Scalability of Deployed LoRa networks

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IoT – from idea to reality

LoRa? What is it for?

- LoRa is one long-range radio technology to connect low power IoT devices

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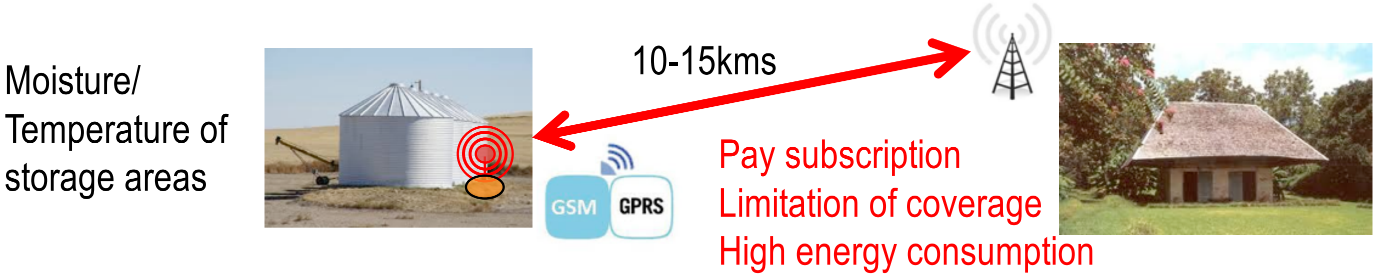
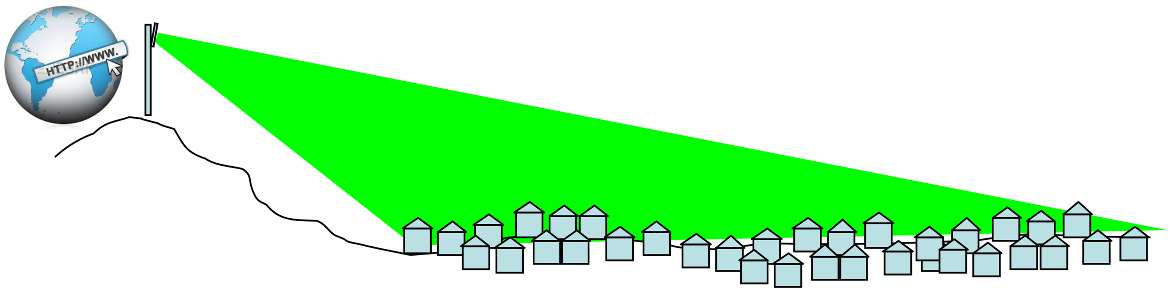
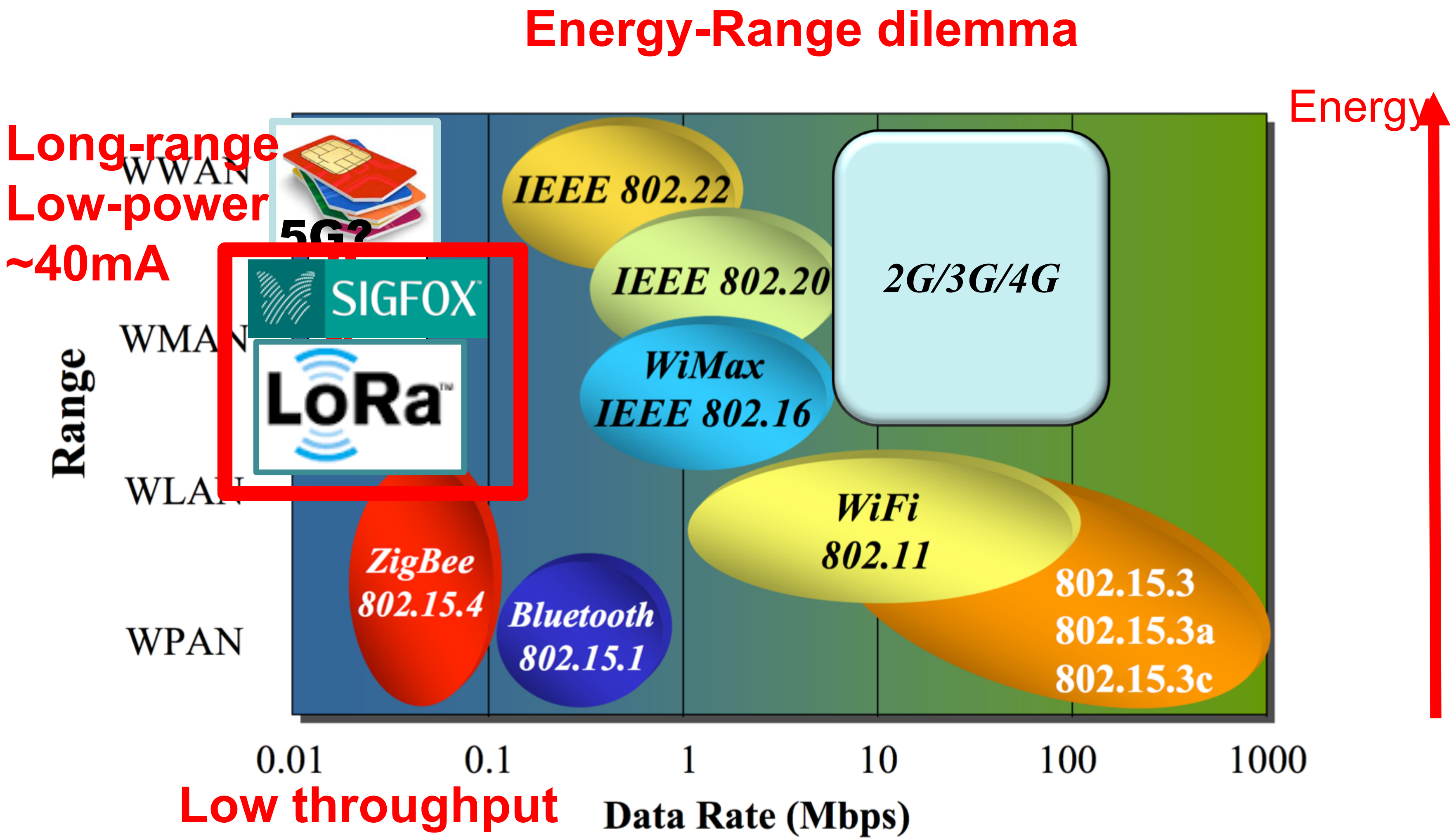
Long-range sensing





