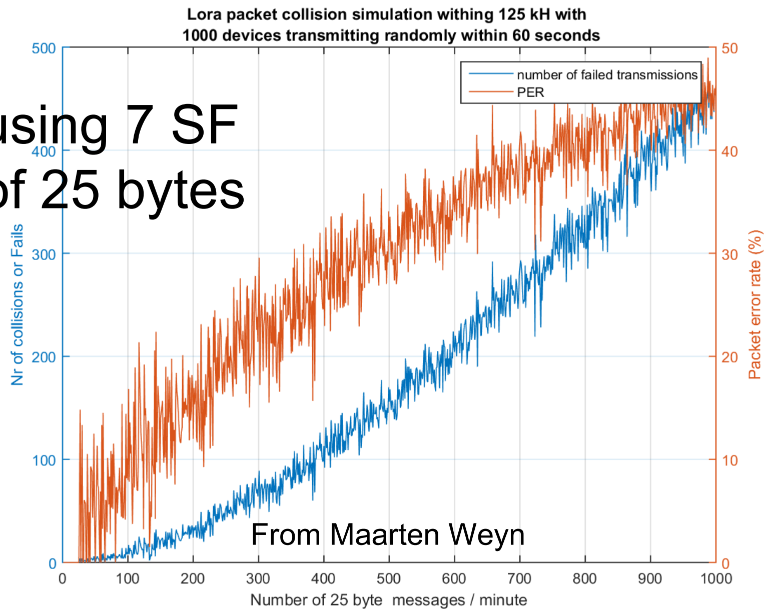
Low-level LoRa interference mitigation techniques

- Frequency diversity
- Use hardware LoRa concentrator (i.e. SX1301)
- Can listen on 8 channels with BW, frequency and SF diversity





uniformly using 7 SF
message of 25 bytes



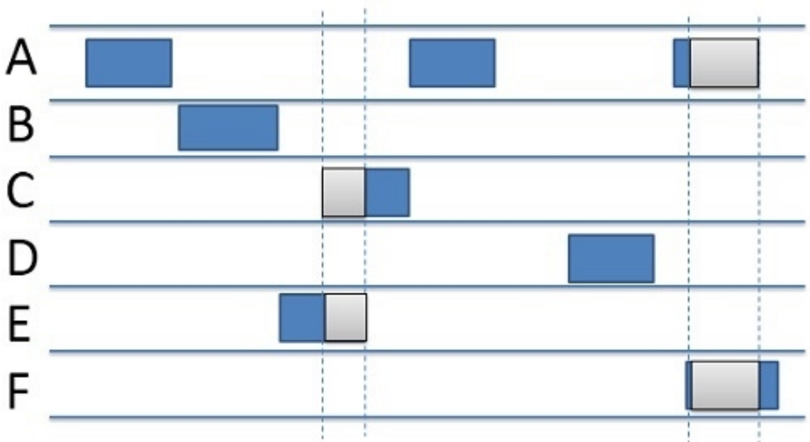
"At 1000 msg/min, 45% of the messages are lost because of collisions. At 100 msg/min 10% are lost"

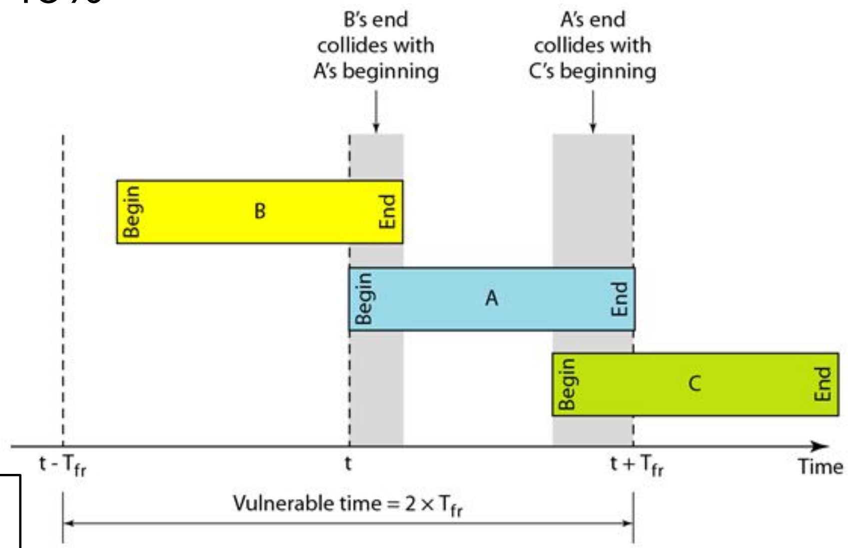
100 messages/min?

Assuming 1msg/h/device it means 6000 devices in the vicinity of the gateway

Concurrent channel access issue

- Considering a given frequency and LoRa settings, multiple transmitters on that setting interfere each other
- LoRa's channel access ~ pure ALOHA system
  - Anybody can talk at any time
  - Efficiency is known to be at about 18%



