Scalability of LoRa Networks for Dense IoT Deployment Scenarios: limitations and perspectives

International Workshop on ADVANCEs in ICT Infrastructures and Services

Zaragoza, Spain
2-4 Februrary 2021

Presented on February 2nd, 2021

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LIUPPA

Horizon 2020

WAZIUP
IoT – from idea to reality
WAZIHUB

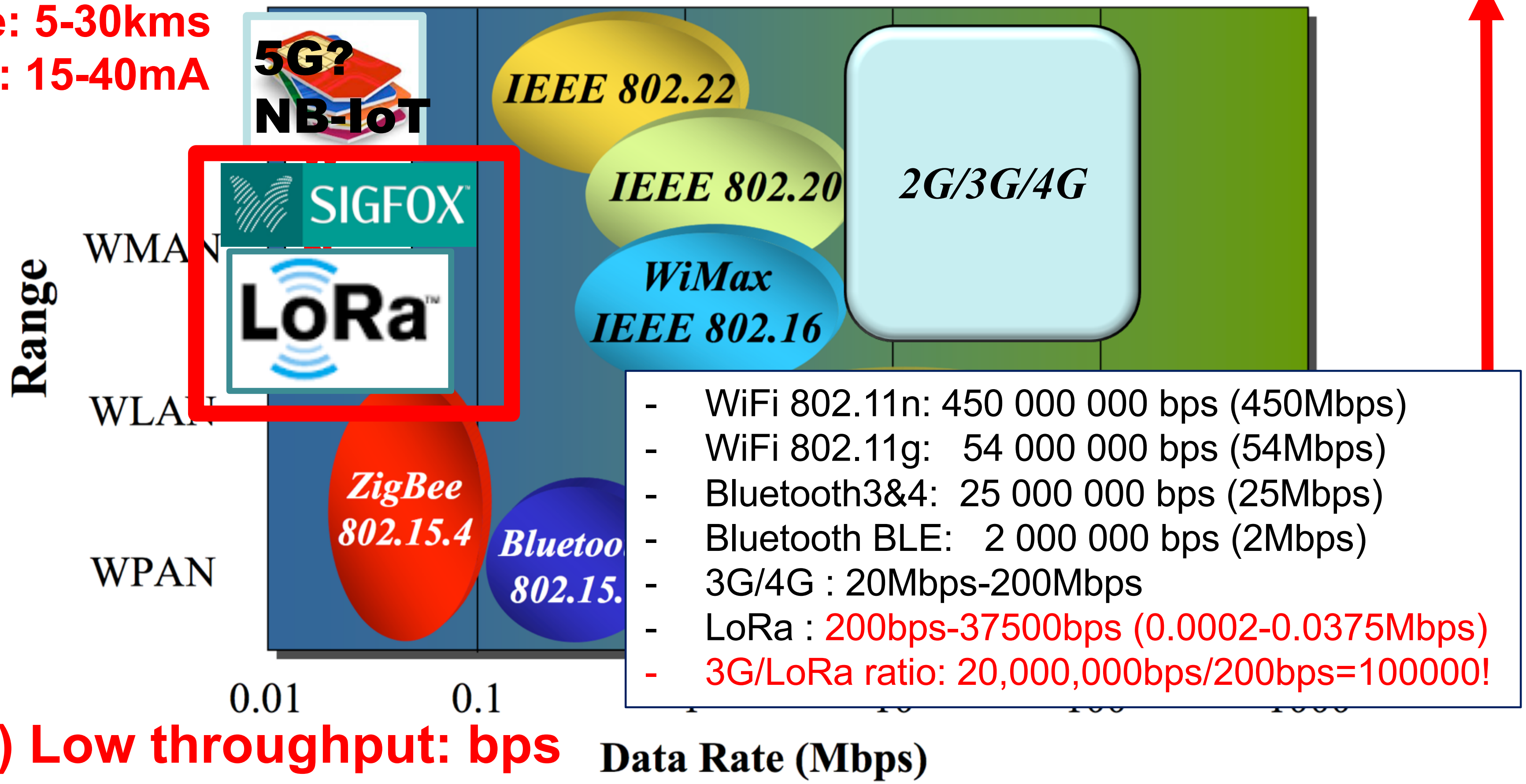
Where am I now?

Sense, Monitor, Optimize & Control

Low-power & long-range radios

Energy-Range dilemma

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

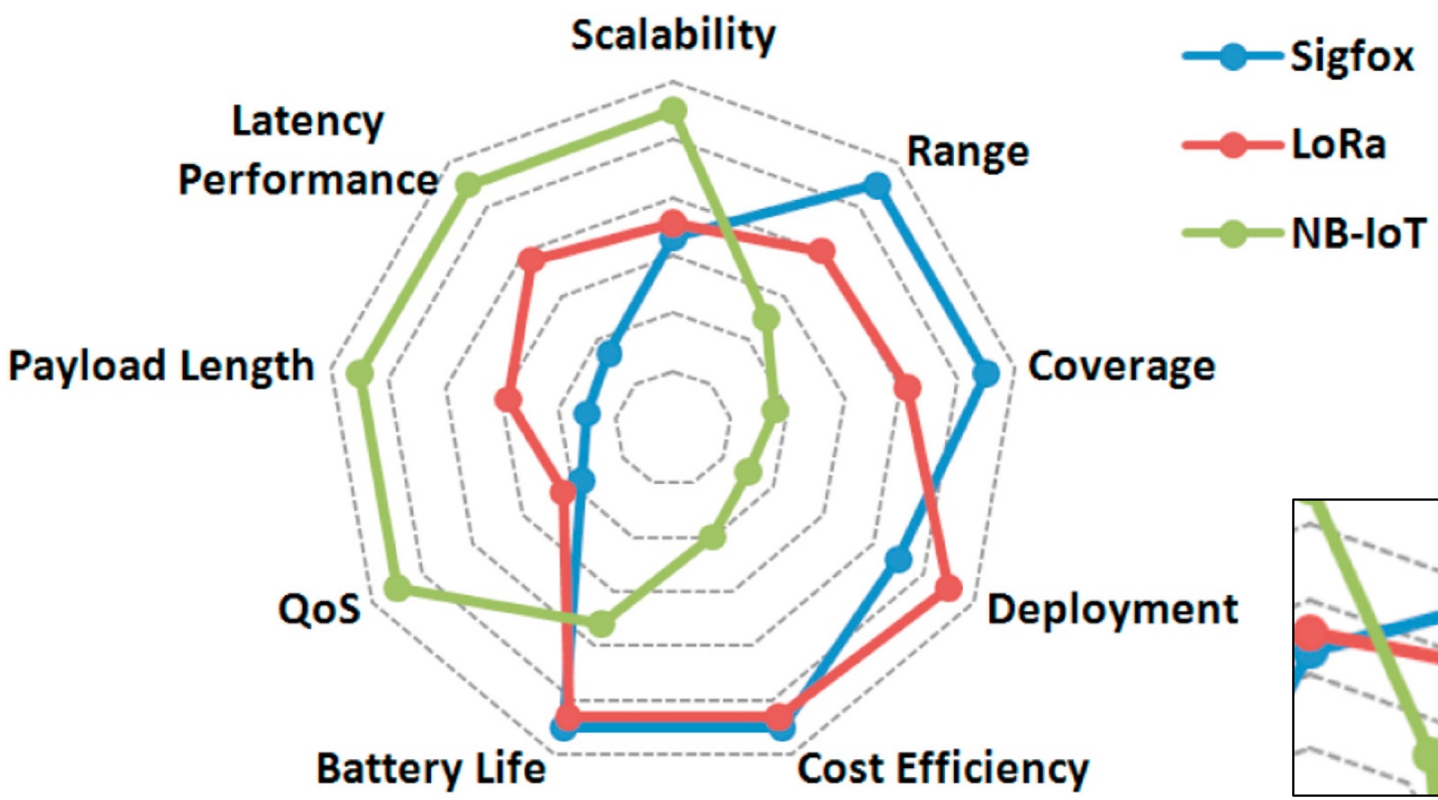


- WiFi 802.11n: 450 000 000 bps (450Mbps)
- WiFi 802.11g: 54 000 000 bps (54Mbps)
- Bluetooth3&4: 25 000 000 bps (25Mbps)
- Bluetooth BLE: 2 000 000 bps (2Mbps)
- 3G/4G : 20Mbps-200Mbps
- LoRa : 200bps-37500bps (0.0002-0.0375Mbps)
- 3G/LoRa ratio: 20,000,000bps/200bps=100000!

(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

![HORIZON 2020 logo] # Expected range?



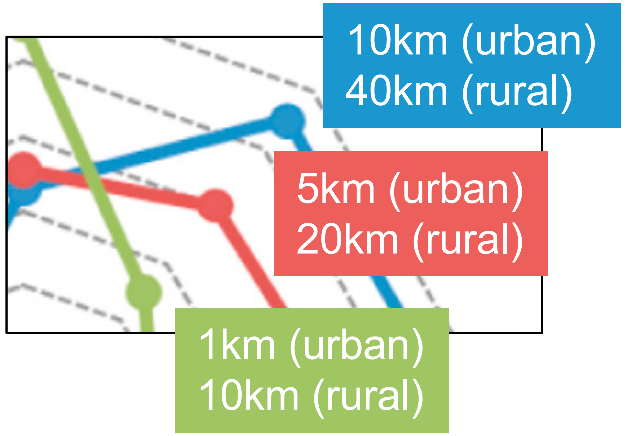


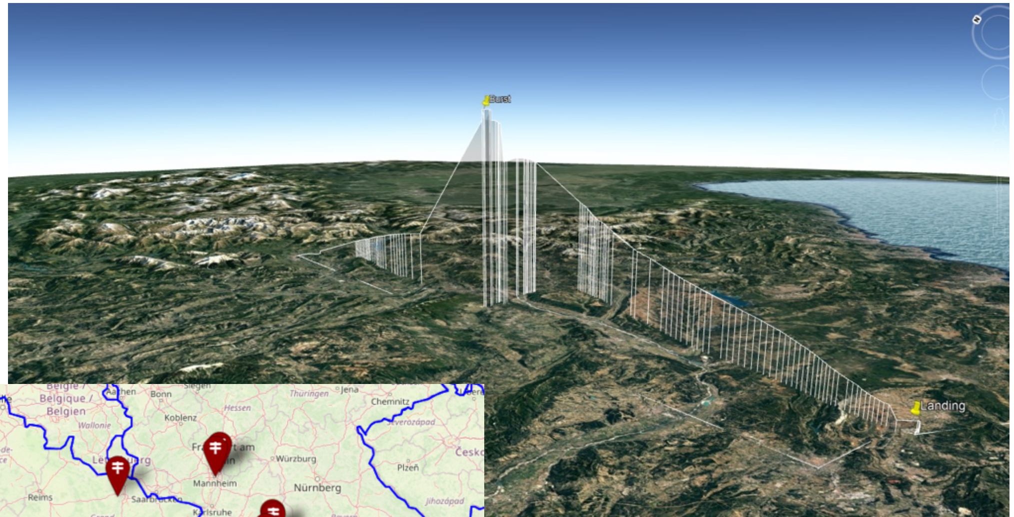
Figure from Kais Mekki, Eddy Bajic, Frederic Chaxel, Fernand Meyer,
A comparative study of LPWAN technologies for large-scale IoT deployment,
ICT Express, Volume 5, Issue 1, 2019.

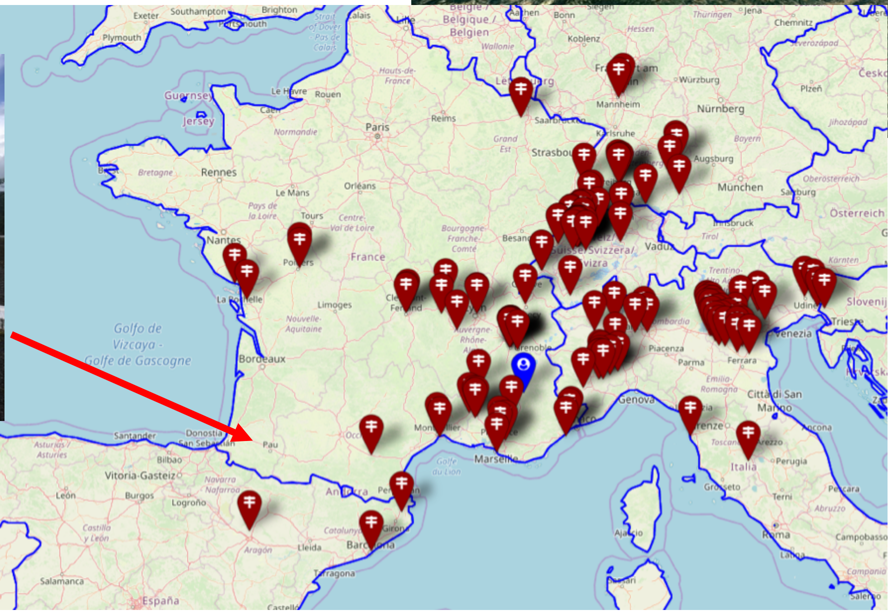
LoRa coverage test by Fabien Ferrero on March 21-22, 2019

- 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!