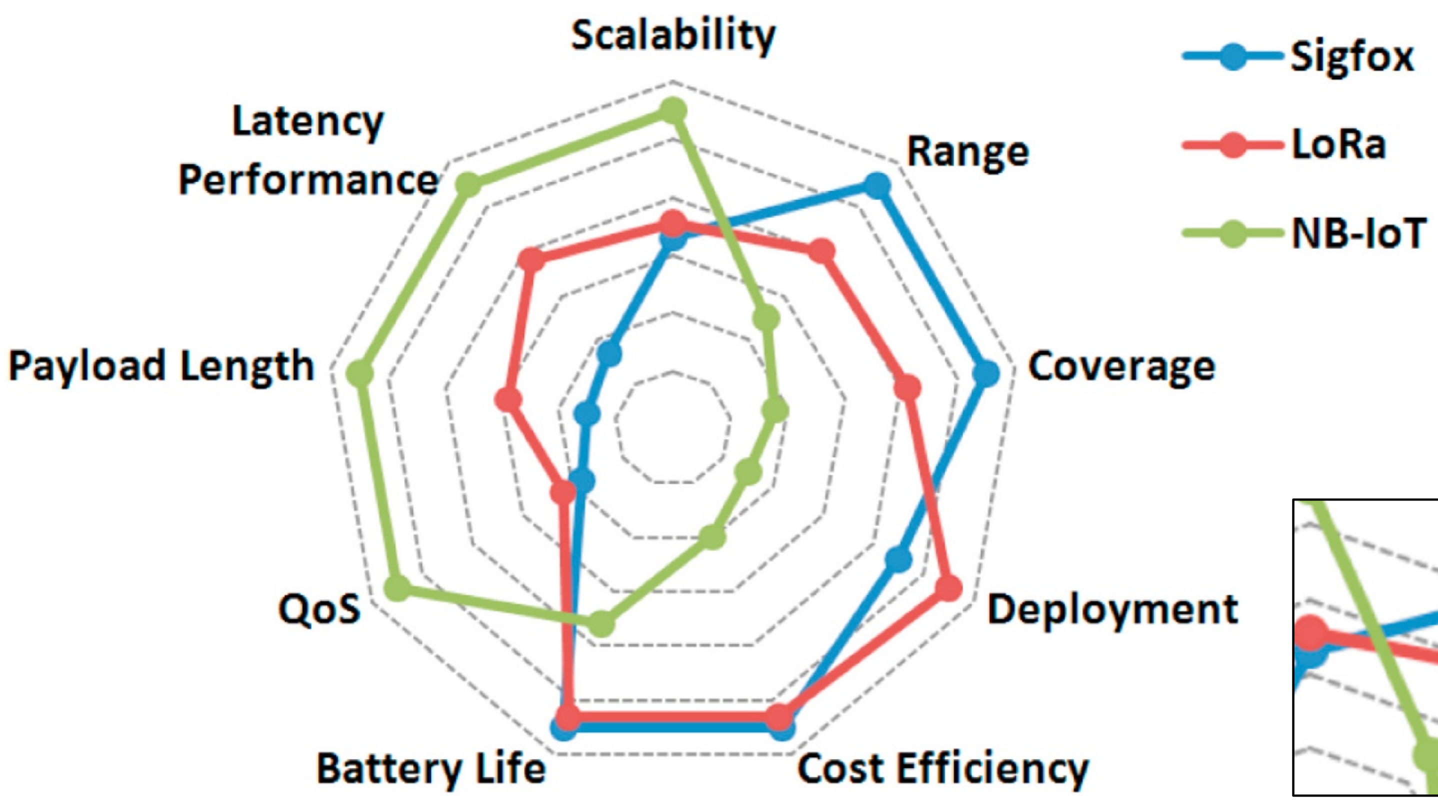
Technology	2G	3G	LAN
Range (I=Indoor, O=Outdoor)	N/A	N/A	O: 300m I: 30m
Tx current consumption	200-500mA	500-1000mA	100-300mA
Standby current	2.3mA	3.5mA	NC

Low-power & long-range radio technologies



Other "long-range" technologies

Expected range?



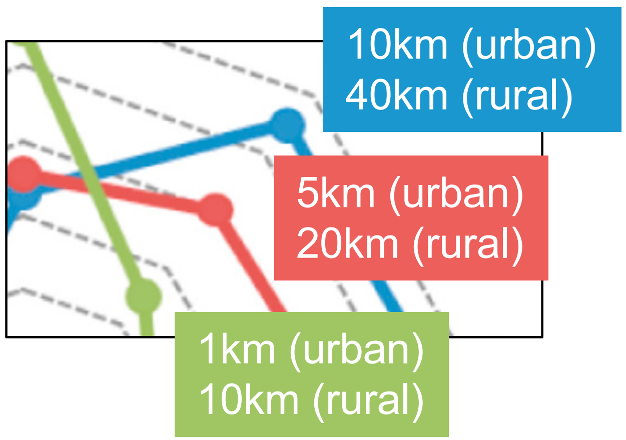
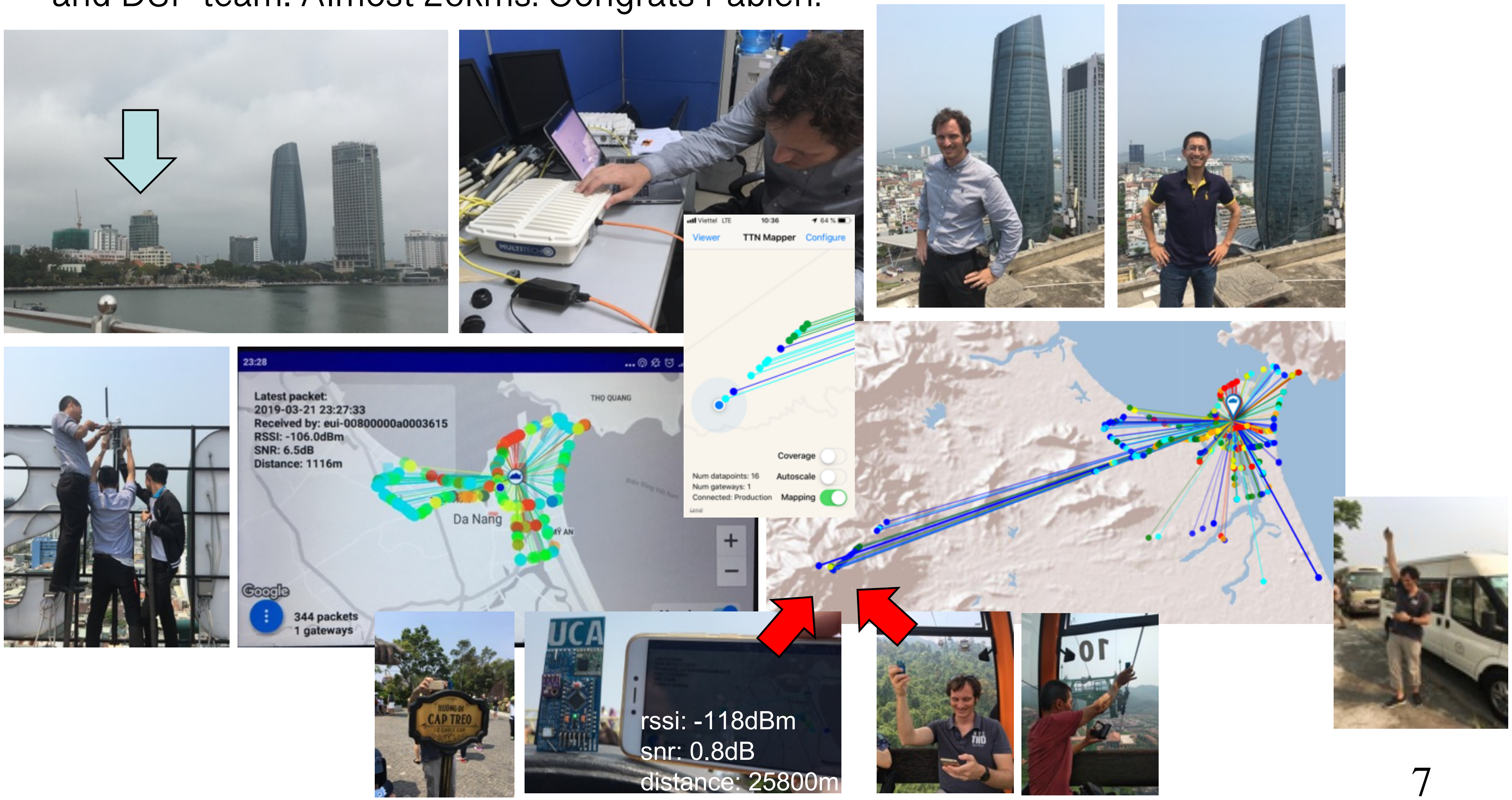


Figure from Kais Mekki, Eddy Bajic, Frederic Chaxel, Fernand Meyer,
A comparative study of LPWAN technologies for large-scale IoT deployment,
ICT Express, Volume 5, Issue 1, 2019.