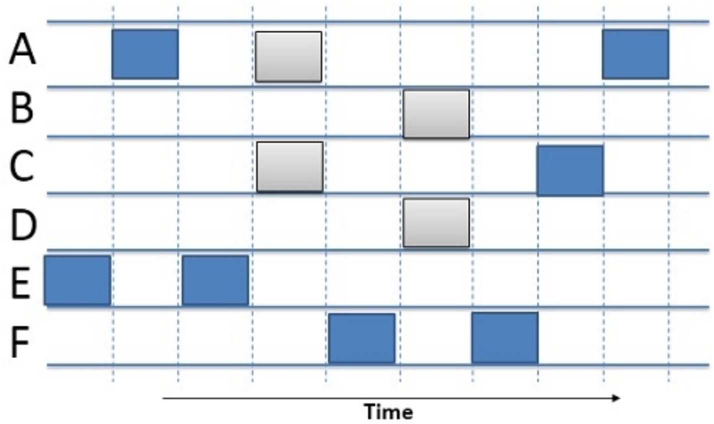


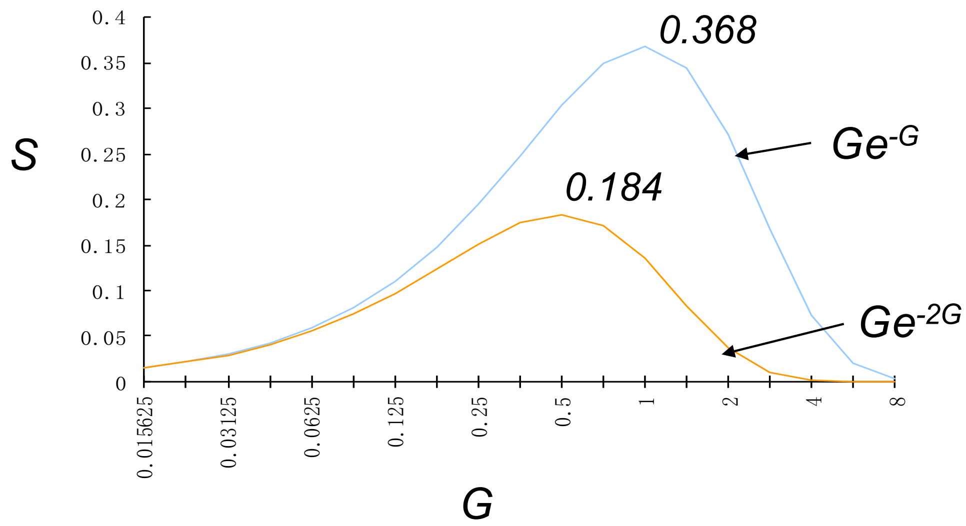
$$\eta = Ge^{-2G}$$

'2' in the superscript of exponential is because the vulnerable time is twice the frame time T_{air}. G represents average number of transmission attempts during frame time.

Slotted ALOHA

- Can only send at the beginning of a slot
- Reduces the vulnerable time
- Efficiency is known to increase to about 37%

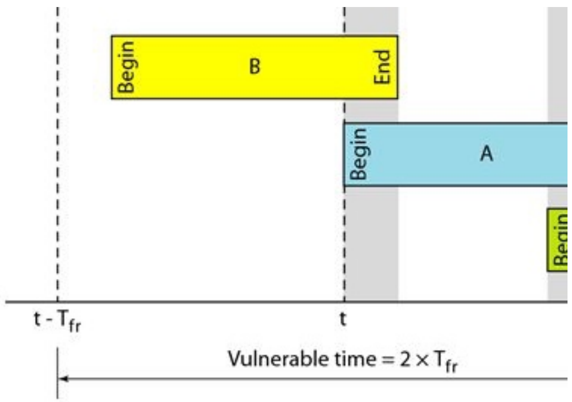




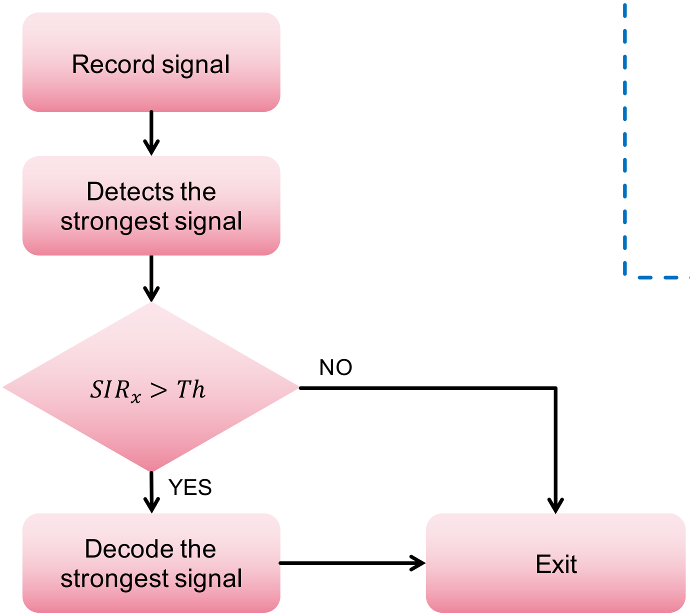
- But slotted mode needs higher level of coordination

Do we really have LoRa = ALOHA?

- LoRa uses a kind of frequency modulation (Chirp Spead Spectrum) so capture effect is possible
- "*In telecommunications, the capture effect, or FM capture effect, is a phenomenon associated with FM reception in which only the stronger of two signals at, or near, the same frequency or channel will be demodulated*." [Wikipedia]
- Capture effect can in some case allow for correct reception of a packet even with concurrent transmissions in the vulnerable time



Capture effect in LoRa



Signal to Interference Ratio > Threshold

$$SIR_x = \frac{P_x}{P_i} > Th$$

P_x: Received power of stronger signal
P_i: Received power of 2nd stronger signal

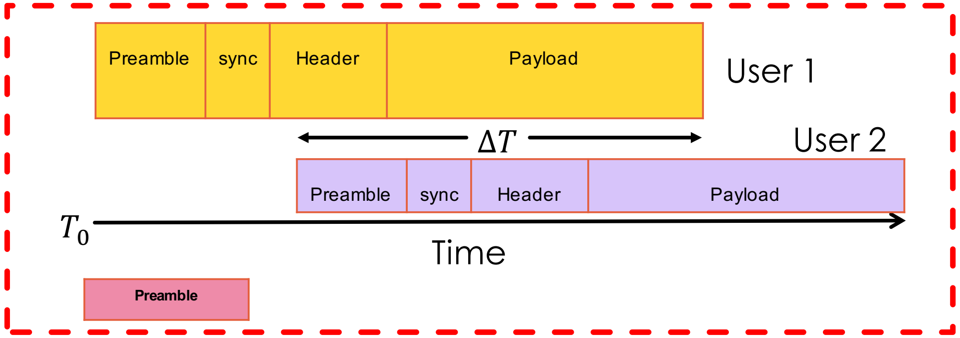
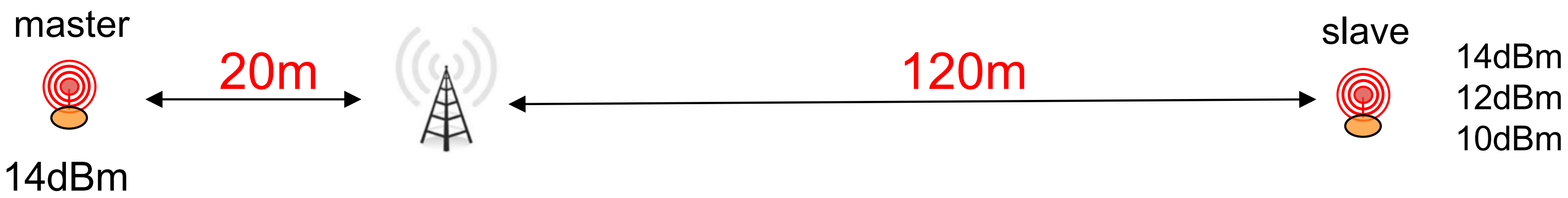