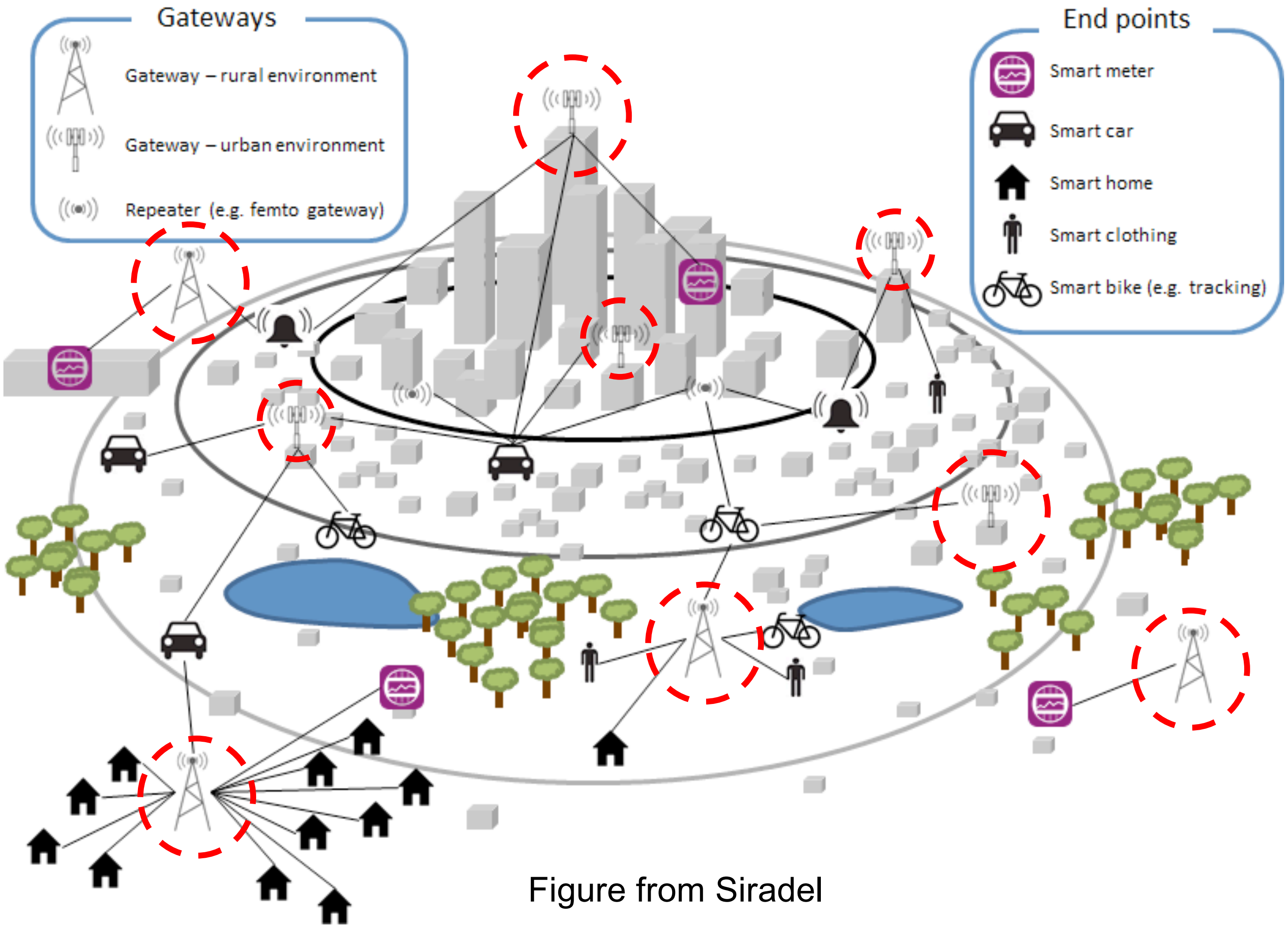
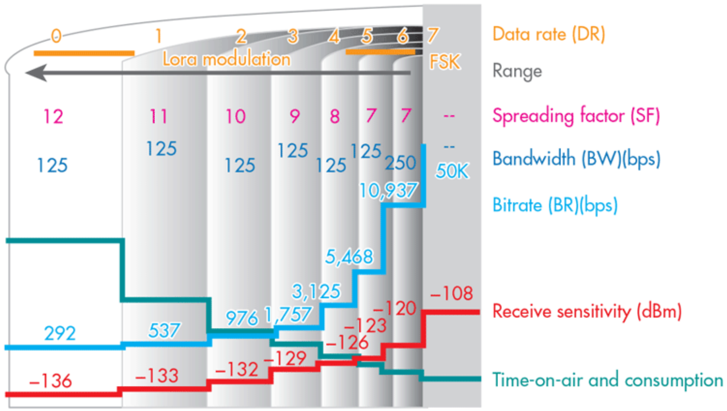


Figure from Siradel

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
  - Spreading Factor defines how many chips will be used to code a symbol. More chip/symbol=longer transmission time ➠ more robustness
- **The price to pay for LPWAN**
  - LoRa has very low throughput: 200bps-37500bps (0.2-37.5kbps)



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!

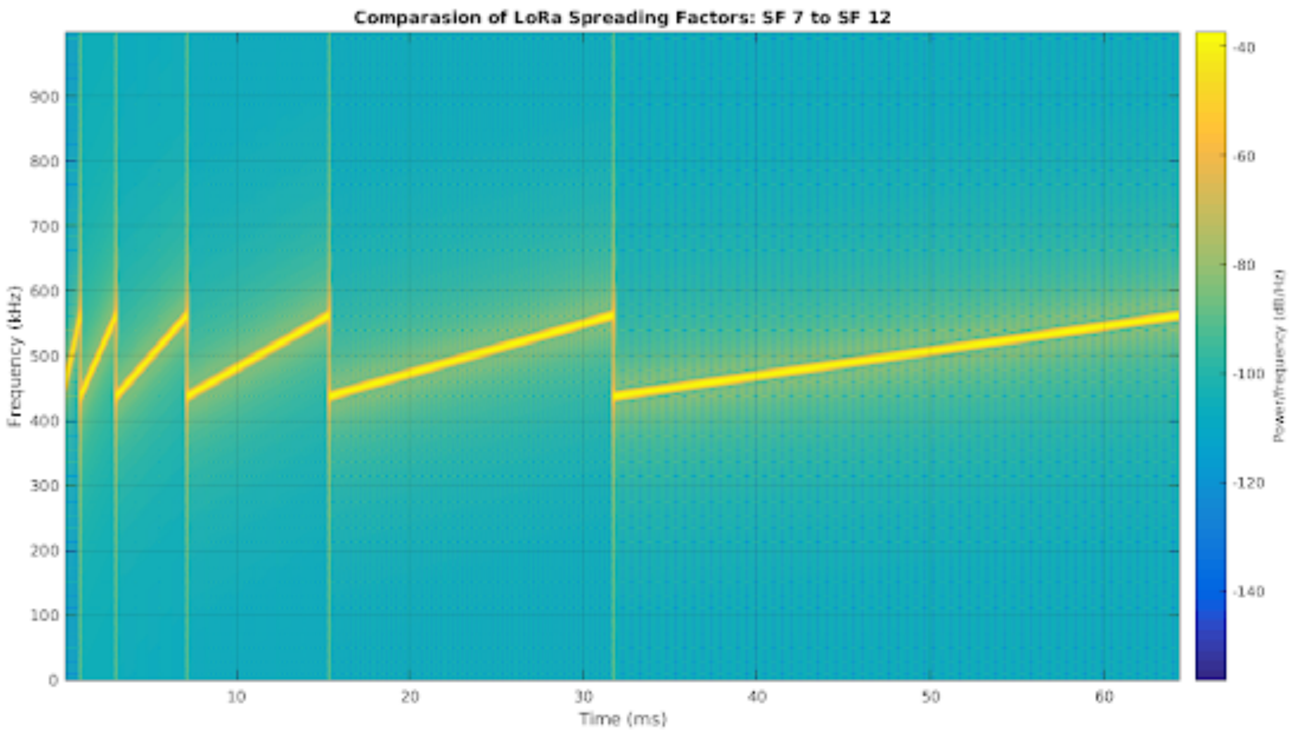
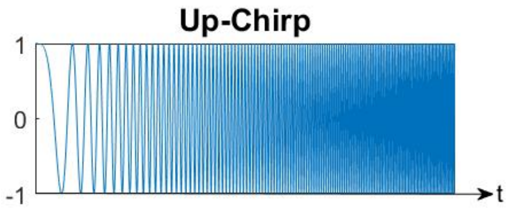


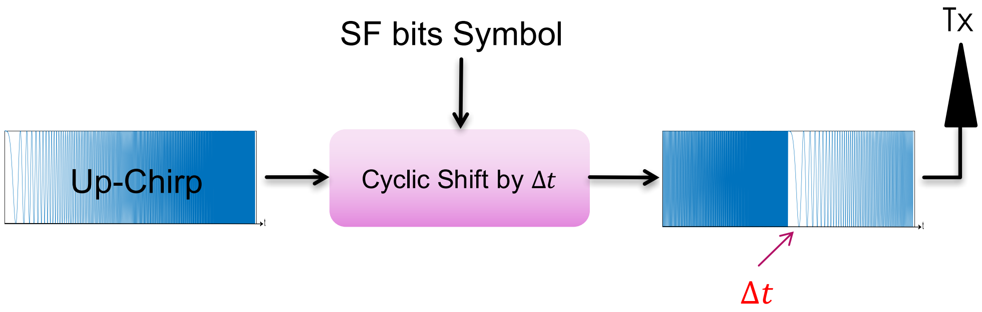
Figure from "All About LoRa and LoRaWAN", https://www.sghoslya.com

Chirp Spread Spectrum Modulation



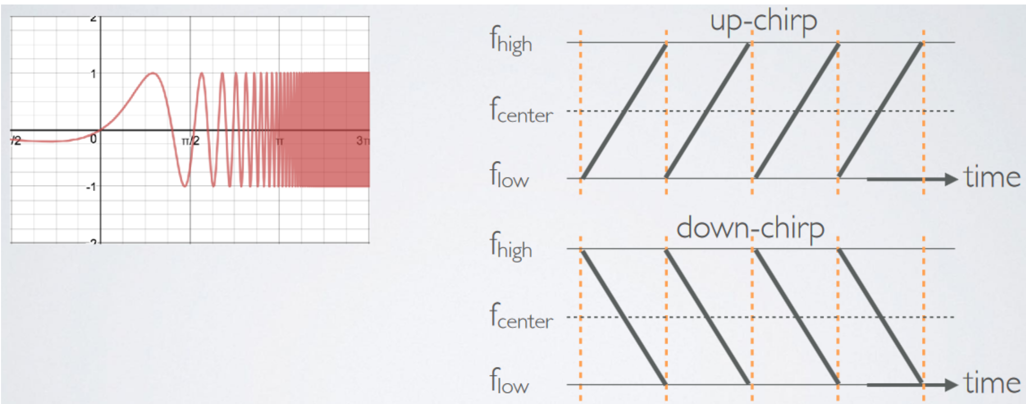
$$C(t) = \begin{cases} \exp(2\pi j(at+b)t) & -\frac{T_s}{2} \leq t \leq \frac{T_s}{2} \\ 0, & otherwise \end{cases}$$

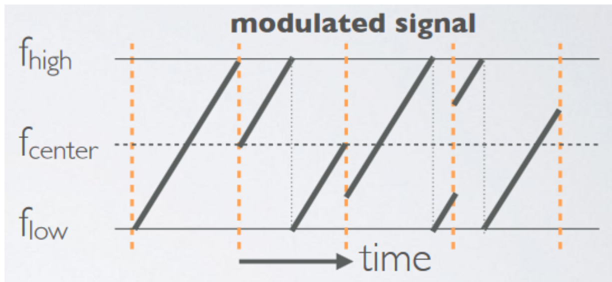
CSS Modulation



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).