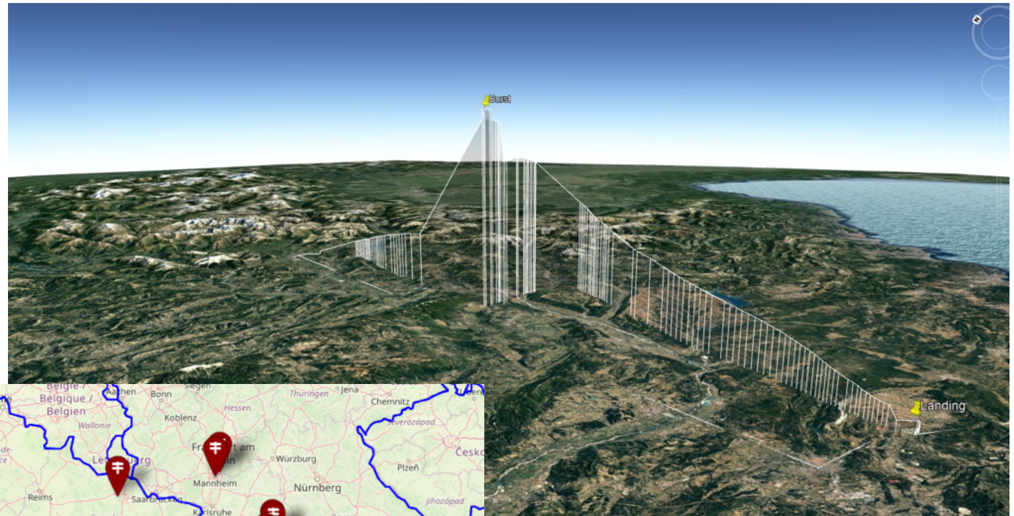
Coverage test by Fabien Ferrero on March 21-22, 2019

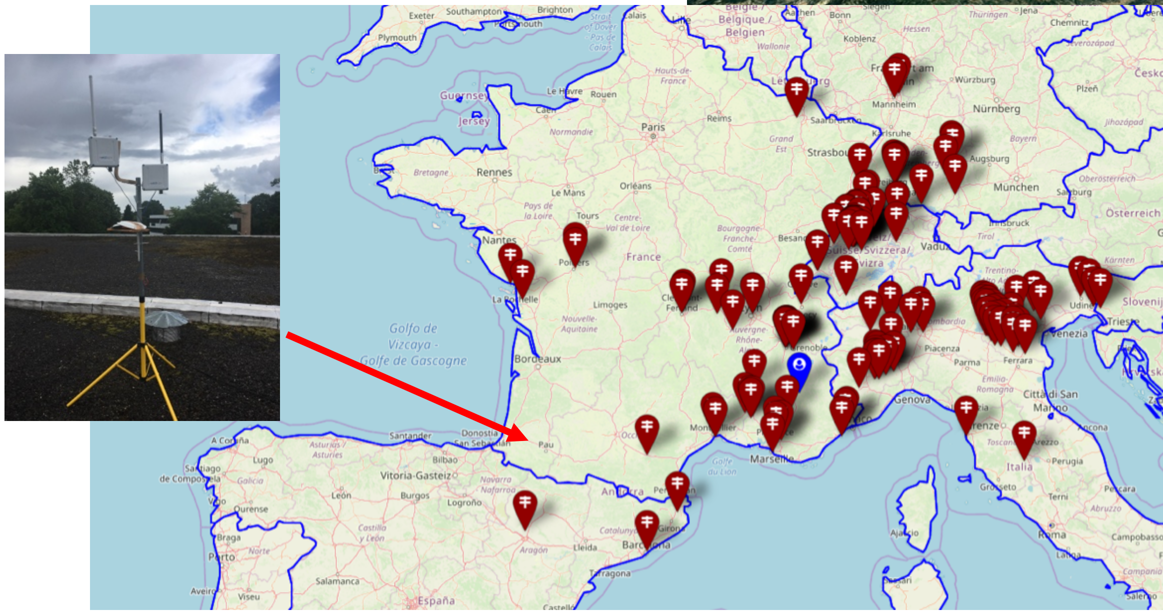
- LoRaWAN gateway on top of Danang's DSP building by Fabien, U. Danang and DSP team. Almost 26kms! Congrats Fabien!



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!