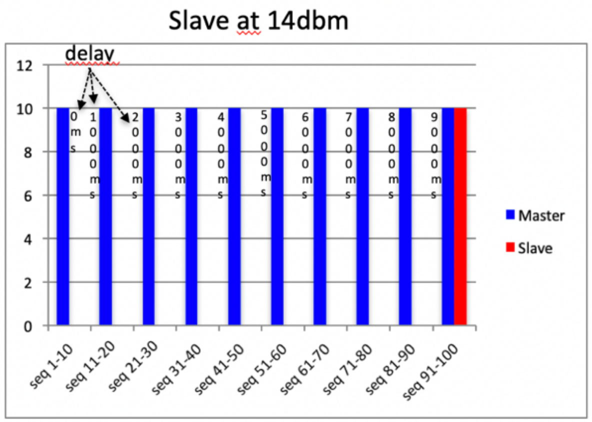
Figure from Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

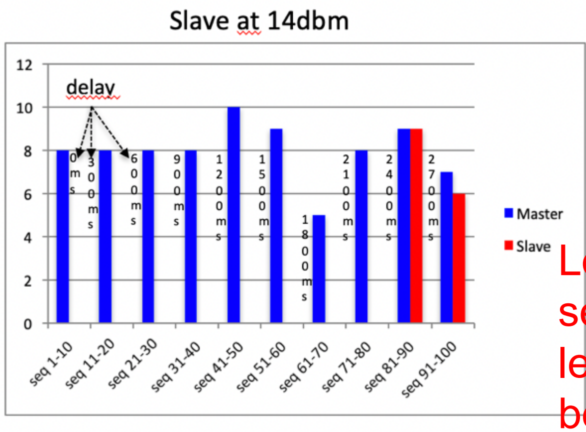
Capture effect in practice



BW=125kHz,SF=12

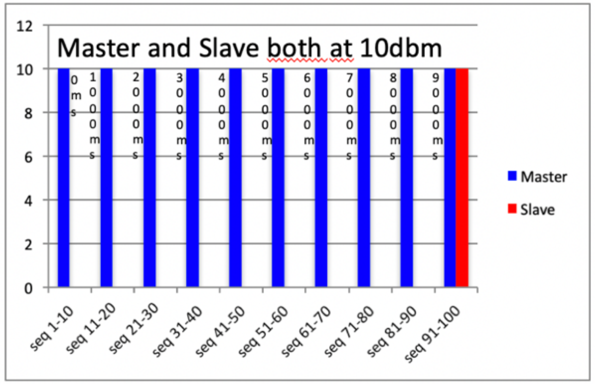
BW=125kHz,SF=10





C. Pham et al., "Investigating and Experimenting Interference Mitigation by Capture Effect in LoRa Networks". Invited paper, ICFNDS'19

Lower SFs seem to show less CE benefit

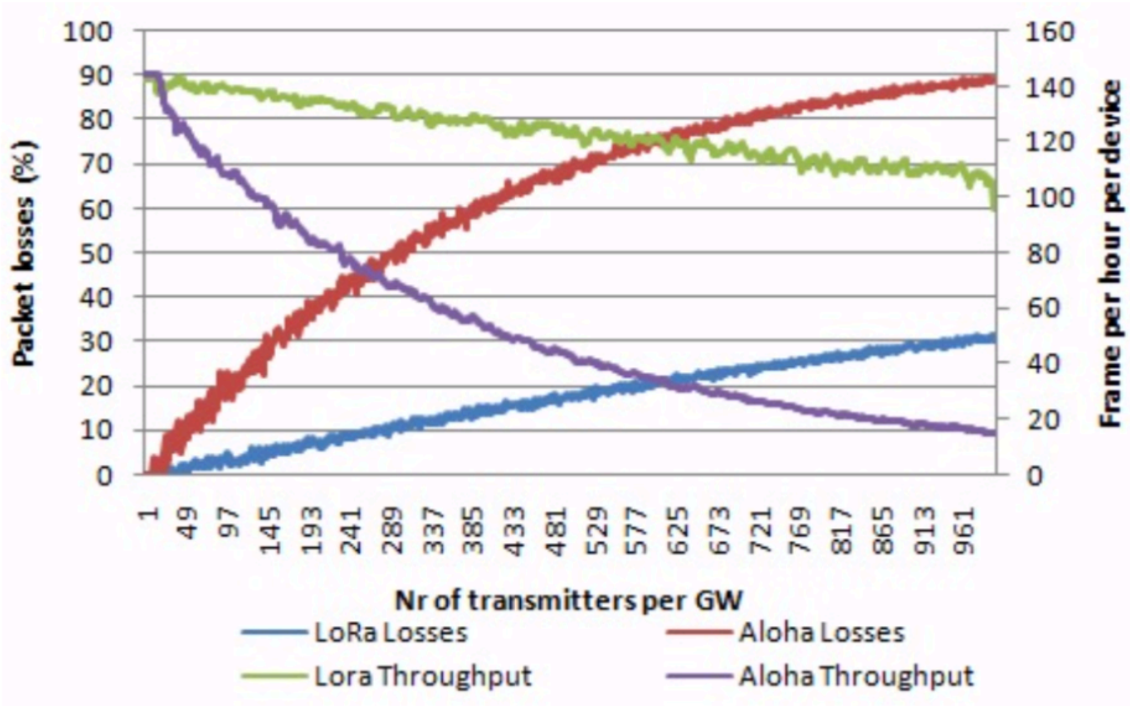


Small distance difference is enough to have SIR enabling CE

Need higher SIR?

Putting it altogether

- 6 different SF, 3 frequencies : 18 logical channels !
- Capture effect



Jetmir Haxhibeqiri, Floris Van den Abeele, Ingrid Moerman and Jeroen Hoebeke. LoRa Scalability: A Simulation Model Based on Interference Measurements. In *Sensors* 2017, *17.*

Successive Interference Cancellation

Yuqi Mo, Claire Goursaud, Jean-Marie Gorce. On the benefits of successive interference cancellation for ultra narrow band networks: Theory and application to IoT. IEEE ICC 2017 - IEEE International Conference on Communications, May 2017, Paris, France.