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

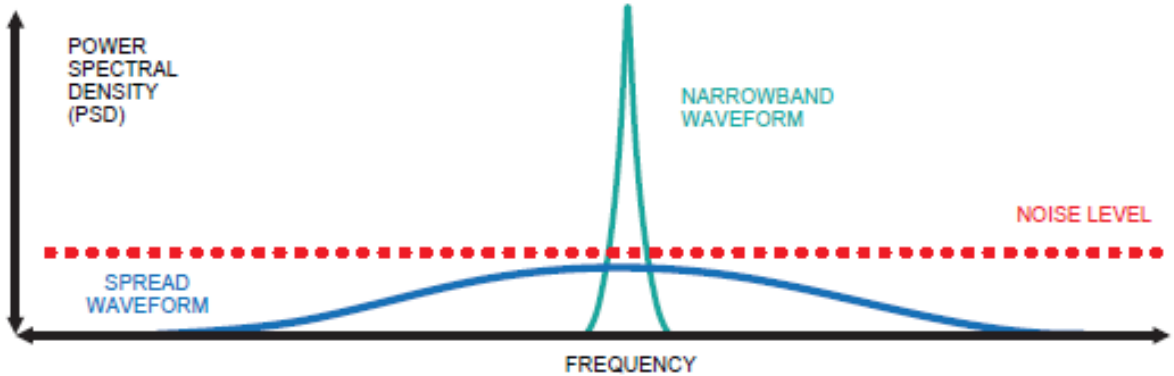


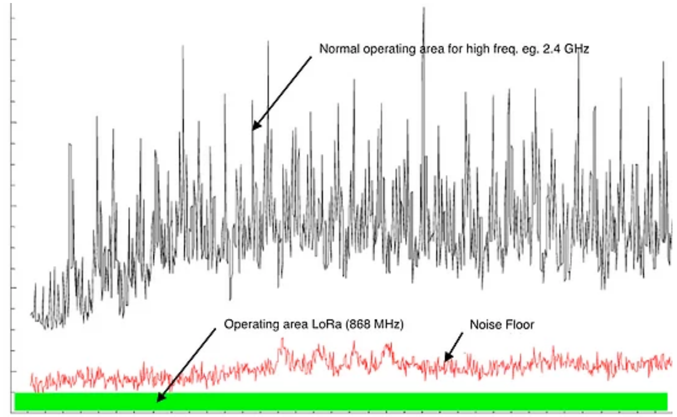


https://lora.readthedocs.io/en/latest/

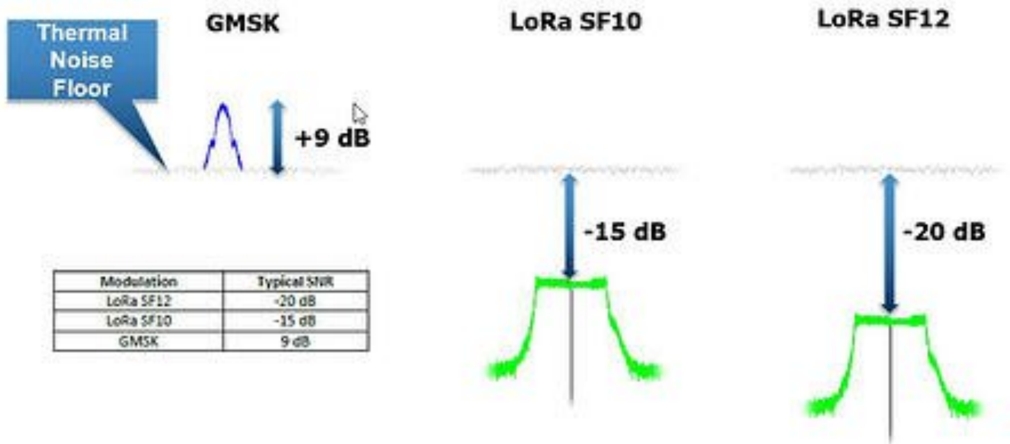
Advantage of Spread Spectrum

- Spread Spectrum techniques are usually more robust to noise





- LoRa signals can be decoded below noise floor



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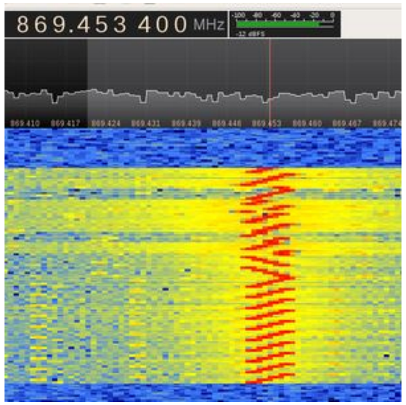
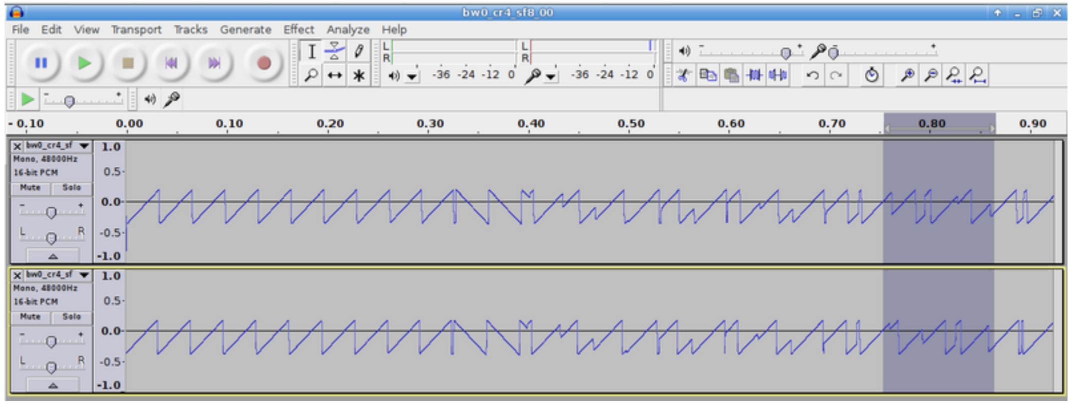
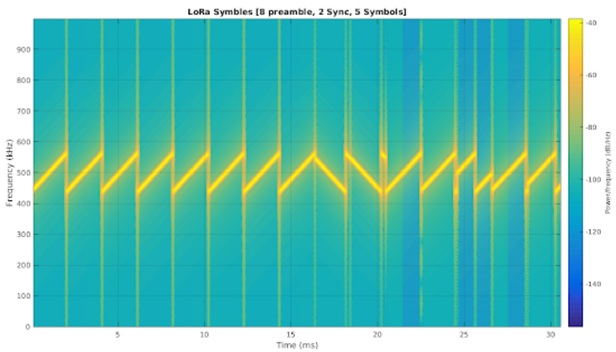
Want to know more on LoRa PHY?

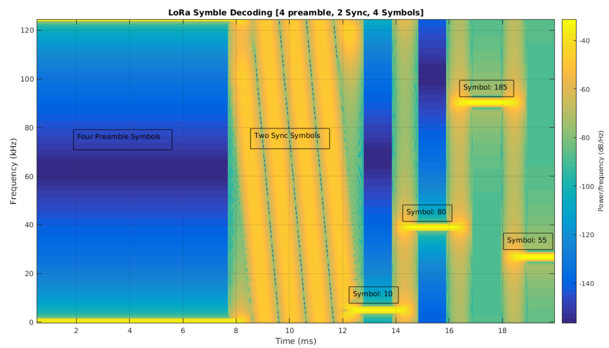
- https://revspace.nl/DecodingLora





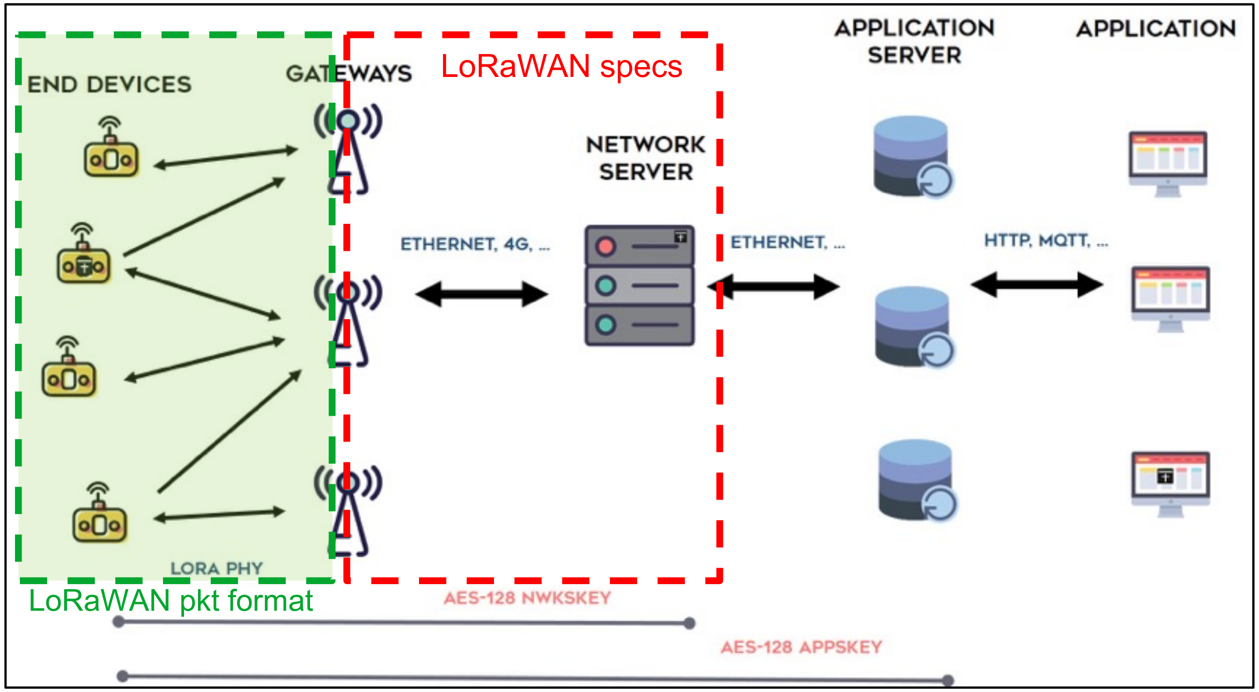
- "All about LoRa and LoRaWAN"
  https://www.sghoslya.com/p/lora-is-chirp-spread-spectrum.html

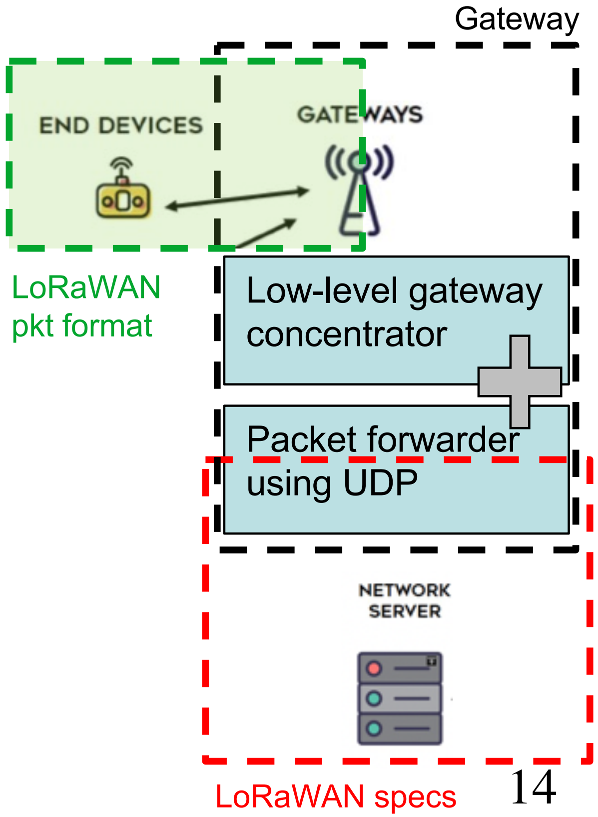




LoRaWAN

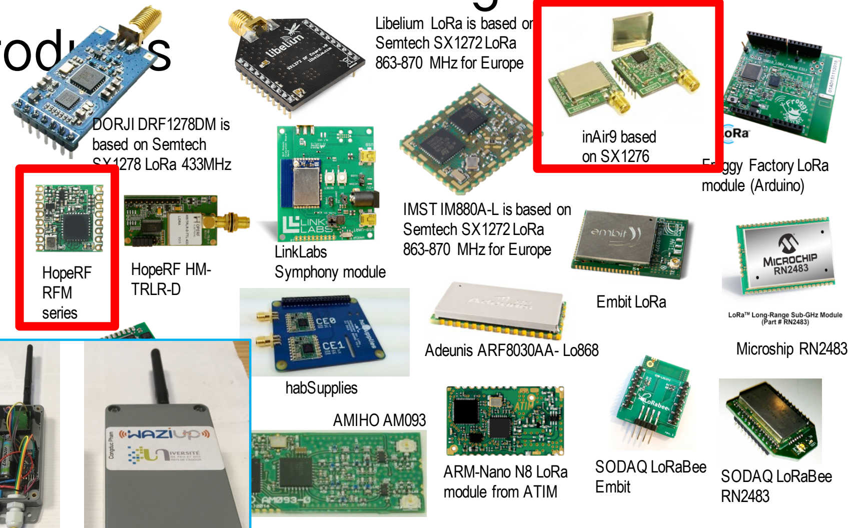
- LoRaWAN protocols run on top of LoRa physical networks. It is defined and managed by the LoRa Alliance
- It specifies protocols to run large-scale, public LoRa networks

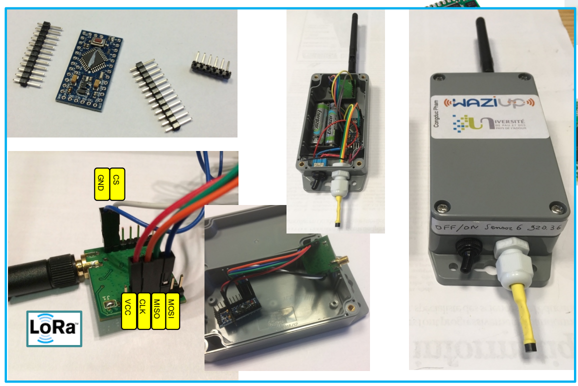




Explaining the success of LoRa

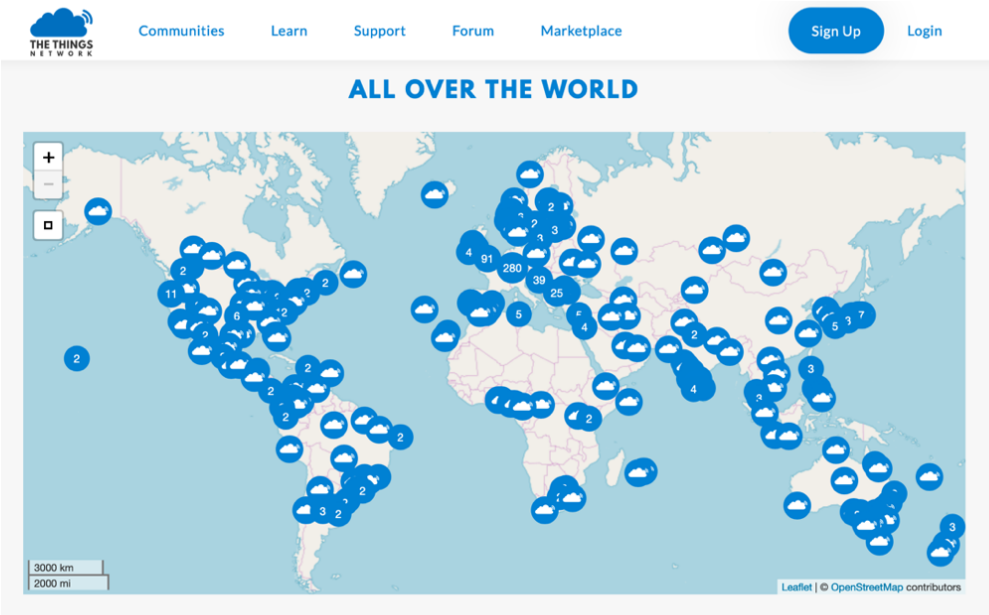
- Long-range, low-power – 5-10 years on battery possible
- Unlicensed frequency bands
- Ad-hoc deployment of devices and gws, no need for operators – many LoRa deployments are currently private including companies
- Large availability of very low-cost radio modules making DIY IoT almost as efficient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





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

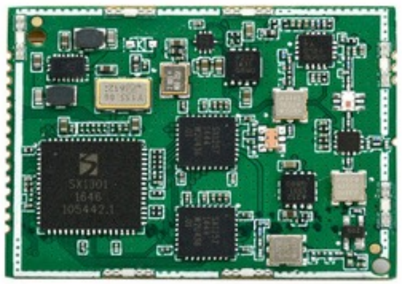
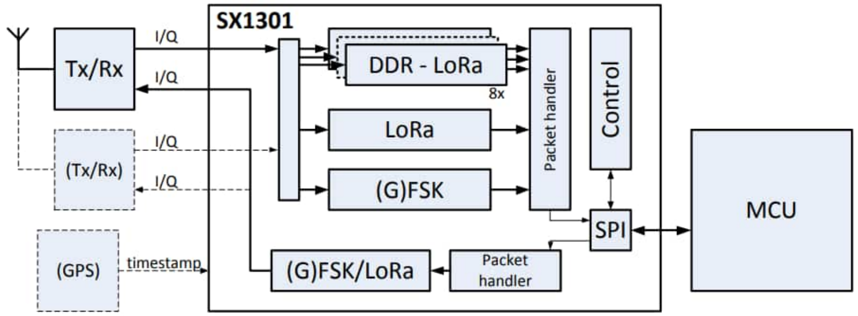
- A full LoRaWAN gateway should be able to listen on multiple channels (x8) and spreading factors (SF7-SF12)