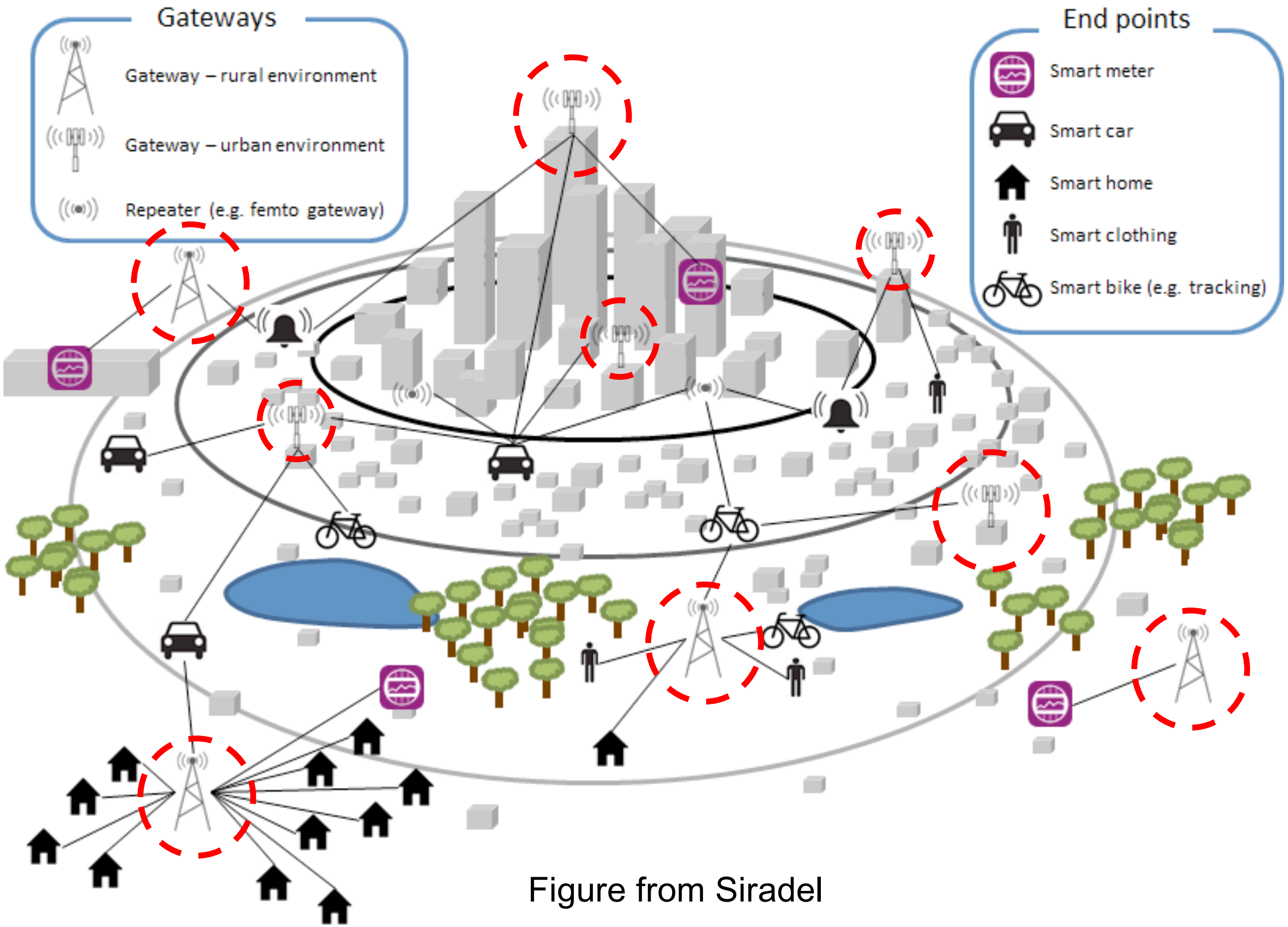


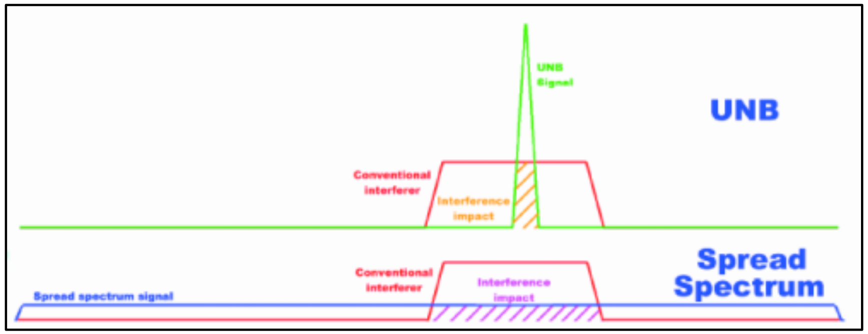
Figure from Siradel

Increasing range?

- Increase TX power and improve RX sensitivity
  - Every 6dB doubles range in LoS
  - Every 12dB doubles range in indoor/urban
- RX sensibility can be increased when transmitting (much) slower
- A [Sigfox message is sent relatively slowly in a very narrow band of spectrum (hence ultra-narrow-band) using Gaussian Frequency-Shift Keying modulation]. Max throughput=~100bps
- LoRa also increases time-on-air when maximum range is needed. But LoRa uses chirp spread spectrum (CSS) instead of UNB. 300bps-37.5kbps

SIGFOX

LoRa



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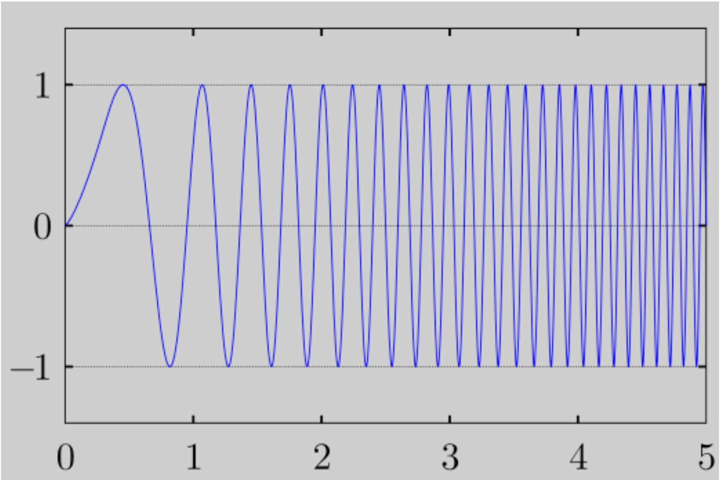
Chirp Spread Spectrum

- Compressed High Intensity Radar Pulse (CHIRP) is a signal which frequency either increase or decrease

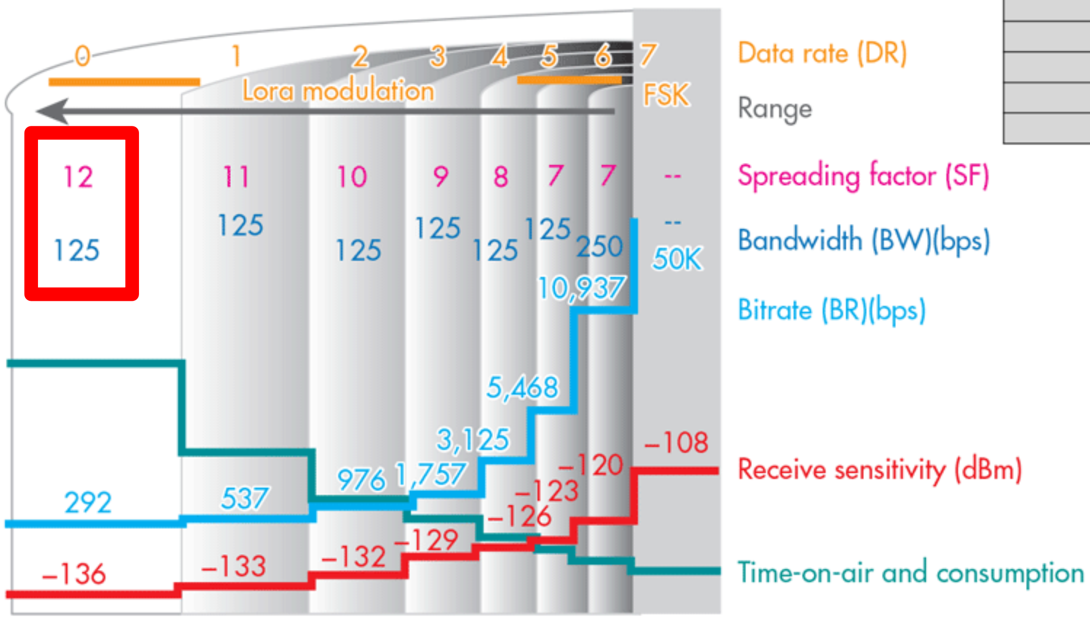


- Can be very low power, but then low data rate
- Very high interference immunity
  - Thus adapted to very large distances
  - Better resistance to frequency shift (e.g. Doppler shift, low-cost oscillator)

Main LoRa parameters

- Common used bandwidth: 125kHz, 250kHz, 500kHz
- Lower BW, i.e. 62.5kHz to 10.5kHz, requires accurate clocks (TXCO)
- Spreading factor: 6 to 12

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



LoRa Data Rate (Rb) Formula : -

$$R_b = SF * \frac{\left[\frac{4}{4+CR}\right]}{\left[\frac{2^{SF}}{BW}\right]} * 1000$$

SF = Spreading Factor (6,7,8,9,10,11,12)
CR = Code Rate (1,2,3,4)
BW = Bandwidth in KHz (10.4,15.6,20.8,31.25,41.7,62.5,125,250,500)
Rb = Data rate or Bit Rate in bps