- Theoretically, successive interference cancellation can be a promising method in LPWAN
- However, experimental studies for LoRa are yet to be realized

Signal to Interference Ratio > Threshold

$$SIR_x = \frac{P_x}{P_i} > Th$$

P_x: Received power of stronger signal
P_i: Received power of 2nd stronger signal

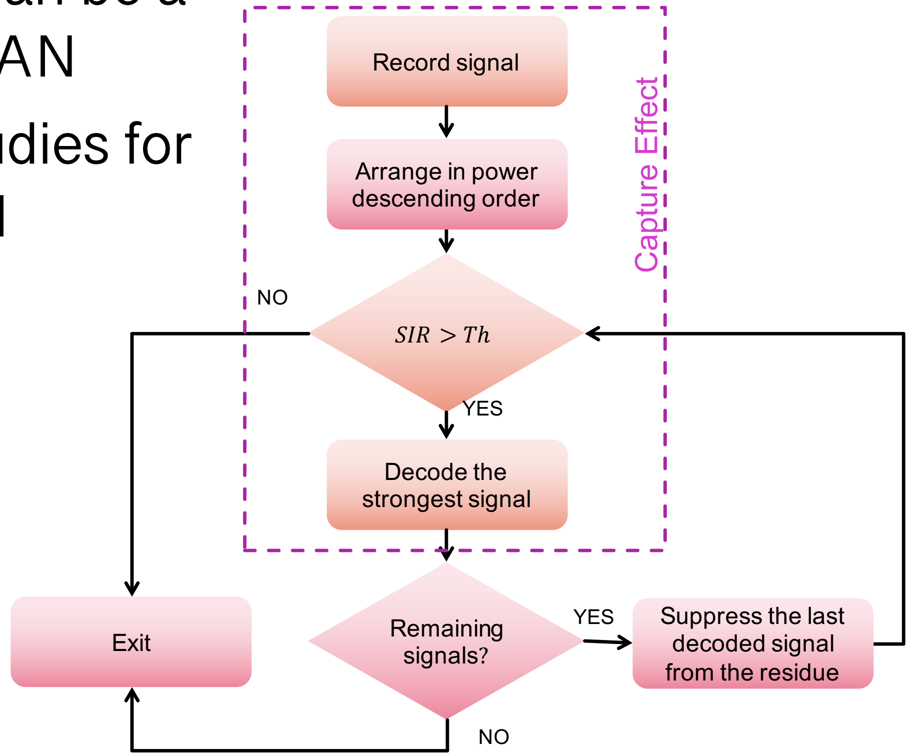


Figure from Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

LoRa with CE and SIC

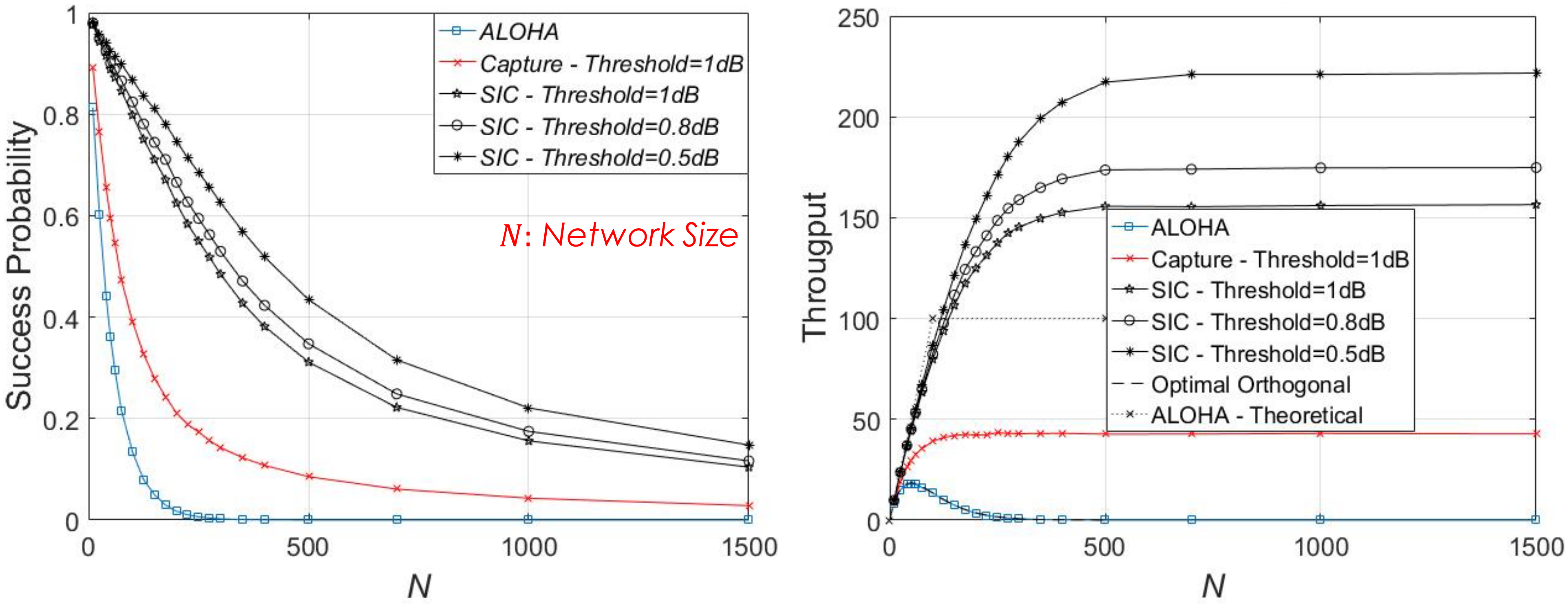


Figure from Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

High-level LoRa interference mitigation techniques

- Policy-based, tight regulations
  - ETSI: duty-cycle (<1%, i.e. 36s/h), transmit power, listen before talk (LBT), adaptive frequency agility (AFA),...
  - FCC: frequency hopping, limited dwell time (400ms), ...
  - ...
- LoRaWAN specifications
  - Enforcing radio inactivity time T_{off}
  - Adaptive Data Rate (ADR)
    - End devices can dynamically change their data rate (mainly through SF control) if link quality is sufficient
- Advanced ad-hoc mechanisms
  - LBT & Carrier Sense
  - Priority/Scheduling, resource allocation/management
  - TDMA-like,...