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

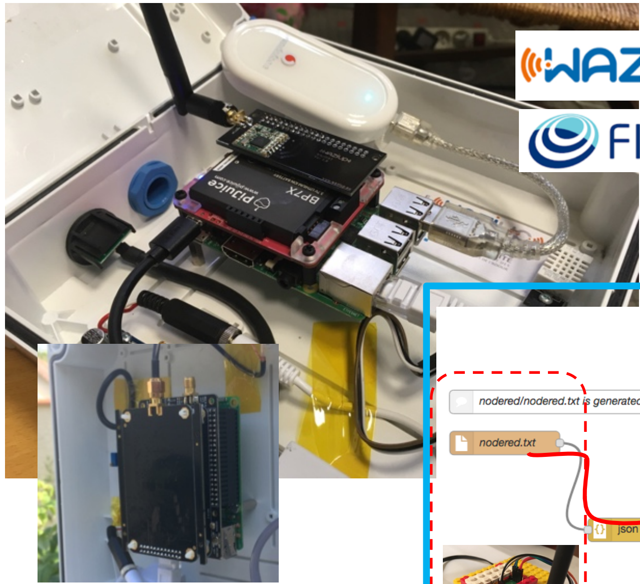



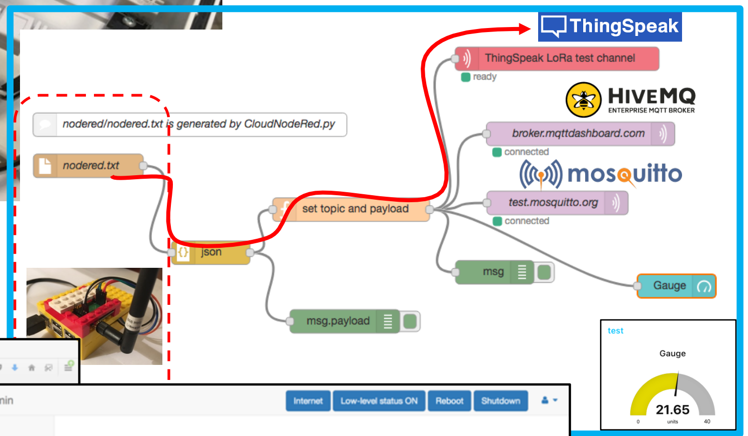
Open, DIY, versatile IoT gateway

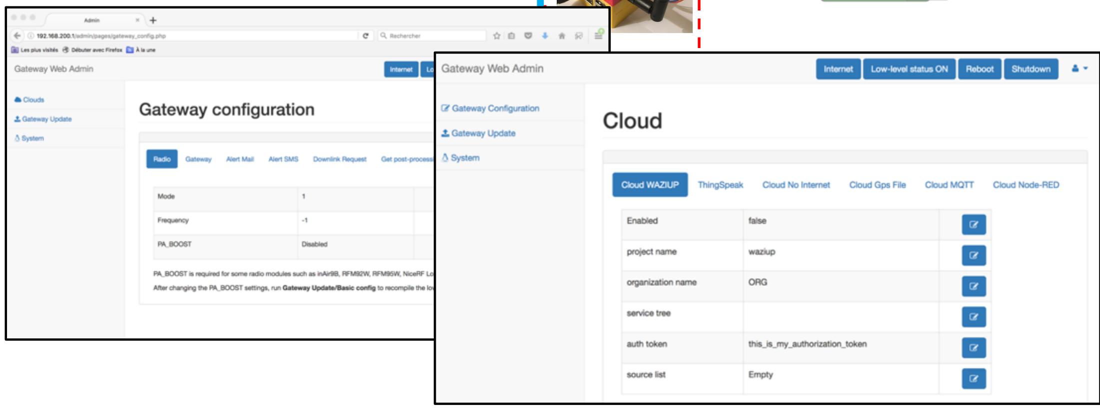
Large customization features

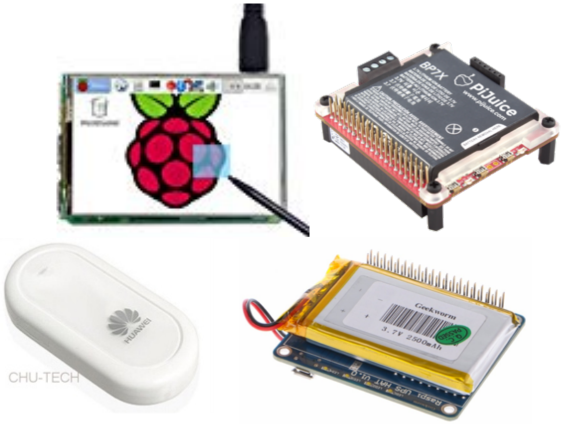
Raspberry PI: lots of libraries, lots of software, lots of hardware, lots of shields,…

https://github.com/CongducPham/LowCostLoRaGw



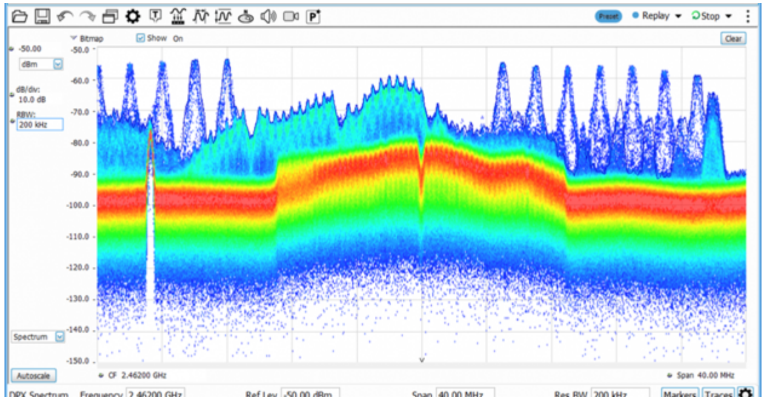






Large-scale IoT deployment

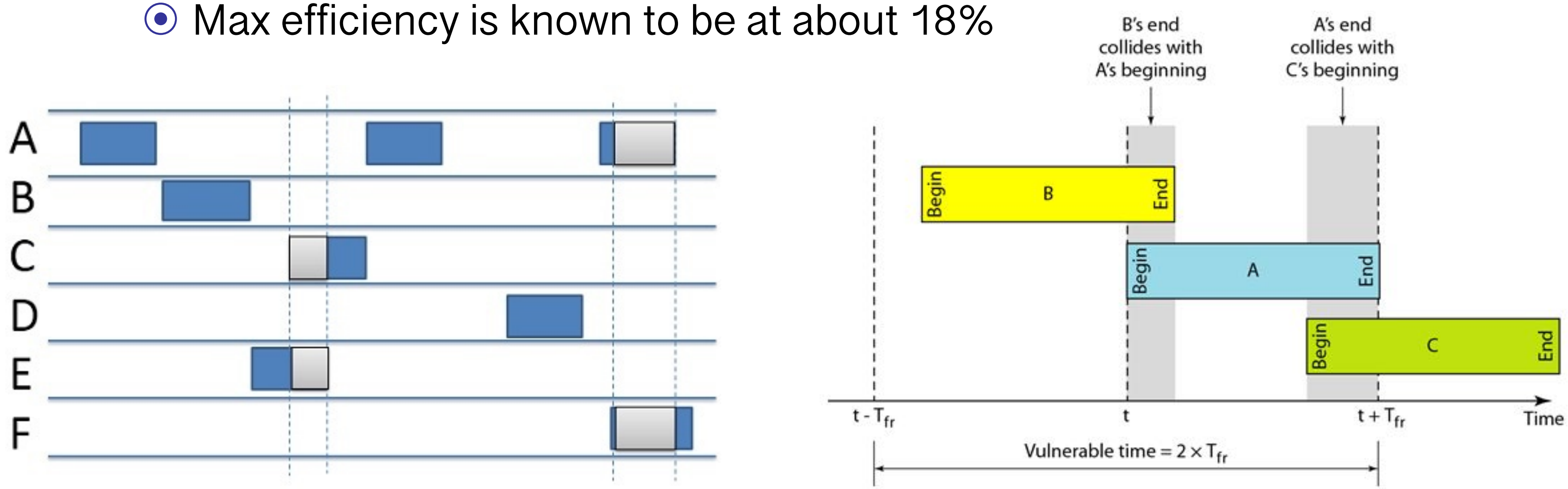
- More devices: more traffic, more interferences & collisions!
- 1 msg/20min = 3 msg/h. For 1000 devices = almost 1 msg/s!



- More gateways increases coverage so can increase SF diversity: transmissions with small SF can reach a gateway

Concurrent channel access

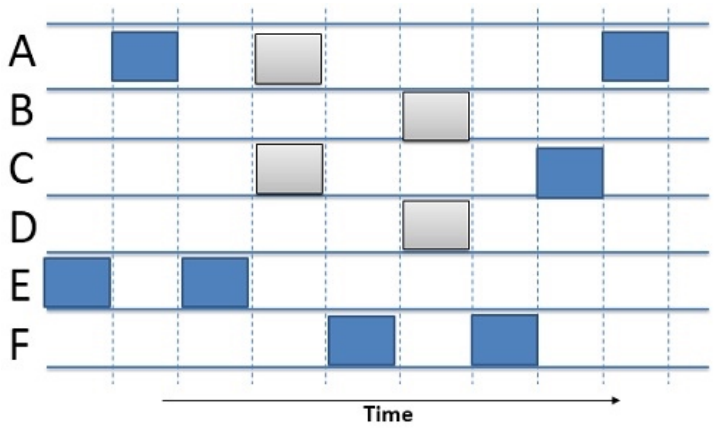
- LoRa's channel access ~ pure ALOHA system
  - Anybody can talk at any time
  - Vulnerable time is 2xT_{pkt}
  - Max efficiency is known to be at about 18%

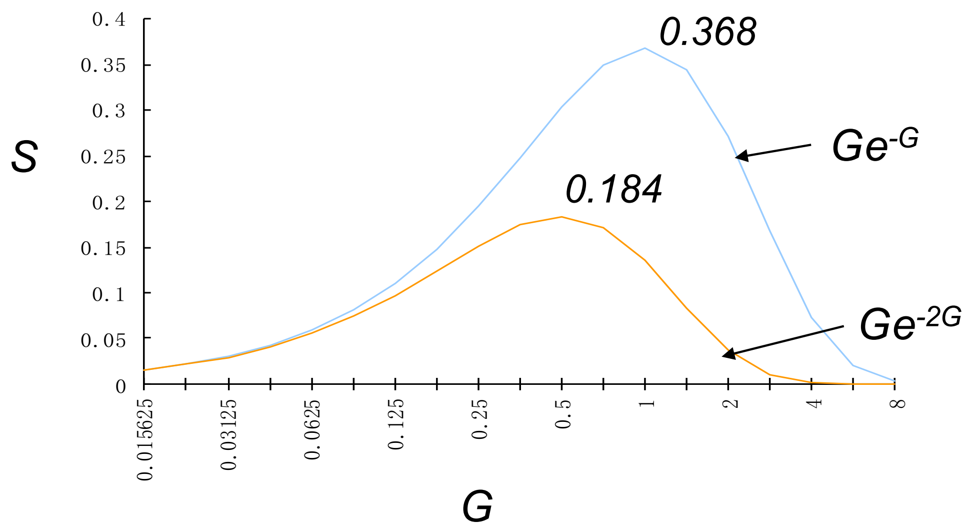


- If there is always overlapping transmissions during the packet transmission time, success probability is close to 0!

In theory, slotted ALOHA

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





- But slotted mode needs higher level of coordination that is not really possible with LoRa

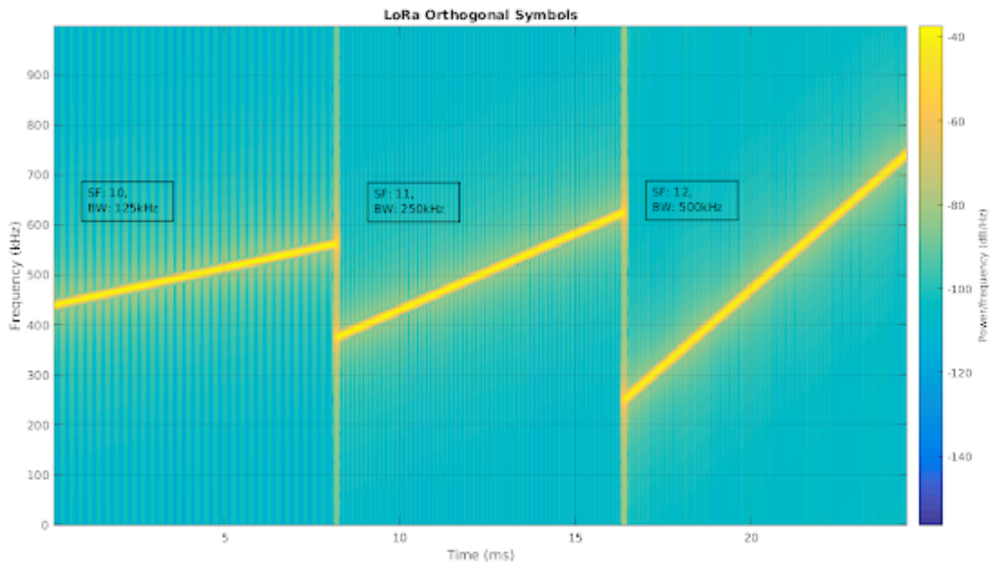
Unlicensed ≠Unregulated

- LoRa currently works in unlicensed band (sub-GHz & 2.4GHz)
- Unlicensed = possible usage free of charge
  - Example: WiFi in the 2.4GHz ISM band
  - Shared between a large variety and number of users
- For sub-GHz band, ETSI's regulations
  - duty-cycle (<1%, i.e. 36s/h),
  - transmit power (i.e. 14dBm),
  - listen before talk (LBT), adaptive frequency agility (AFA),...
- For sub-GHz band, FCC's regulations
  - Mandatory frequency hopping,
  - Minimum number of frequency sub-channels
  - limited dwell time (400ms),
- **GOAL = limit radio activity for a "reasonable" usage**

Prof. Congduc Pham
http://www.univ-pau.fr/~cpham

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

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 = $(f_{max}-f_{min})/Ts = BW/(2^{SF}/BW) = BW^2/2^{SF}$