Chirp Spread Spectrum Modulation

SpreadingFactor (RegModulationCfg)	Spreading Factor (Chips / symbol)	LoRa Demodulator SNR
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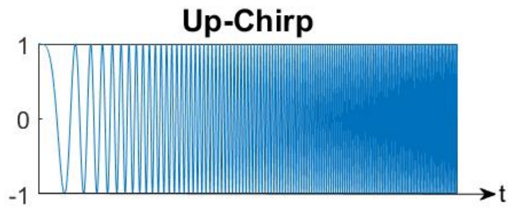
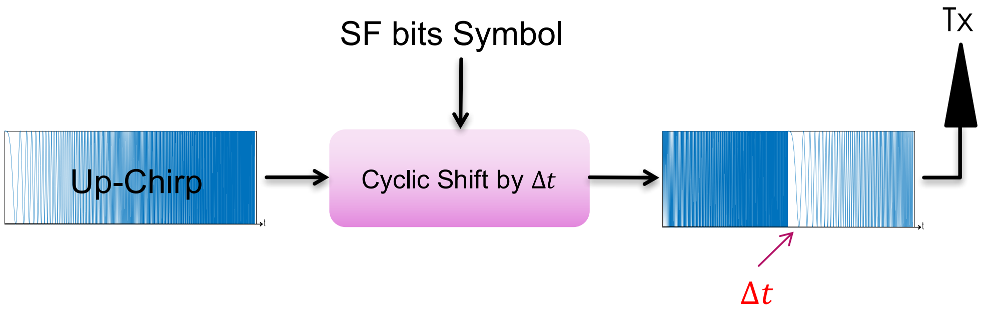


$$C(t) = \begin{cases} \exp(2\pi j(at+b)t) & -\frac{T_s}{2} \le t \le \frac{T_s}{2} \\ 0, & otherwise \end{cases}$$



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

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).

Spreading factor in image

- Higher spreading factor means lower data rate but increased receiver sensibility

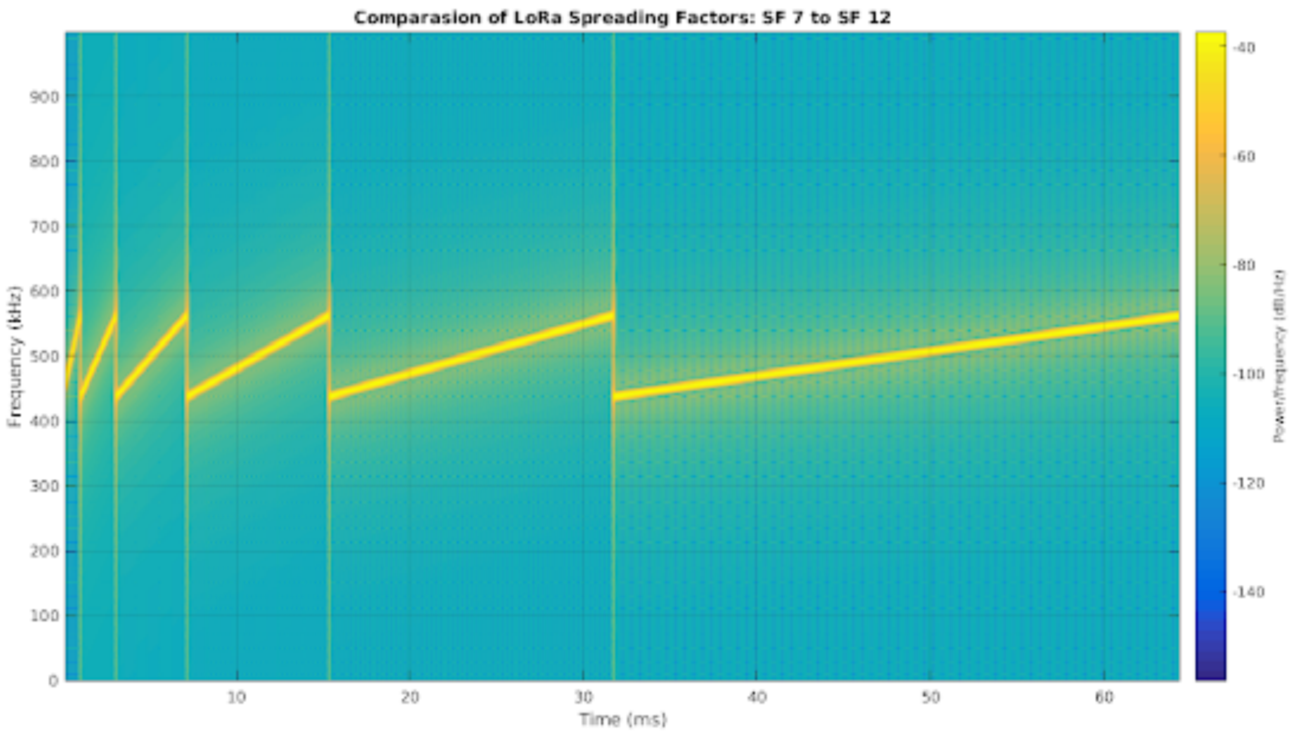
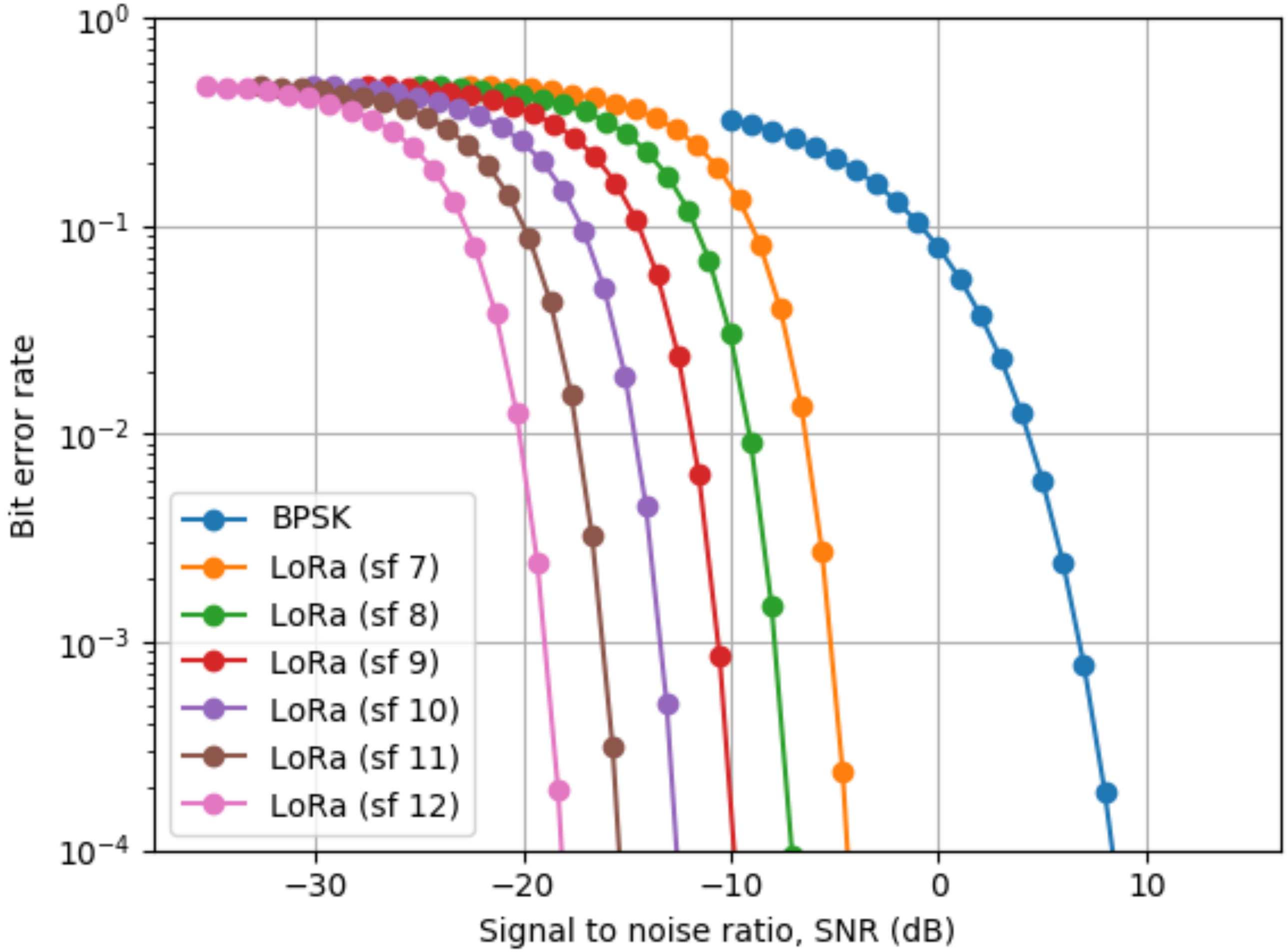