Duty-cycle

- ETSI duty-cycle, D
  - Generally assumed to be 1% for end-device, i.e. 36s/h
  - Some bands allow 10% and are usually reserved for the gateway (for downlink traffic)

- g (863.0 – 868.0 MHz): 1%
- g1 (868.0 – 868.6 MHz): 1%
- g2 (868.7 – 869.2 MHz): 0.1%
- g3 (869.4 – 869.65 MHz): 10%
- g4 (869.7 – 870.0 MHz): 1%

- With duty-cycle, the ALOHA-like system exibits smaller load, supporting higher number of devices

$$\lambda_i = \frac{D}{T_{air_i}} \quad \text{or} \quad \lambda_i = \frac{1}{T_{off_i} + T_{air_i}}$$

- For instance LoRaWAN specification adds *Toff* requirement after each transmission

$Toff_{subband} = (TimeOnAir / DutyCycle_{subbband}) - TimeOnAir$

The impact of frequency plan

LoRa Alliance

Modulation	Bandwidth [kHz]	Channel Frequency [MHz]	FSK Bitrate or LoRa DR / Bitrate	Nb Channels	Duty cycle
LoRa	125	868.10 868.30 868.50	DR0 to DR5 / 0.3-5 kbps	3	<1%

Table 2: EU863-870 default channels

Modulation	Bandwidth [kHz]	Channel Frequency [MHz]	FSK Bitrate or LoRa DR / Bitrate	Nb Channels	Duty cycle
LoRa	125	923.20 923.40	DR0 to DR5 / 0.3-5 kbps	2	< 1%

Table 39: AS923 default channels

EU863-870

THE THINGS NETWORK

Uplink:

1. **868.1** - SF7BW125 to SF12BW125
2. **868.3** - SF7BW125 to SF12BW125
3. **868.5** - SF7BW125 to SF12BW125
4. **867.1** - SF7BW125 to SF12BW125
5. **867.3** - SF7BW125 to SF12BW125
6. **867.5** - SF7BW125 to SF12BW125
7. **867.7** - SF7BW125 to SF12BW125
8. **867.9** - SF7BW125 to SF12BW125
9. **868.8** - FSK

Frequency plan means common adoption for uplink frequencies which will increase interference level

AS923-925

Used in Brunei, Cambodia, Hong Kong, Indonesia, Laos, Taiwan, Thailand, Vietnam

Uplink:

THE THINGS NETWORK

1. **923.2** - SF7BW125 to SF12BW125
2. **923.4** - SF7BW125 to SF12BW125
3. **923.6** - SF7BW125 to SF12BW125
4. **923.8** - SF7BW125 to SF12BW125
5. **924.0** - SF7BW125 to SF12BW125
6. **924.2** - SF7BW125 to SF12BW125
7. **924.4** - SF7BW125 to SF12BW125
8. **924.6** - SF7BW125 to SF12BW125
9. **924.5** - SF7BW250
10. **924.8** - FSK

Towards more frequency diversity?

- 8 channels is standard
- 16 channels is now becoming available and affordable
- Not unrealistic to foreseen 24 & 32 channels gateways

Part Number	8 Channel SX1301	16 channel SX1301	Cat4 Cellular	GPS	WIFI	Battery Backup
RAK7249-0x-14x	√		√	√	√	
RAK7249-1x-14x		√	√	√	√	
RAK7249-2x-14x	√		√	√	√	√
RAK7249-3x-14x		√	√	√	√	√
RAK7249-0x	√			√	√	
RAK7249-1x		√		√	√	
RAK7249-2x	√			√	√	√
RAK7249-3x		√		√	√	√

So? Is there something new under the hood?

- Deployed LoRa networks can be viewed as aggregation of multiple enhanced (i.e. CE) ALOHA systems
  - Multiple frequencies, Multiple SF providing orthogonal transmissions
- As LoRa is gateway-centric (or cellular-like) scalability can increase linearly with number of channels (or carriers)
  - 6 SF, 16 frequencies: 96 logical channels!
  - ~200 devices / logical channel → 19200 devices / gateway
- Packet reception rate can increase as gateway density increases
  - Outdoor gateways on high buildings (deployed by operators, organizations, agencies, municipalities,...)
  - Indoor gateways deployed by citizens (with incentive mechanism?)
    - Indoor gateways ~ 180€
    - DIY ~ 120€
    - Single-channel ~ 35€