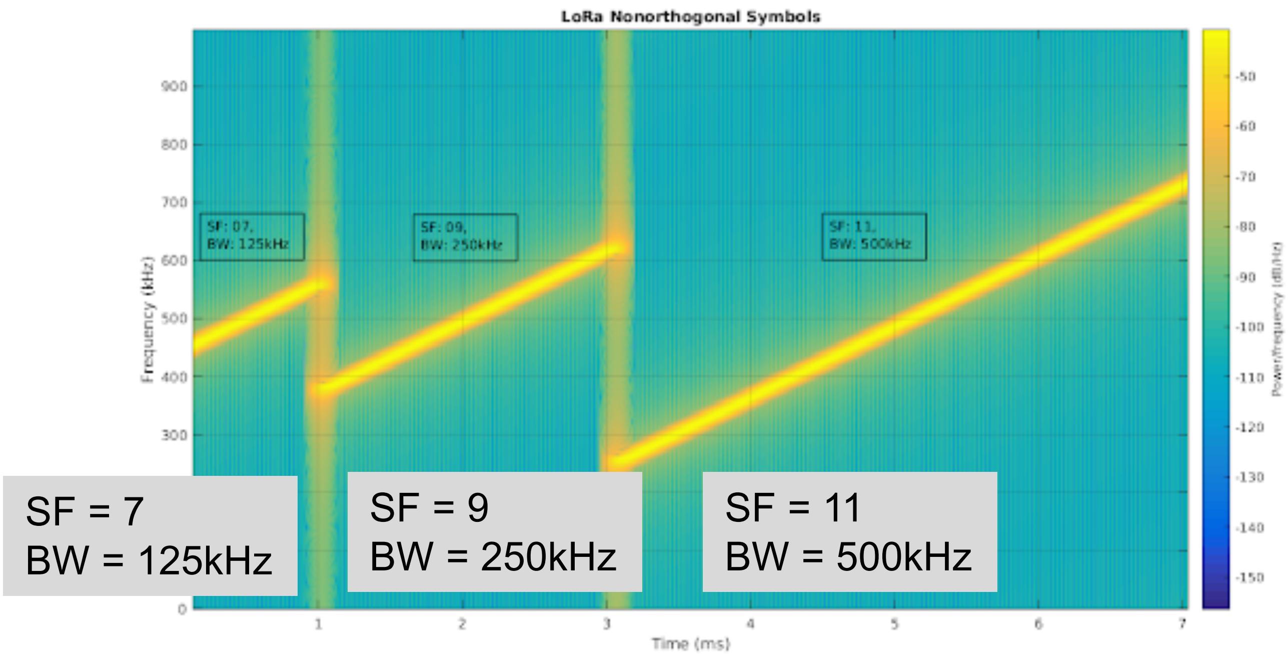


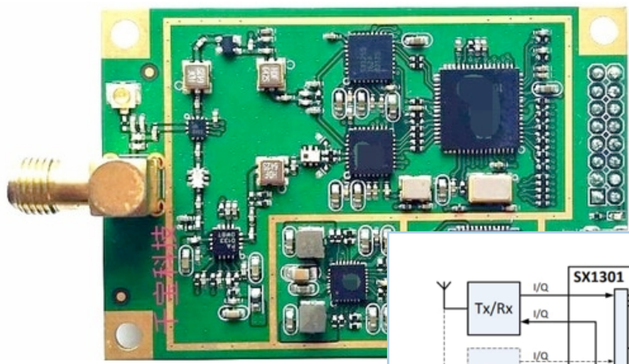
Figure from "All About LoRa and LoRaWAN", https://www.sghoslya.com

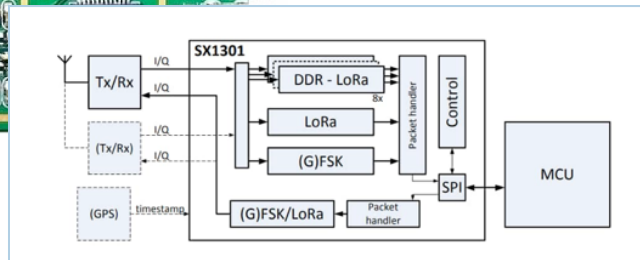
Orthogonal combinations

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

Frequency + SF diversity

- Full LoRaWAN gateway
- Frequency diversity
- Use hardware LoRa concentrator (i.e. SX1301)
- Can listen on 8 channels with SF diversity
- Impact of frequency plans





EU863-870 (THE THINGS NETWORK)

Uplink:

1. **868.1** - SF7BW125 to SF12BW125
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7. **867.7** - SF7BW125 to SF12BW125
8. **867.9** - SF7BW125 to SF12BW125
9. **868.8** - FSK

LoRa Alliance

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

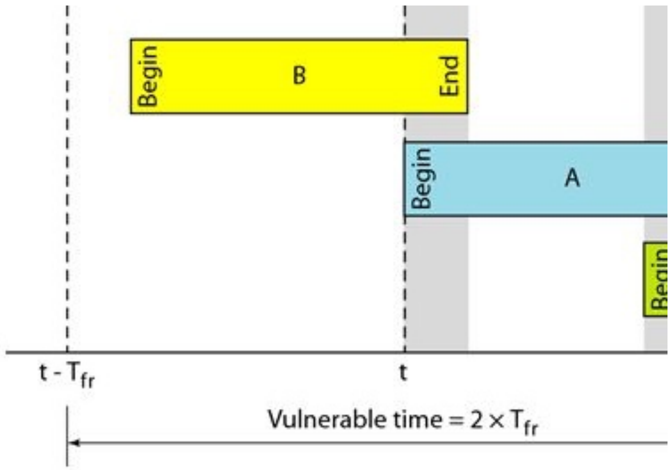
Towards more frequency diversity

- 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		√		√	√	√

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

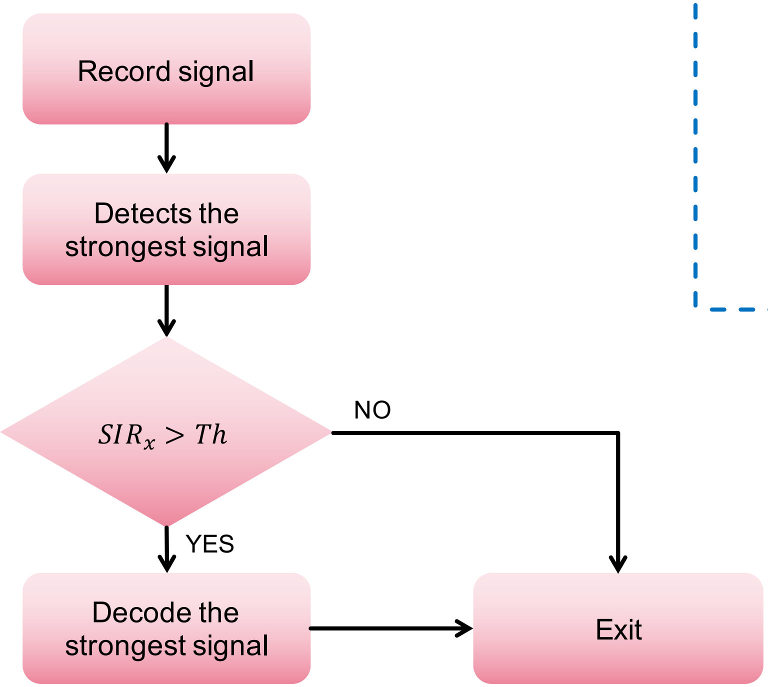


Capture effect in LoRa

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



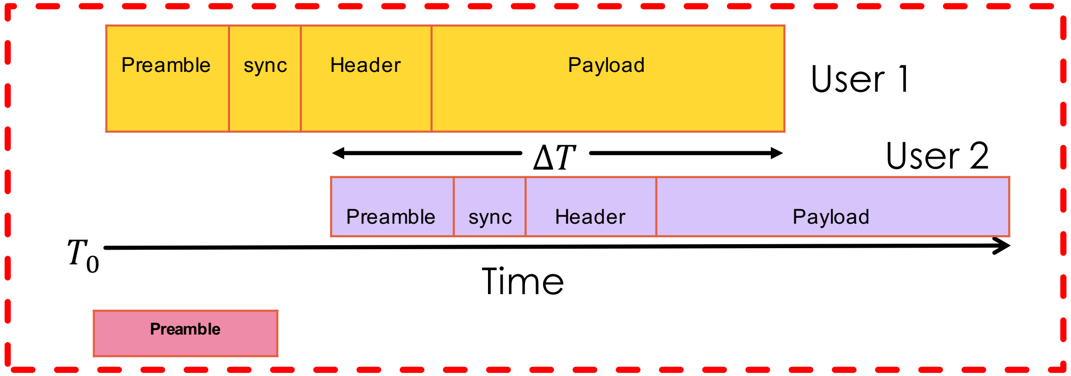
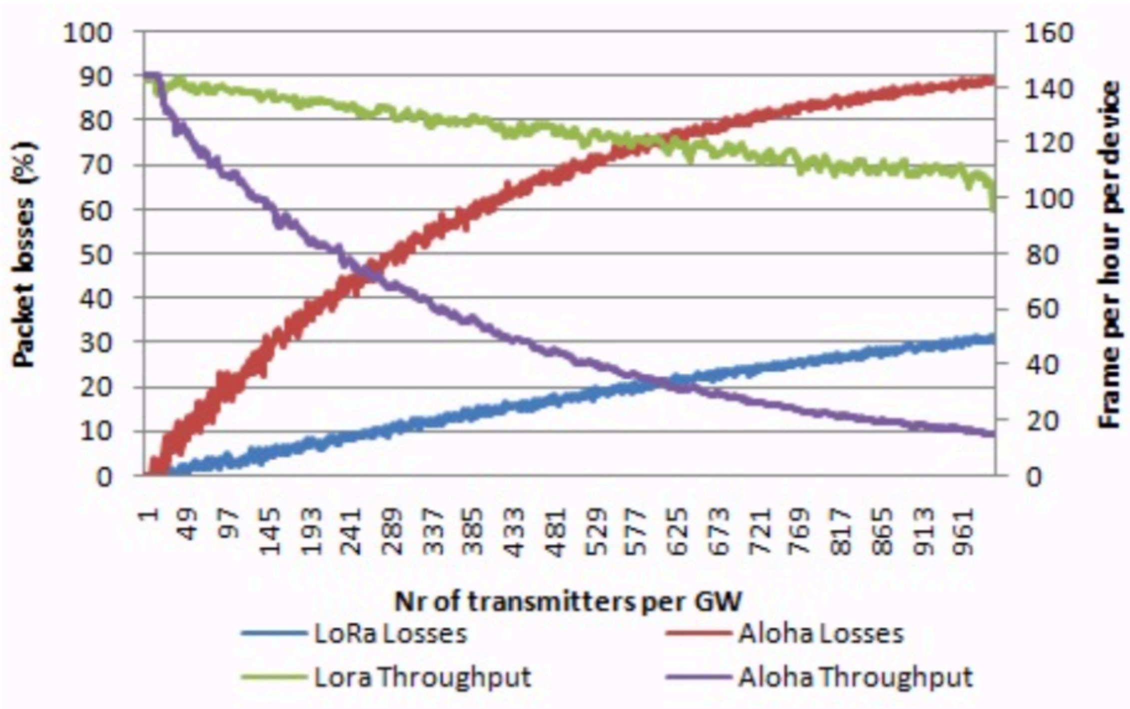


Figure from Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

In theory…

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

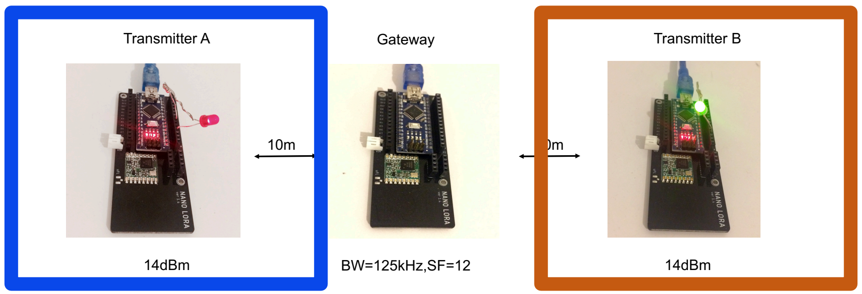


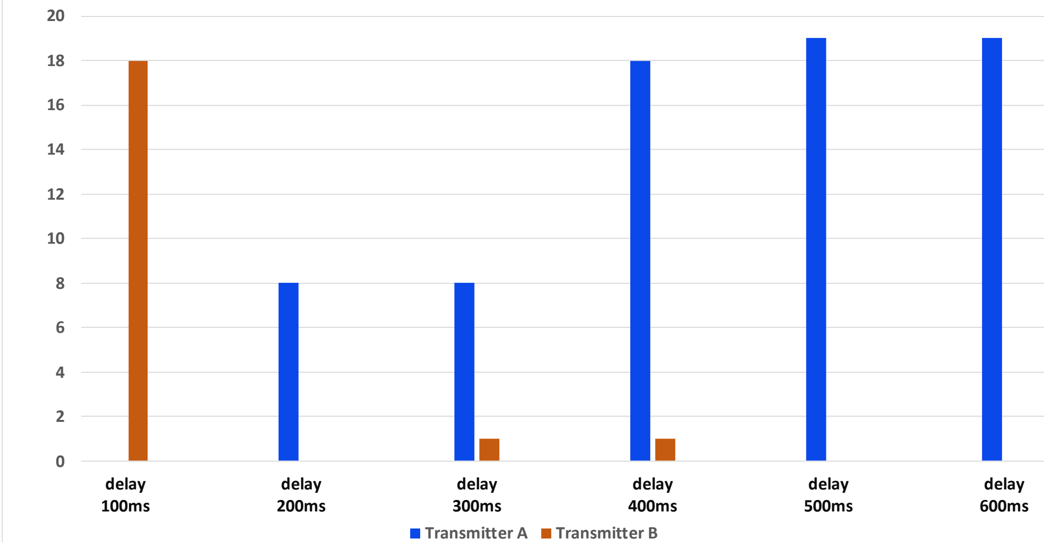
Jetmir Haxhibeqiri, Floris Van den Abeele, Ingrid Moerman and Jeroen Hoebeke. LoRa Scalability: A Simulation Model Based on Interference Measurements. In *Sensors* 2017, *17.*

In practice: with 2 nodes

- 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

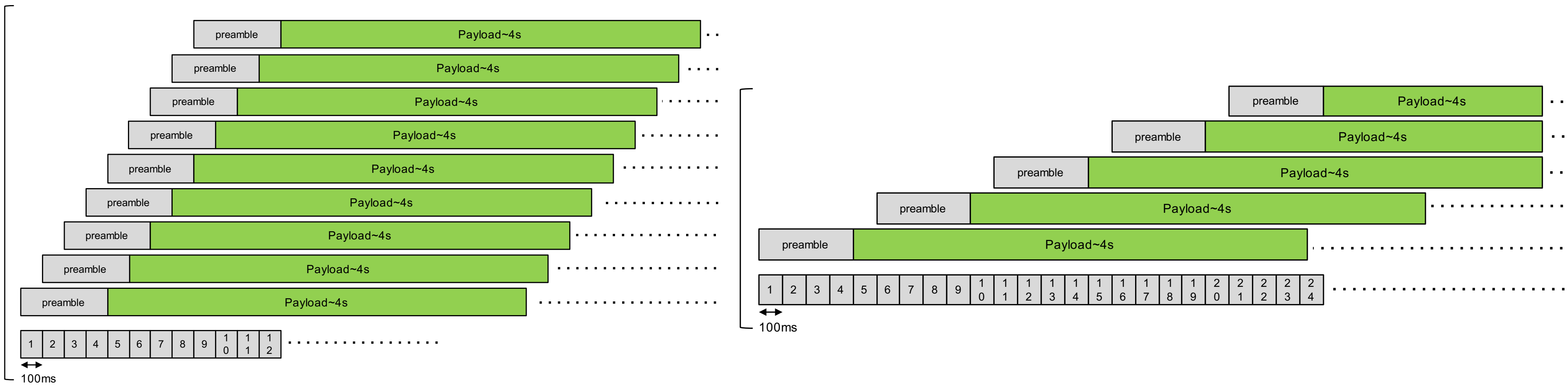
Concurrent transmission during preamble should be avoided
Concurrent transmission after preamble is inefficient but not that harmful





In practice: with high traffic load

- When there are many overlapping transmissions, Capture Effect is not able to help ☹
- Most of packets are corrupted!
- Neither first nor last packet seems to have higher reception probability!