Figure from "All About LoRa and LoRaWAN", https://www.sghoslya.com

BER with various SF



The price to pay!

Very low throughput: 200bps is 0.0002Mbps! WiFi is 54Mbps
Transmission time can be several seconds

Range ↕ Throughput

LoRa mode	BW	CR	SF	time on air in second for payload size of 5 bytes	55 bytes	105 bytes	155 Bytes	205 Bytes	255 Bytes	max thr. for 255B in bps
1	125	4/5	12	0.95846	2.59686	4.23526	5.87366	7.51206	9.15046	223
2	250	4/5	12	0.47923	1.21651	1.87187	2.52723	3.26451	3.91987	520
3	125	4/5	10	0.28058	0.69018	1.09978	1.50938	1.91898	2.32858	876
4	500	4/5	12	0.23962	0.60826	0.93594	1.26362	1.63226	1.95994	1041
5	250	4/5	10	0.14029	0.34509	0.54989	0.75469	0.95949	1.16429	1752
6	500	4/5	11	0.11981	0.30413	0.50893	0.69325	0.87757	1.06189	1921
7	250	4/5	9	0.07014	0.18278	0.29542	0.40806	0.5207	0.63334	3221
8	500	4/5	9	0.03507	0.09139	0.14771	0.20403	0.26035	0.31667	6442
9	500	4/5	8	0.01754	0.05082	0.08154	0.11482	0.14554	0.17882	11408
10	500	4/5	7	0.00877	0.02797	0.04589	0.06381	0.08301	0.10093	20212

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

Higher RX sensibility for higher versatility

Dense urban areas

Rural areas

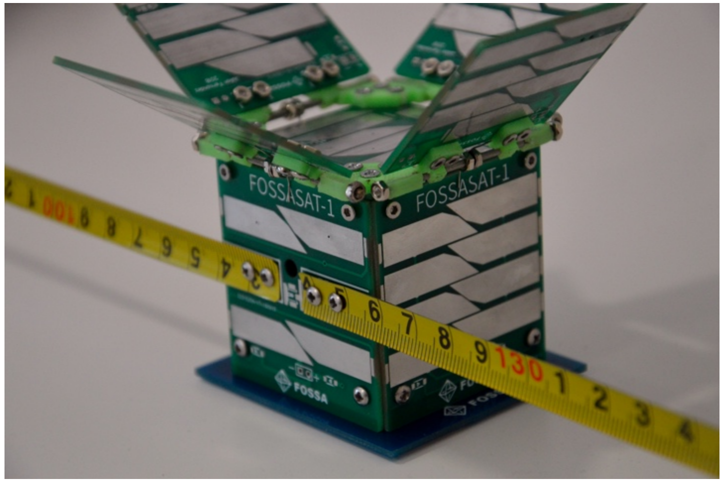
Indoor

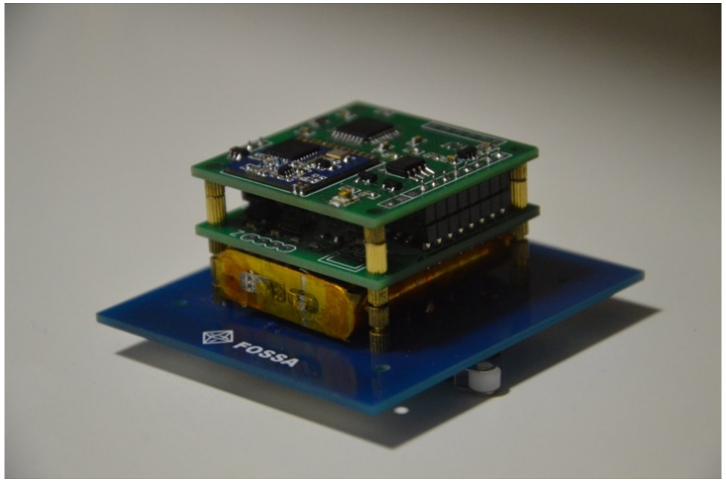
Underground

LoRa with satellites?

- Lots of activity around LoRa IoT <-> satellite <-> LoRa IoT

"FossaSat-1, an Open Source Satellite for the Internet of Things"





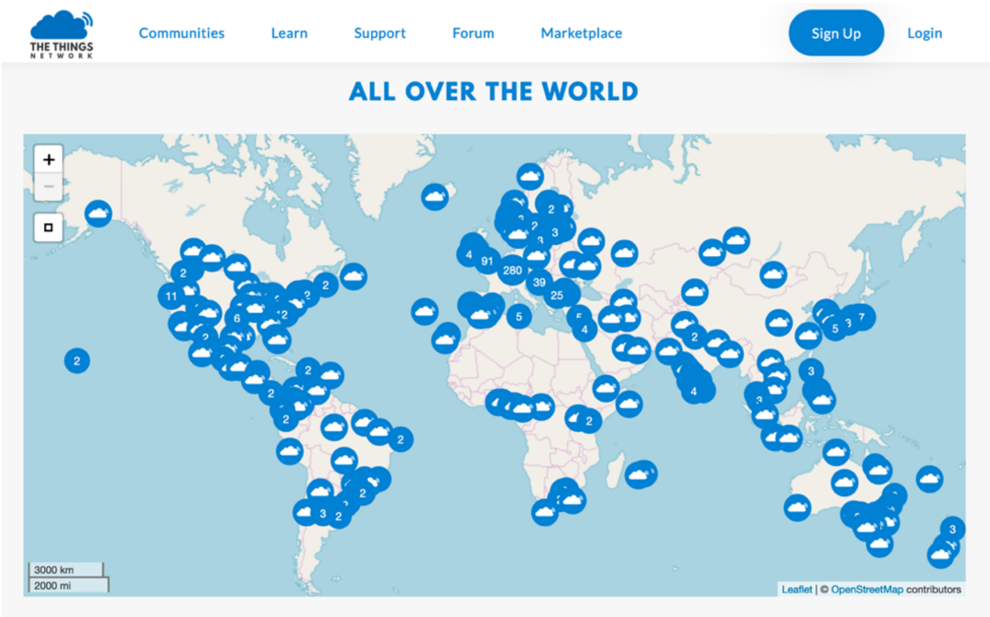
Lacuna Space commits to test IoT satellite system