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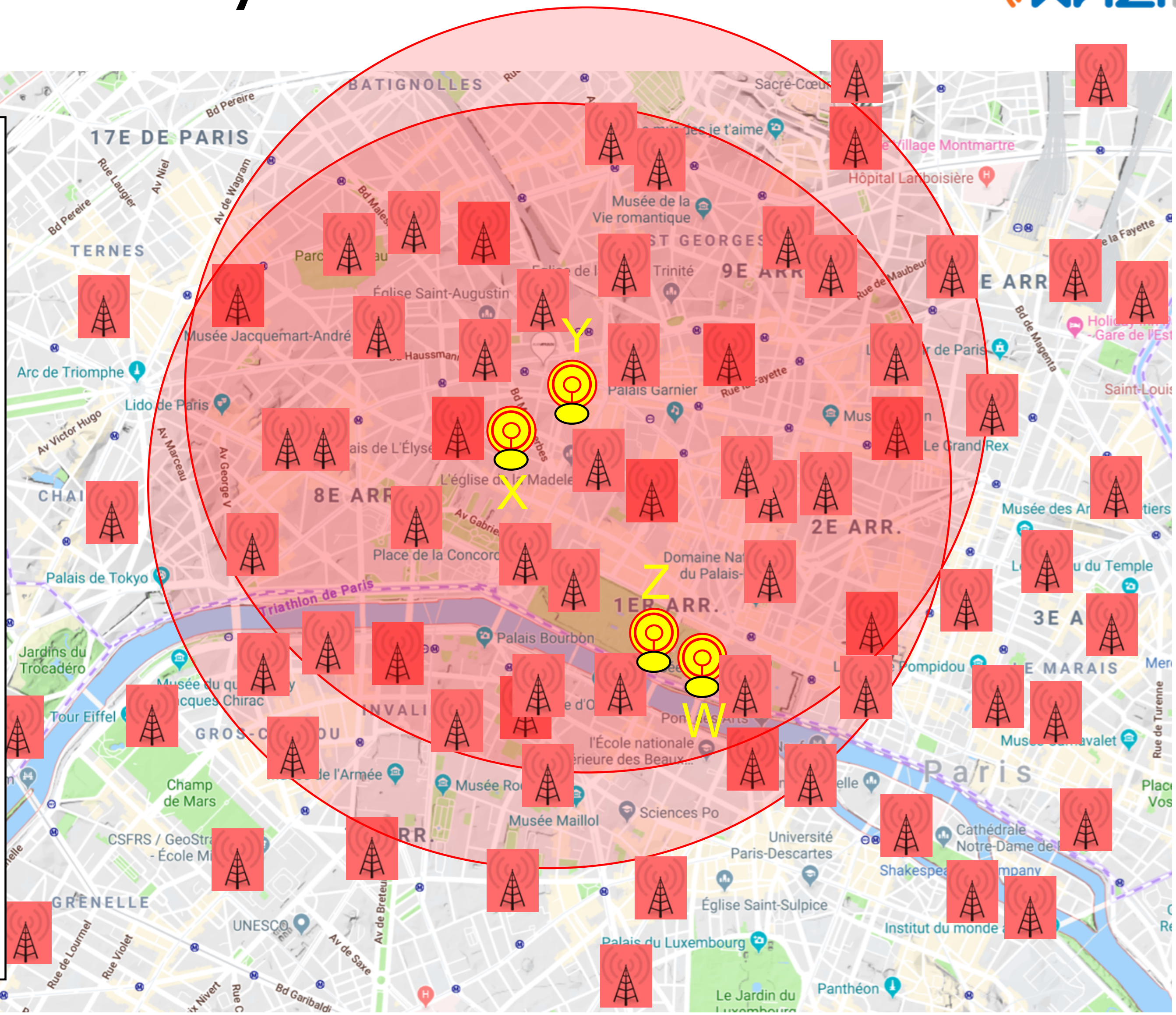
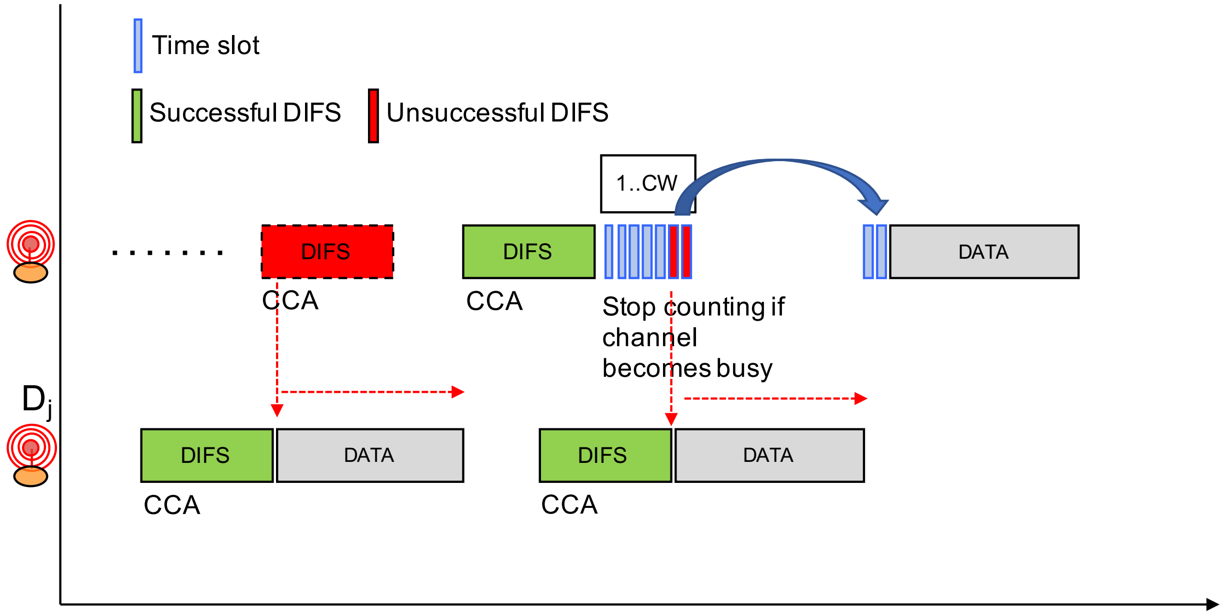
Dense gateway scenario

- Large # of GW
  - There will be a GW closer to X to allow CE to happen
- How to distribute SF to increase CE benefit?
  - Need more experiments
- How to distribute SF to reduce packet collision?
  - Can not be always based on distance (e.g. ADR)



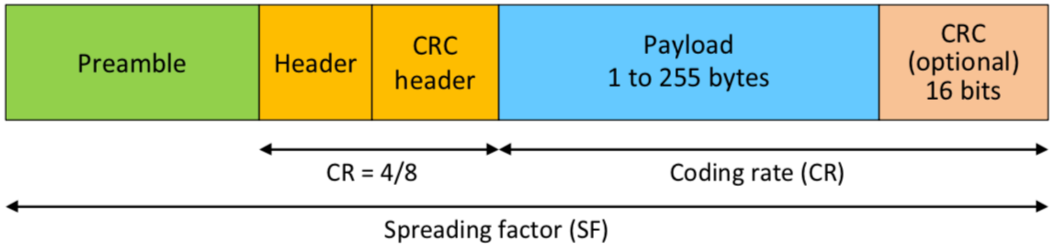
What about CSMA approach?

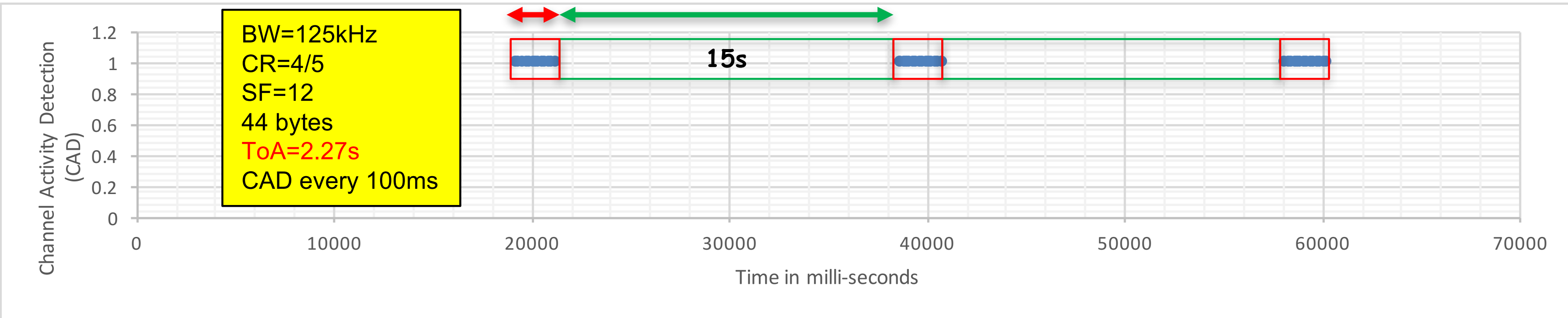
- Can we implement Listen-Before-Talk or CSMA?
- Ex: Carrier Sense/Collision Avoidance in 802.11 (WiFi)
  - DIFS, SIFS
  - Clear Channel Assessment
  - Random backoff [0..W[