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

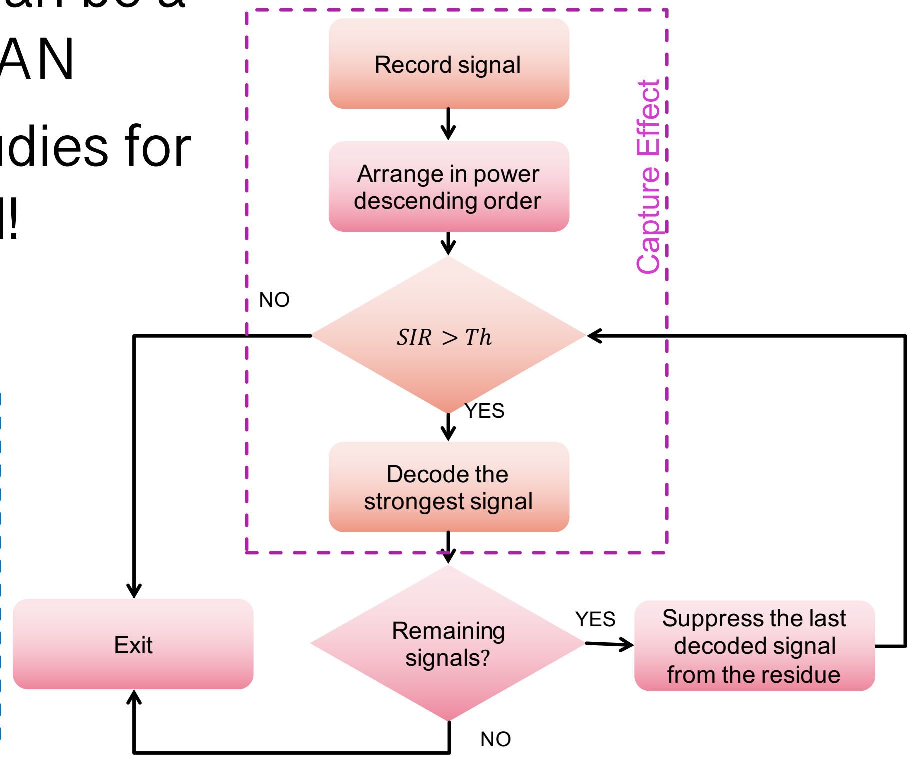


Figure from Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

LoRa with CE and SIC

- Again, in theory...

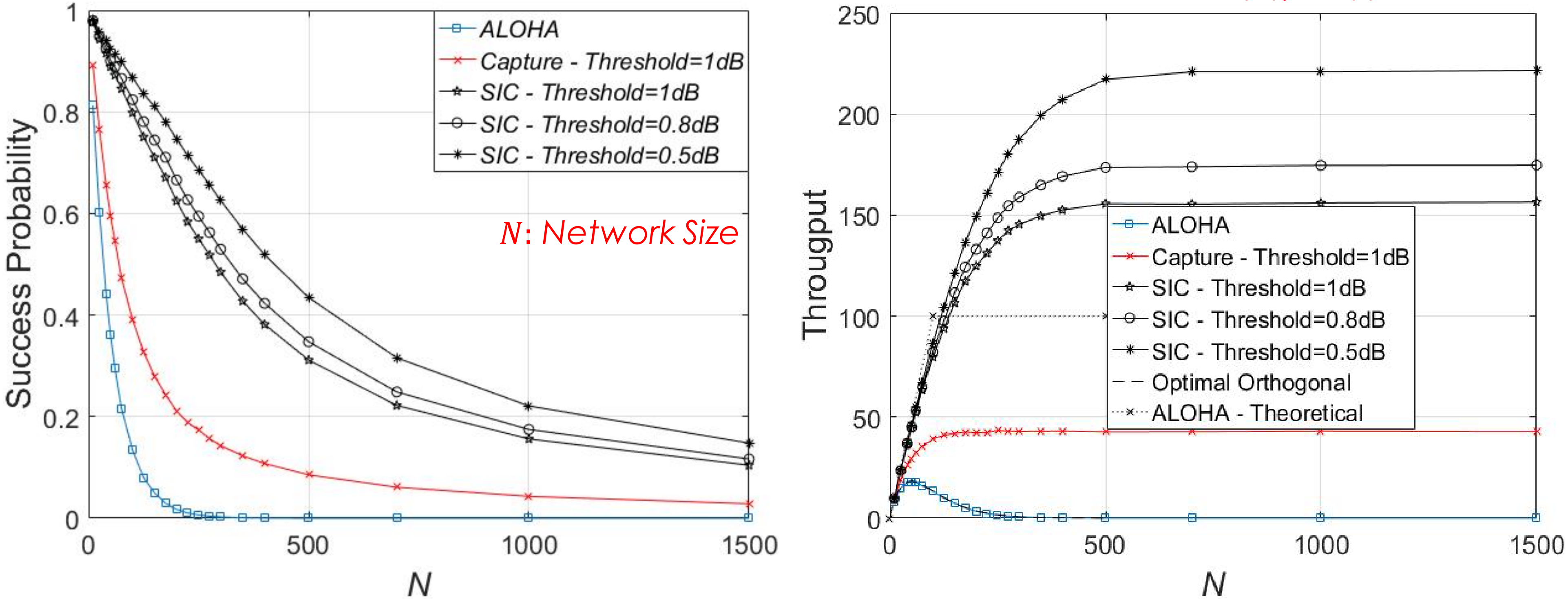


Figure from Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

How dense is dense LoRa?

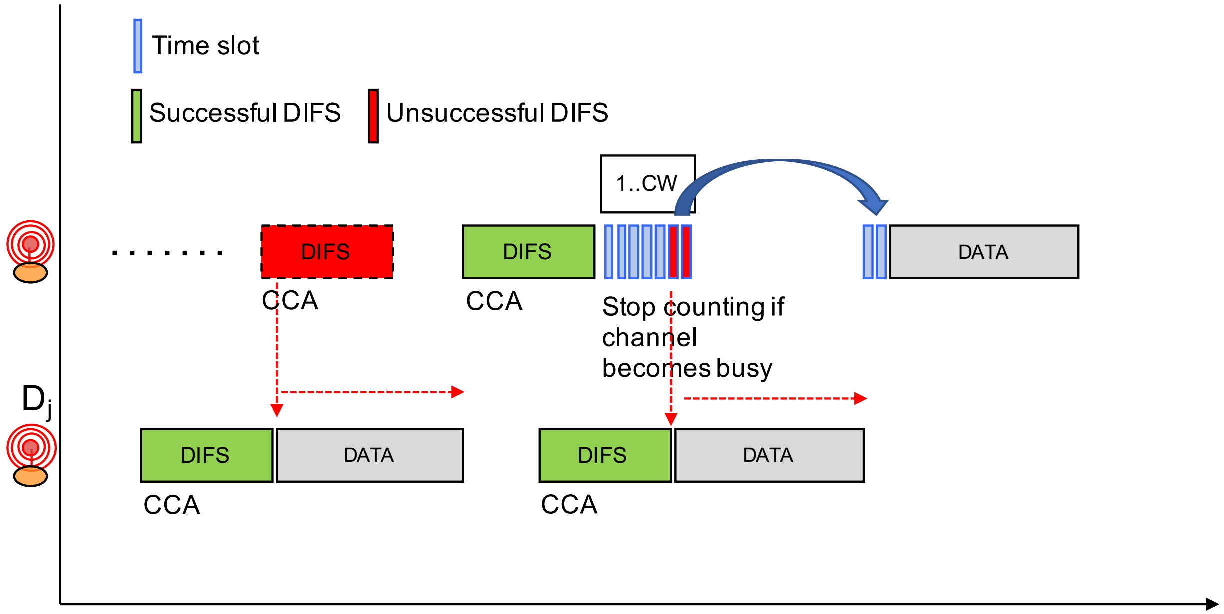
- Considering uniform usage of SF7 to SF12 is in practice not true: usage of high SF values is most likely to be prominent
- SF12 provides the highest receiver sensibility but at the cost of highest transmission time

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

- Vulnerable time would be close to 3s
- 1 msg/20min/node = 3 msg/hour/node
- With 400 nodes = 1 msg every 3s
- 400 nodes at SF12, success probability is already very low!
- For more than 400 devices, capture effect will bring no benefit!

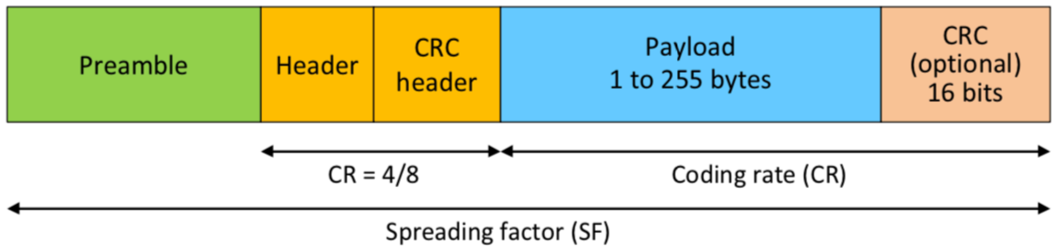
What about Carrier Sense approach?

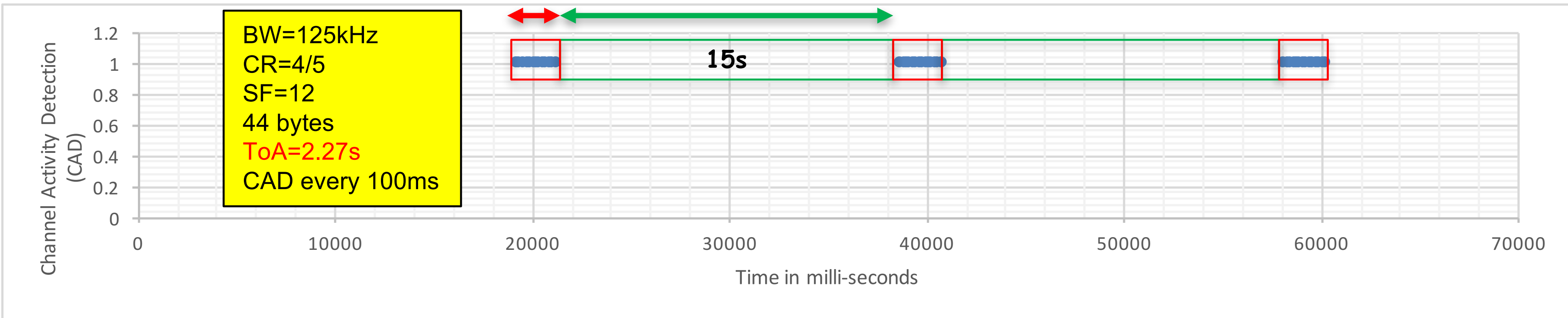
- Can we implement Listen-Before-Talk or Carrier Sense?
- Ex: Carrier Sense Multiple Access/Collision Avoidance in WiFi
  - CSMA/CA in DCF mode with DIFS, SIFS
  - Clear Channel Assessment: is radio channel free?
  - Random backoff [0..W[

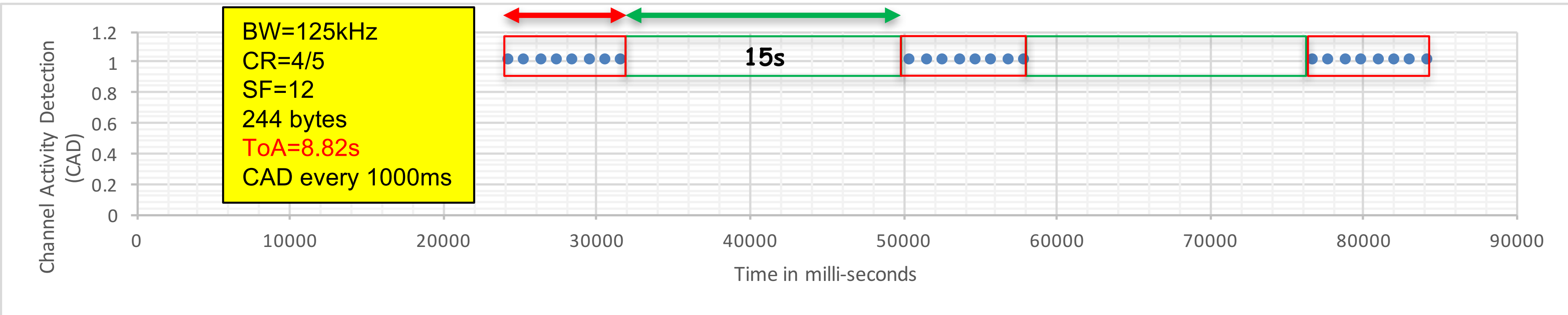


CCA with LoRa

- LoRa's Channel Activity Detection (CAD)

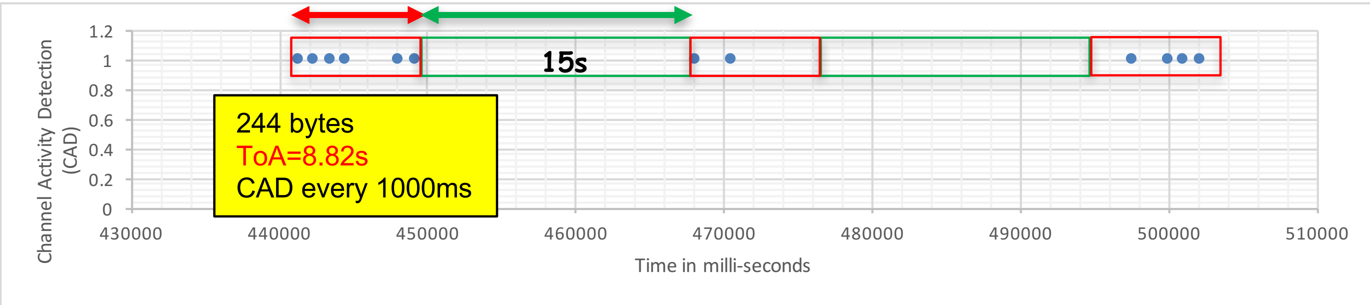




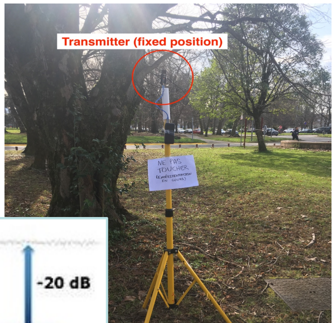


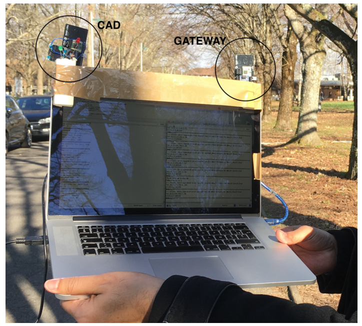
CAD reliability?