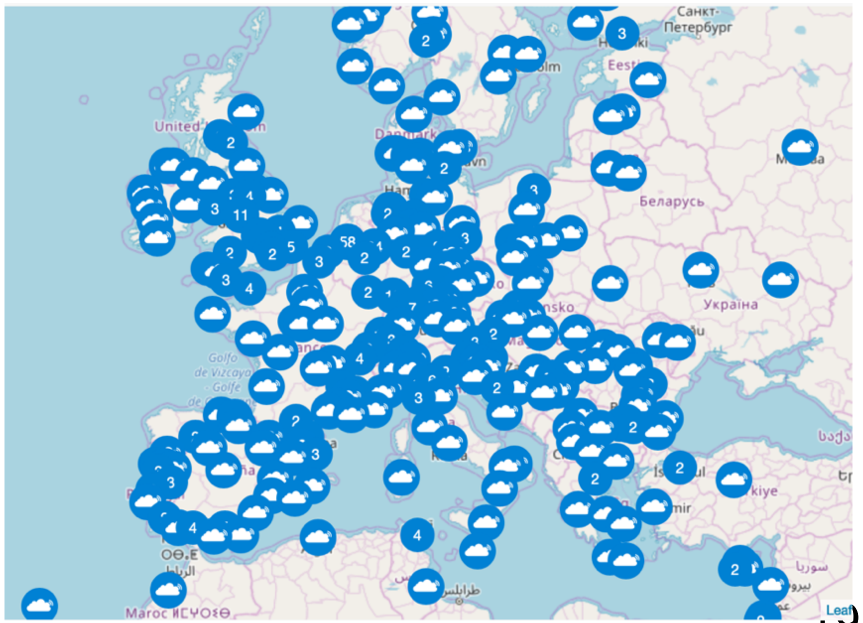
BY DOUG MOHNEY APRIL 30, 2018 IOT, SPACE IT LEAVE A COMMENT

Lacuna Space signed a contract with NanoAvionics to conduct an in-orbit demonstration of an Internet of Things (IoT) network. Testing is set to begin this year using NanoAvionics M6P satellite platform and integration services. Operations are expected to pave the way for Lacuna to deploy a 32 IoT satellite constellation.

LoRa networks boosted by community-based deployments

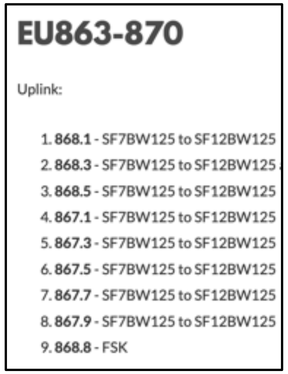
- e.g. TheThingNetwork (TTN)
- Community-based deployment of LoRa gateways (using LoRaWAN stack)
  - User A can buy a LoRa gateway, register it and deploy it
  - User B then creates an account on TTN to register its devices
  - Messages from registered devices received by a TTN gateway will be made available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





LoRaWAN gateway

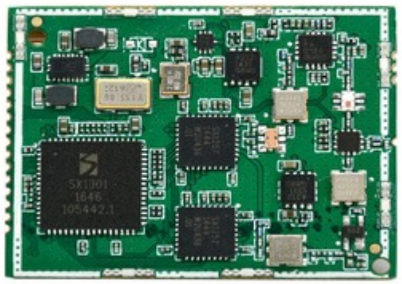
- A full LoRaWAN gateway should be able to listen on multiple channels and spreading factors

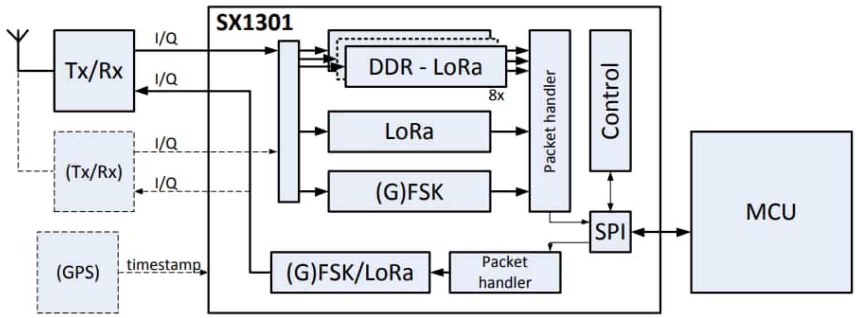

EU863-870

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





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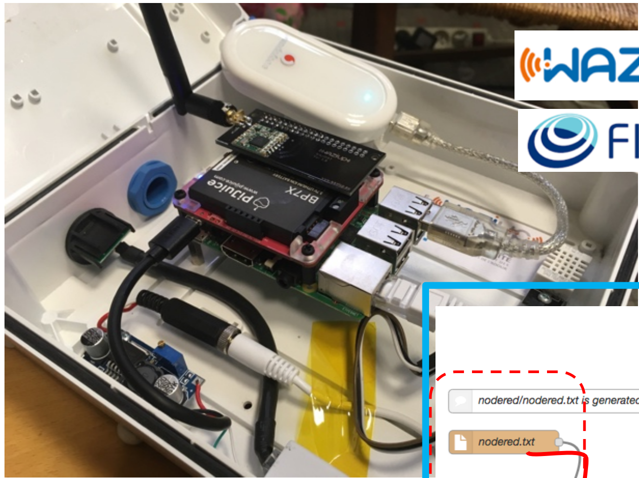
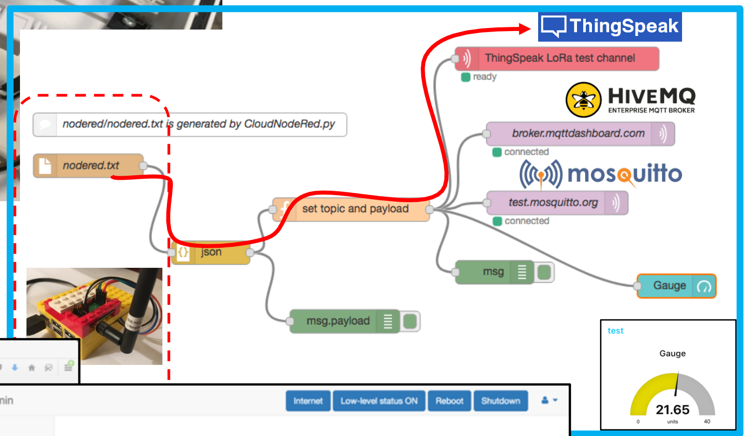
Open, DIY, versatile IoT gateway