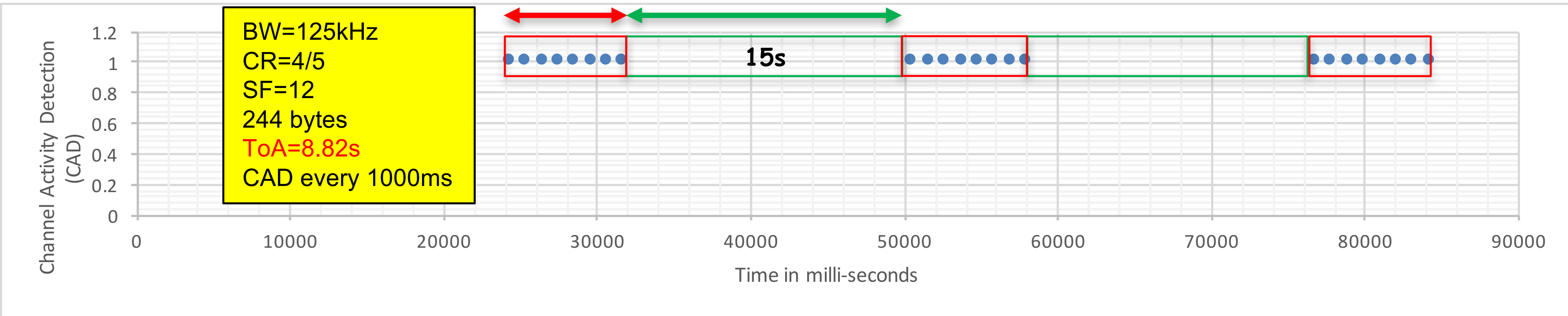


Clear Channel Assessment with LoRa

- LoRa's Channel Activity Detection (CAD)







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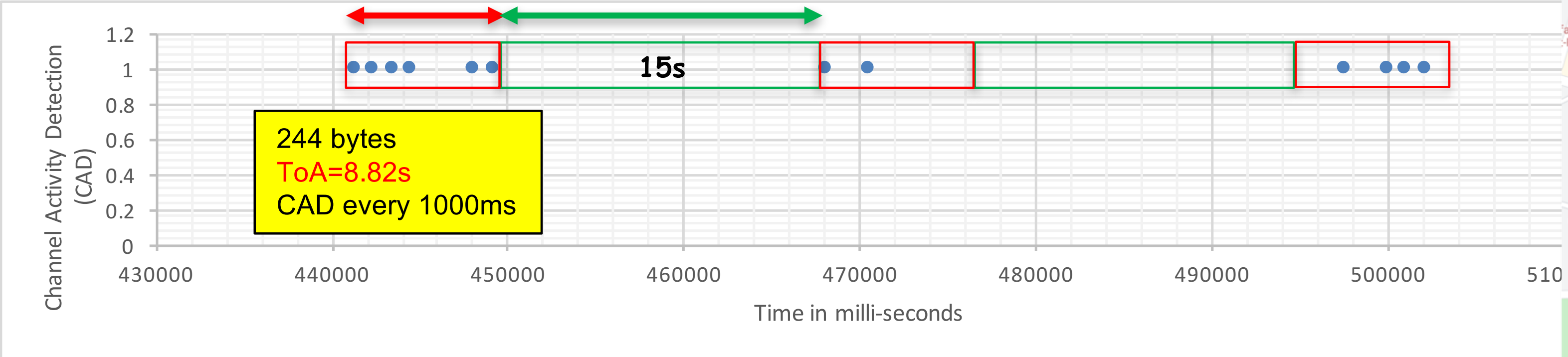
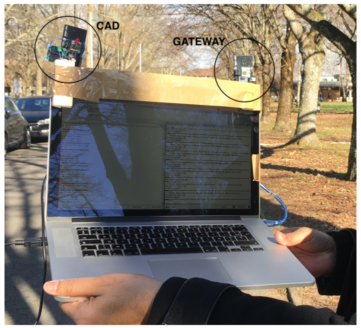
http://www.univ-pau.fr/~cpham

CAD reliability?

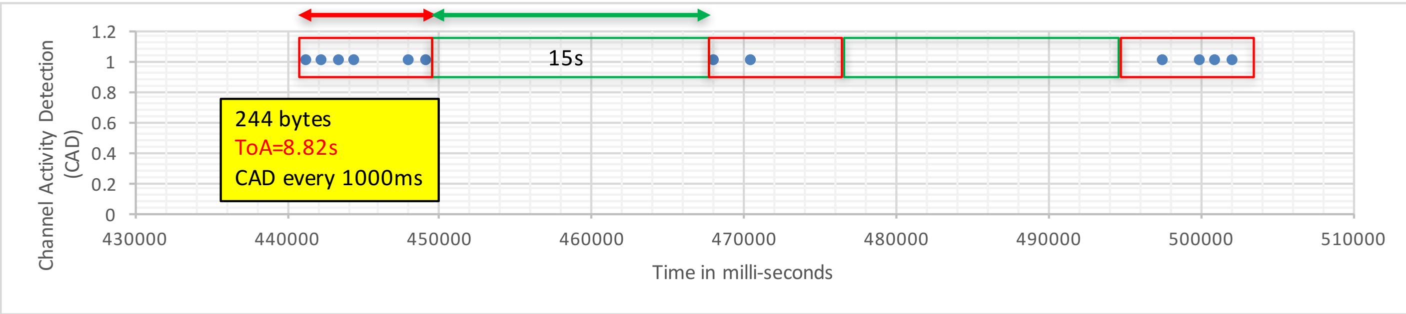
- CAD reliability decreases as distance increases
  - A CAD returning false does not mean that there is no activity!
  - Similar to hidden terminal issue
  - But RTS/CTS mechanism is not realistic with LoRa