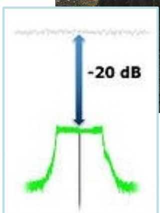
- CAD reliability decreases as distance increases
  - A CAD returning false does not mean that there is no activity!
  - Similar to hidden terminal issue

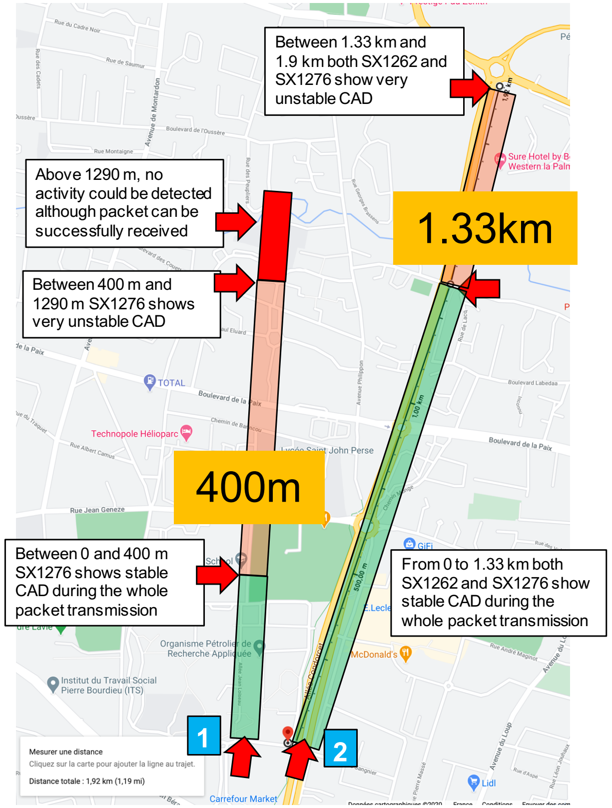


- CAD sensitivity not as good as full reception sensitivity
- CAD returns "no activity" but packet can be received!
- Because LoRa can receive below noise flow!



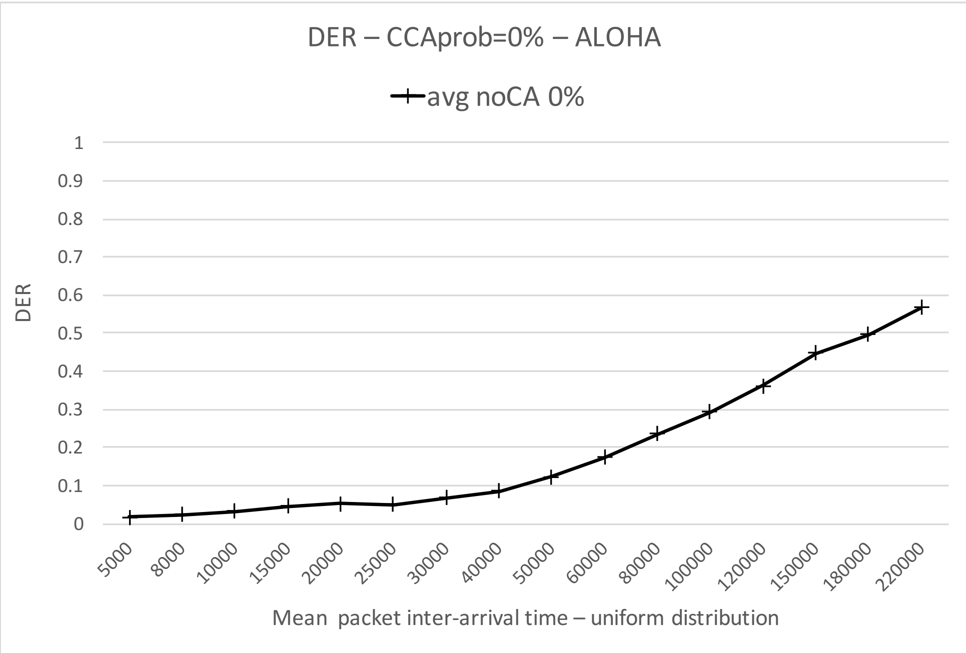


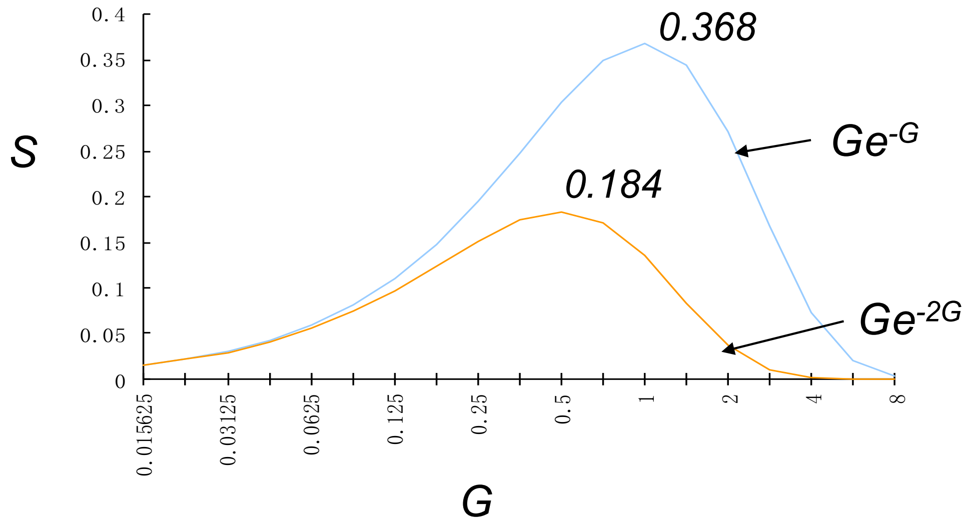




LoRa = ALOHA?

- With unreliable CCA and inefficient Capture Effect, channel access is limited to ALOHA
- 20 nodes, T_{pkt}=4s, packet inter-arrival time [5s, 220s]
- Data Extraction Rate= nb_pkt_received/nb_pkt_sent

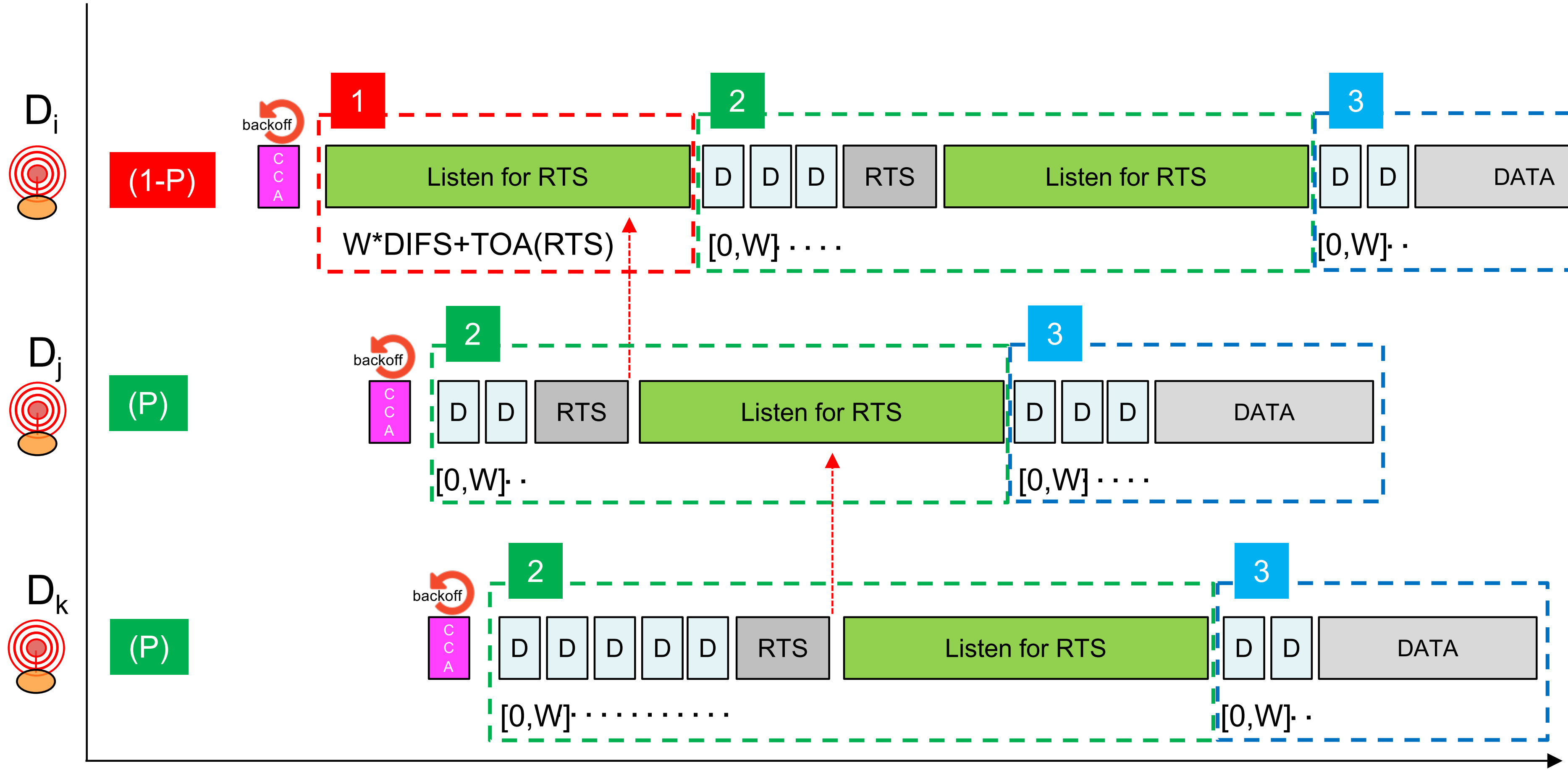




What can be done?

- It is not possible to entirely rely on CCA
- A Request to Send (RTS) approach can provide collision avoidance mechanism as in WiFi RTS/CTS
- RTS/CTS is very costly, so use only RTS. A node willing to send first issue a very short RTS packet
- To receive an RTS indicating a future data transmission, a node willing to transmit needs first to listen for an RTS
- Correct reception of RTS(data_size) can enable a Network Allocation Vector mechanism (wait for a known time interval)
- While the majority of transmitter nodes should start by listening for an RTS, a minority proportion should start by sending the RTS
- Therefore, a node willing to transmit will first determine whether it will start listening for RTS or start sending the RTS
- **Goal: maximize overlapping RTS transmission with listening for RTS**

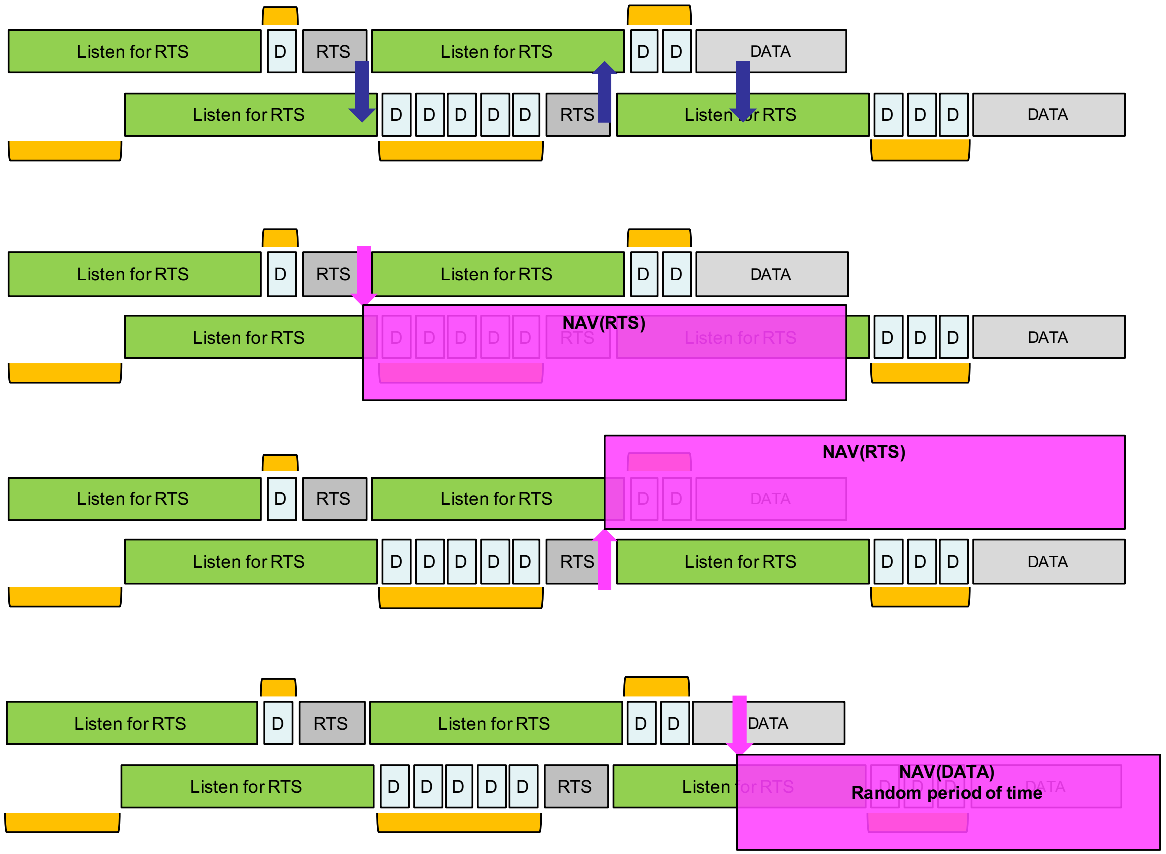
Proposed collision avoidance (CA)



Keep a small proportion of nodes starting directly at phase 2. P=10% for instance