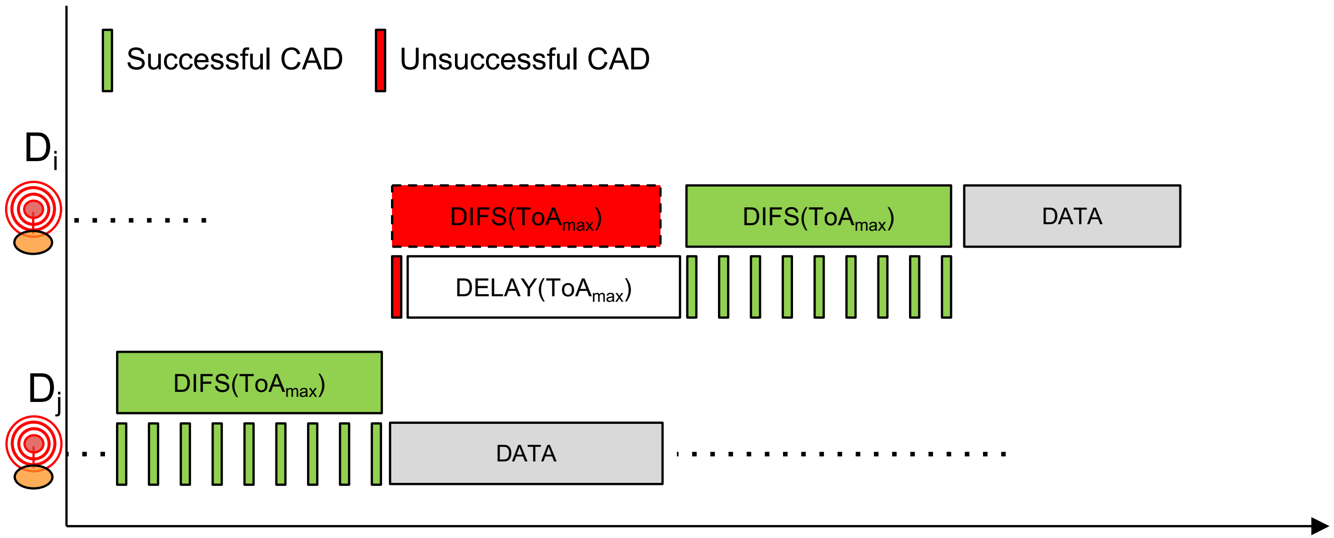


- CAD sensitivity not as good as full reception sensitivity
- CAD returns 'no activity' but packet can be received!



LoRa CSMA to protect longer msg

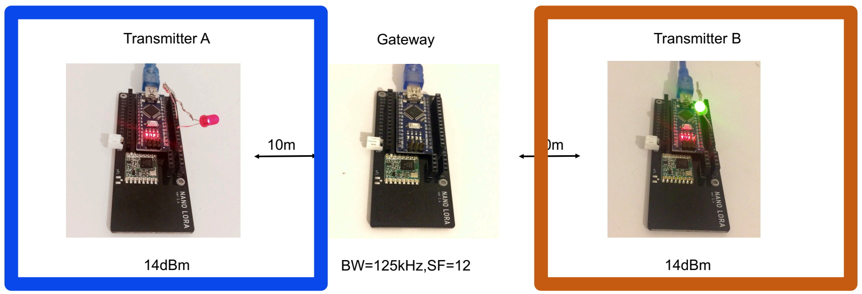


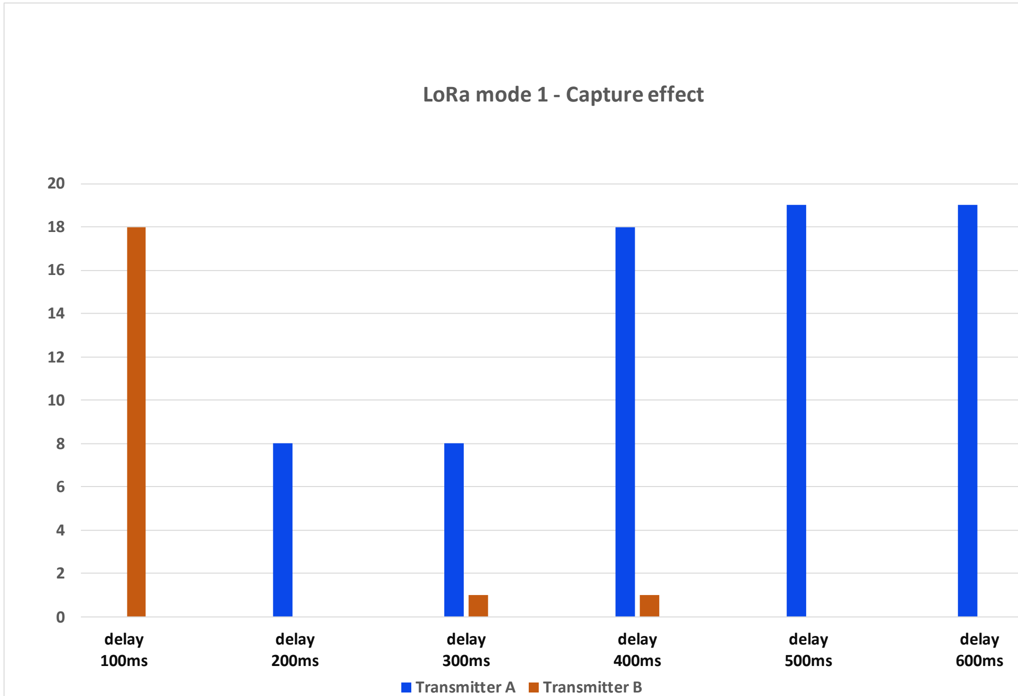


C. Pham, "Investigating and Experimenting CSMA Channel Access Mechanisms for LoRa IoT Networks", Proceedings of the IEEE WCNC conference, Barcelona, Spain, April 15-18, 2018.

Overlapping transmission – Capture Effect

- SF12BW125: preamble duration is about 401ms
- If interferer (B) transmit during A's preamble (100ms-400ms)
  - 100ms: B takes over A's transmission
  - 200ms: A can be successful
  - 300ms: A can be successful
  - 400ms: A is mostly successful
- After A's preamble
  - A is always successful





Finally, is ALOHA that bad?

- Concurrent transmission during preamble should be avoided
- Concurrent transmission after preamble is inefficient but not that harmful
- Given the unreliability of CAD procedure, CCA can not be reliably determined
- For all these reasons, we can ask whether ALOHA access is really that bad for LoRa network under the perspective of maximizing Packet Delivery Rate and reducing latency for a given device
- If energy efficiency is considered then ALOHA is very bad because many transmissions will never be received

Conclusions

- LoRa networks are deployed world-wide is unlicensed bands
  - Telco operators, Communities, Private, ad-hoc infrastructures
  - LoRa 2.4GHz is also available with range of about 3kms
- There is currently little control on channel access
  - Basically similar to an ALOHA system, but
    - regulations may apply to limit radio usage
    - Promising enhanced features: CE, SIC
    - number of logical channels increases scalability
- There are tremendous community-based gateway deployment initiatives
  - No other radio technologies (apart from WiFi) have similar involvement from community and citizens!
  - Density of LoRa gateway is expected to be high in cities
  - Frequency diversity is also expected to be high (x16, x24, x32 GW)