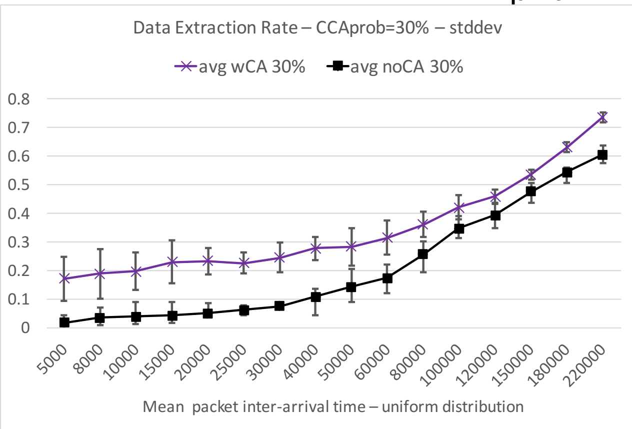
Maximizing transmit/listen overlap

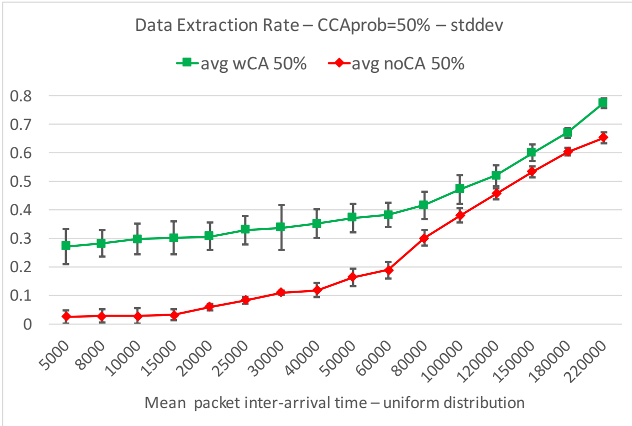
- Random timers (orange blocks) to maximize overlap
- Somehow similar to neighbor discovery or schedule-sharing

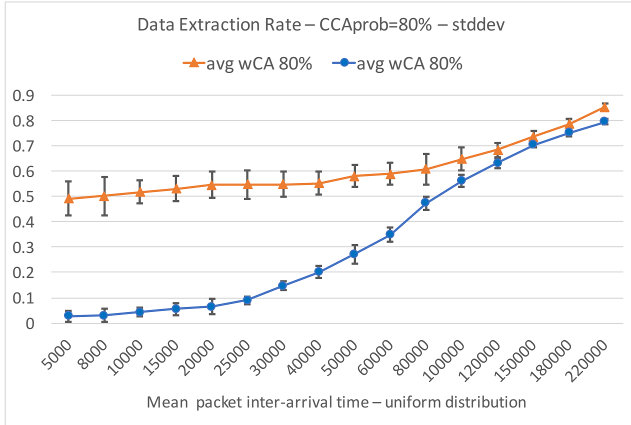


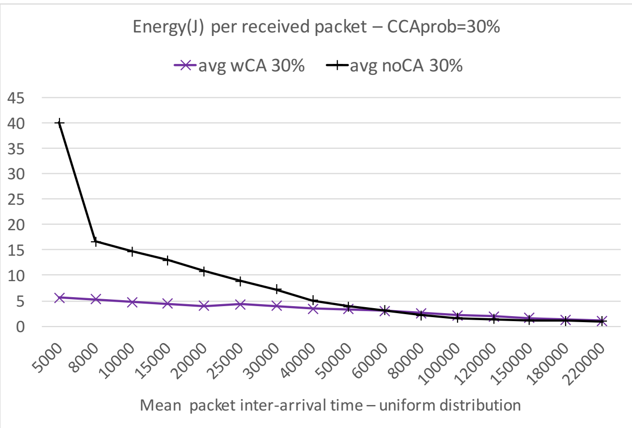
Data Extraction Rate: CA vs CSMA

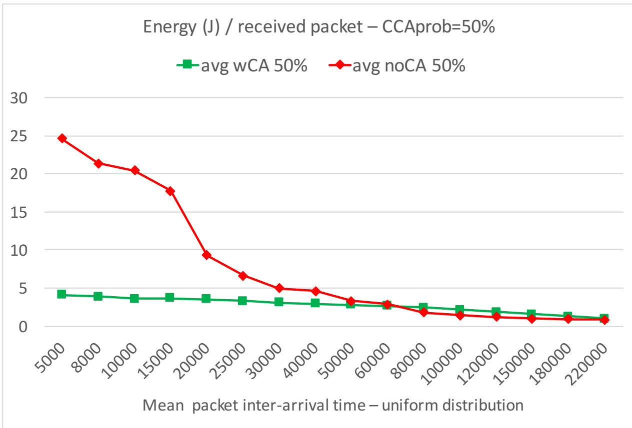
- CCAprob=30%, 50% or 80% (ability to detect radio activity)
- 20 nodes, T_{pkt}=4s, packet inter-arrival time [5s, 220s], DER

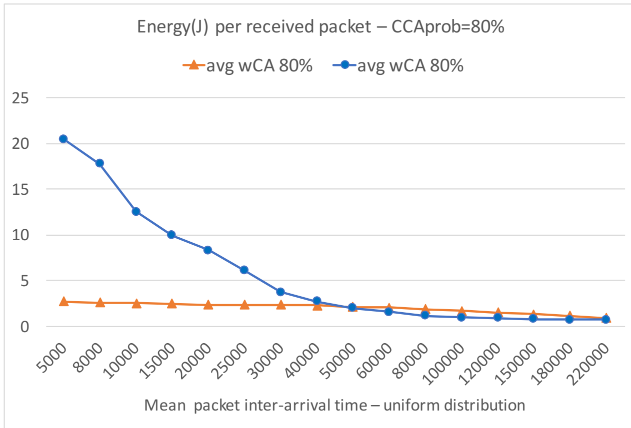






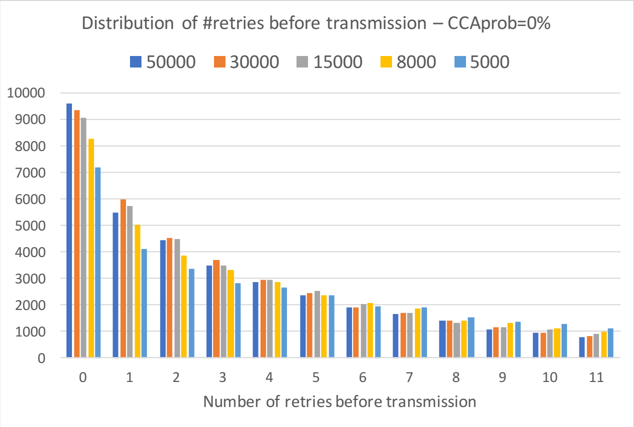


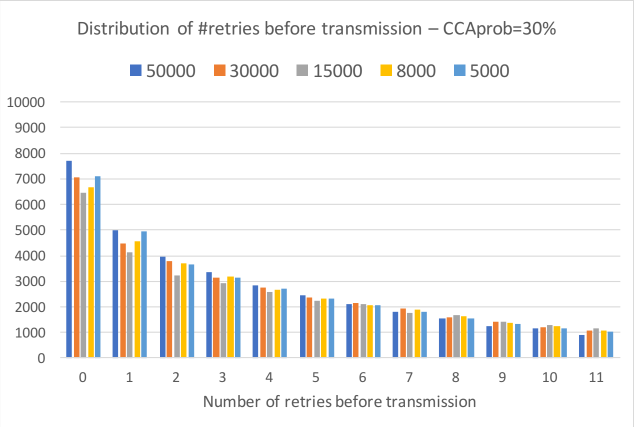


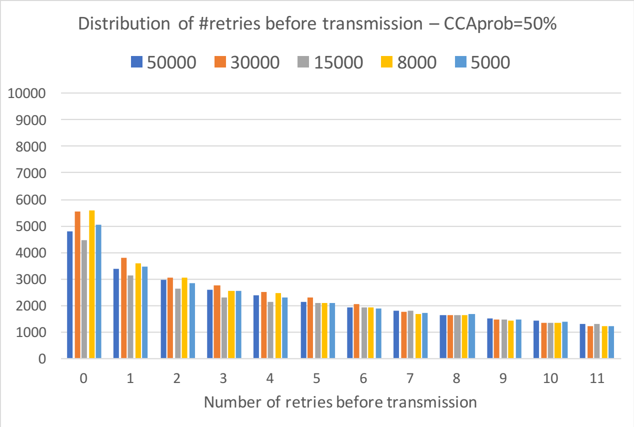


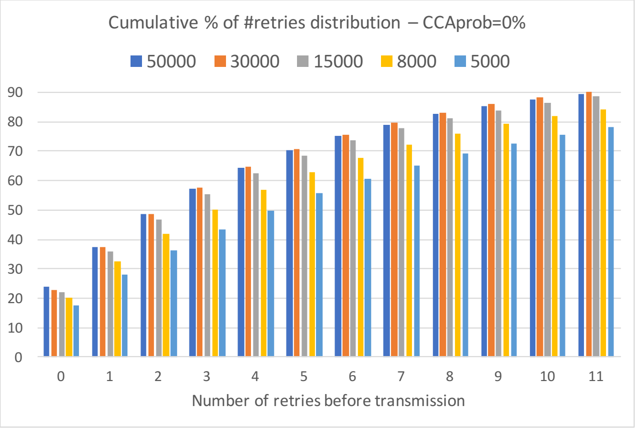
How many retries?

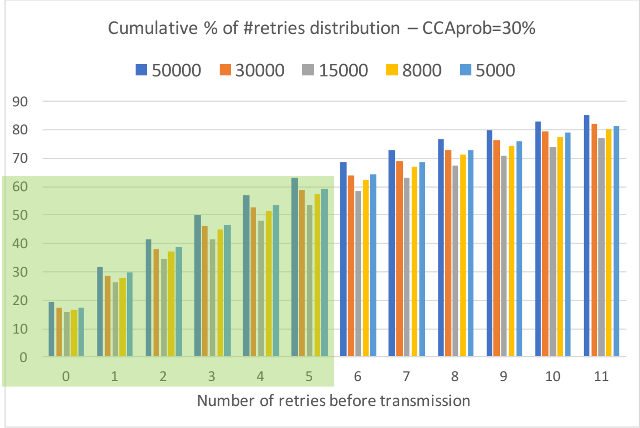
- CCAprob=0%, 30%, 50% (ability to detect radio activity)
- 20 nodes , T_{pkt}=4s, packet inter-arrival time [5s, 220s], #retries

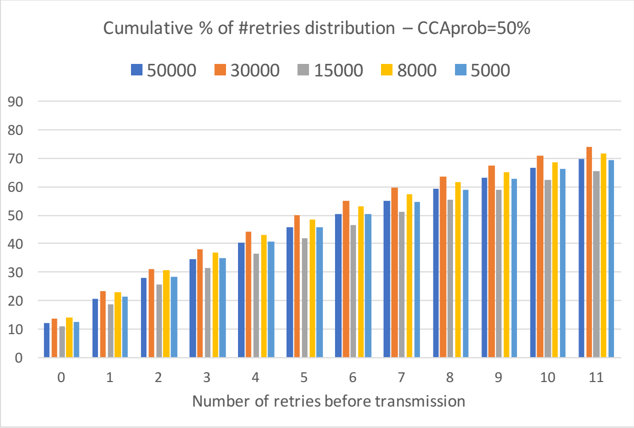






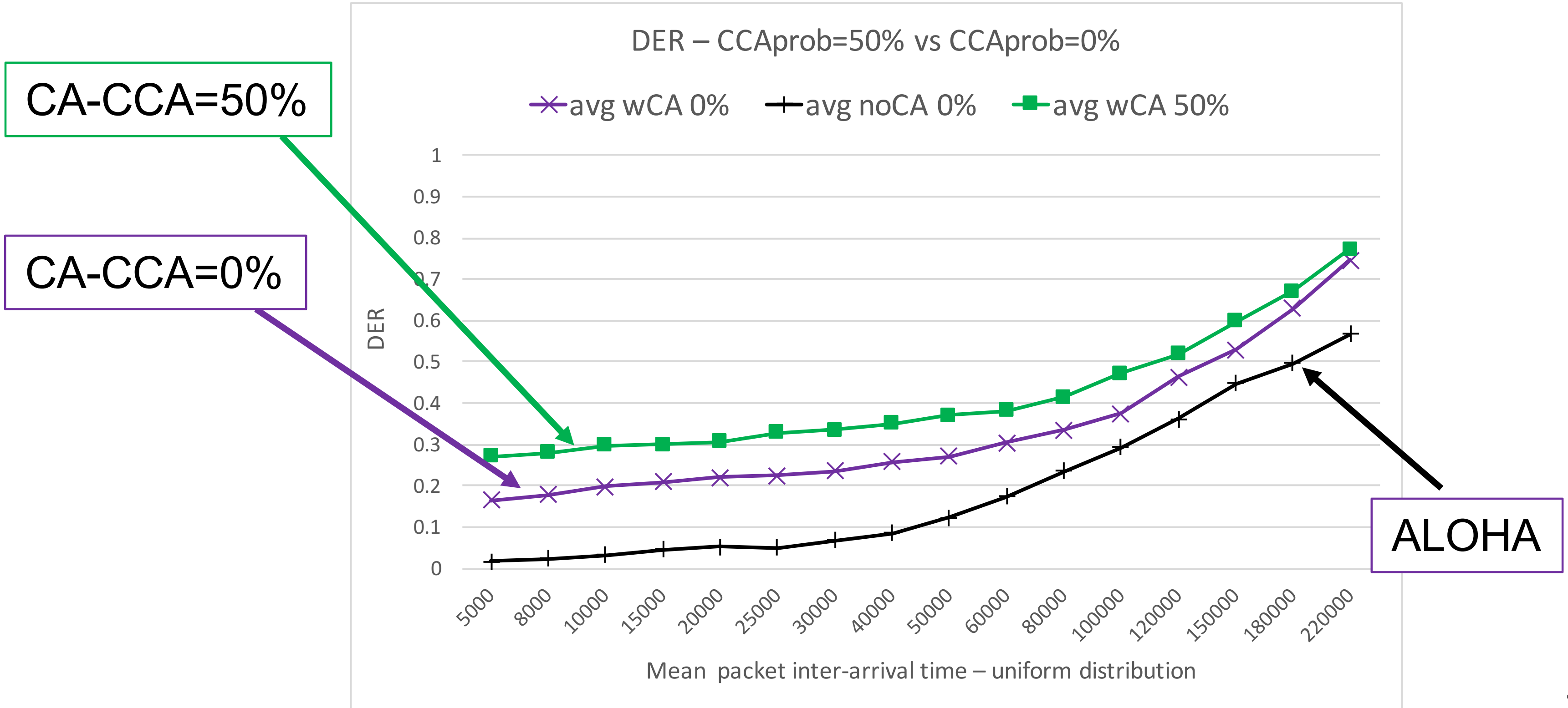






Completely disabling CCA

- Proposed CA when disabling CCA (purple) can still maintain a higher DER
- 20 nodes, T_{pkt}=4s, packet inter-arrival time [5s, 220s],



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
- 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)
- Efficient channel access is challenging
  - Due to LPWAN PHY modulations, CCA is unreliable
  - Difficulty to go beyond ALOHA system
- But, new perspectives in
  - Adapting Neighbor Discovery protocols
  - Investigating cyclic differential set (CDS) to maximize overlap period

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Scalability of LoRa Networks for Dense IoT Deployment Scenarios: limitations and perspectives

Presented on February 2nd, 2021

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