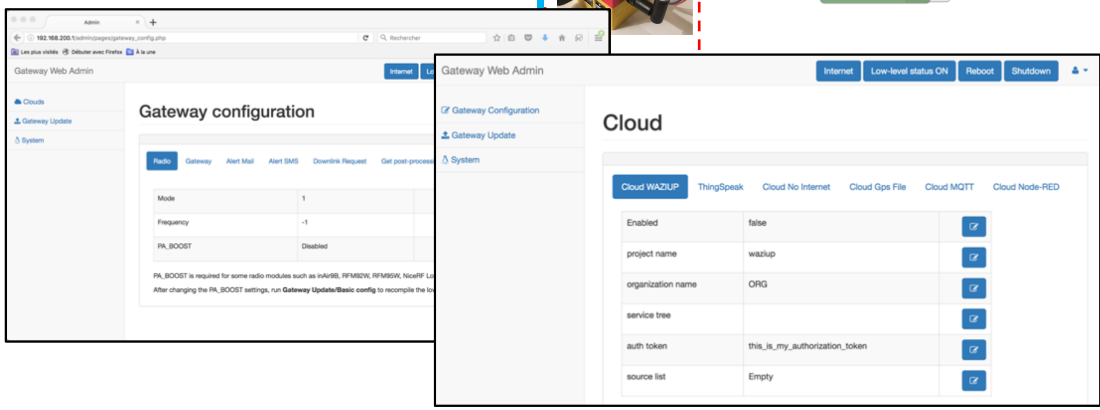
Large customization features

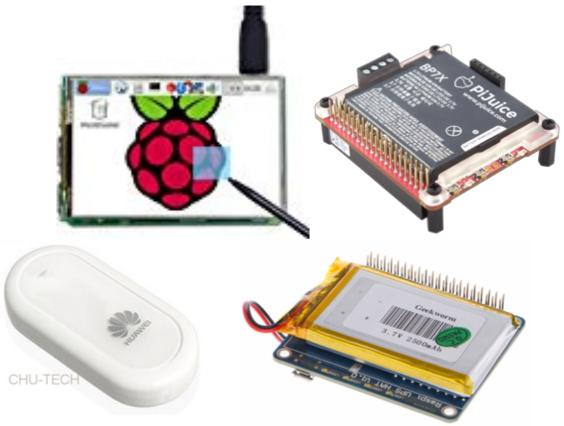
https://github.com/CongducPham/LowCostLoRaGw



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

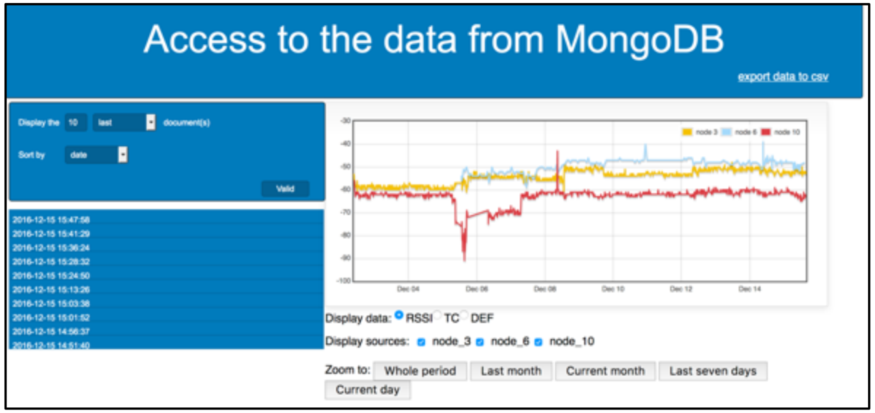


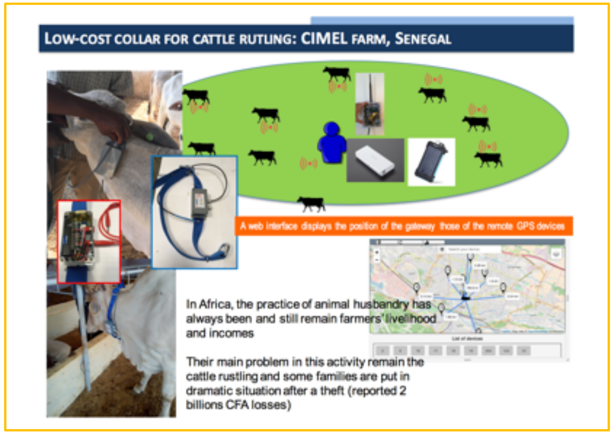


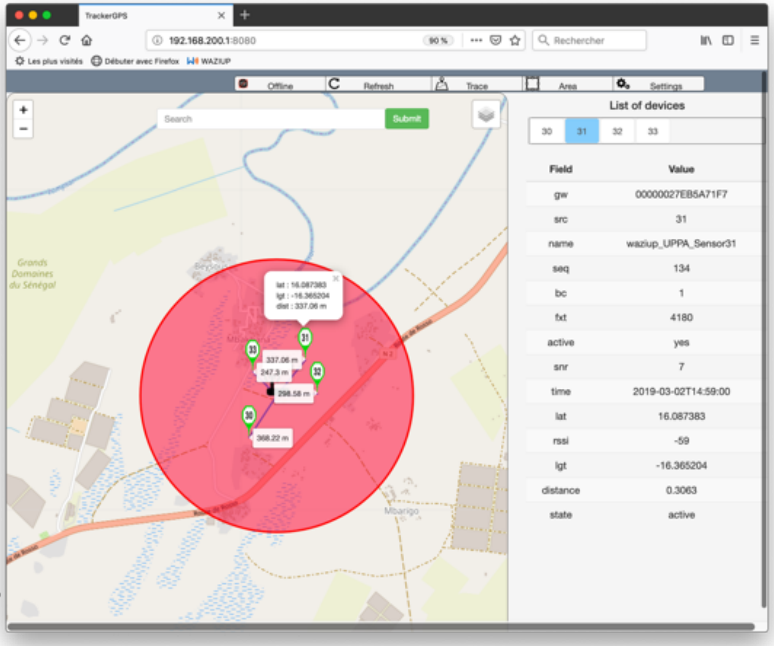


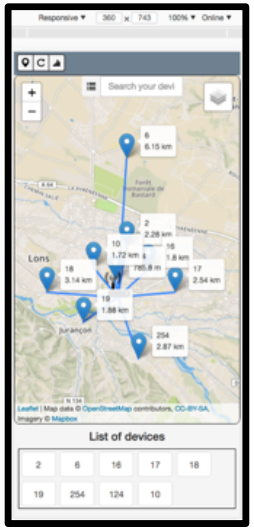
WAZIUP: deploying IoT in Africa

Autonomous gateway – no Internet scenario





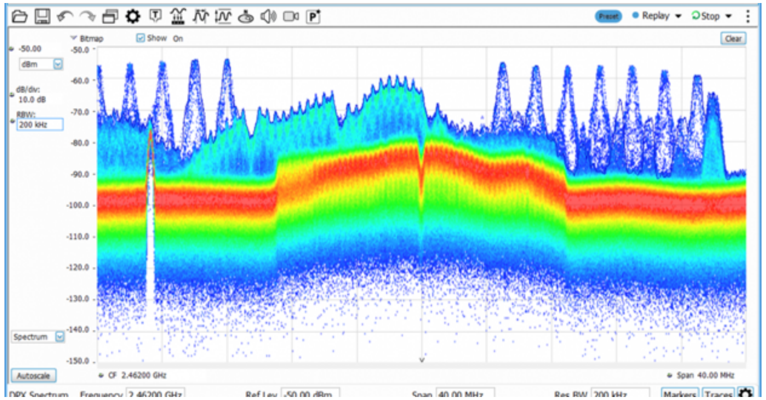




Link to a short demo video of the collar web interface: https://youtu.be/meFDav1SLPI

Deploying in dense environment

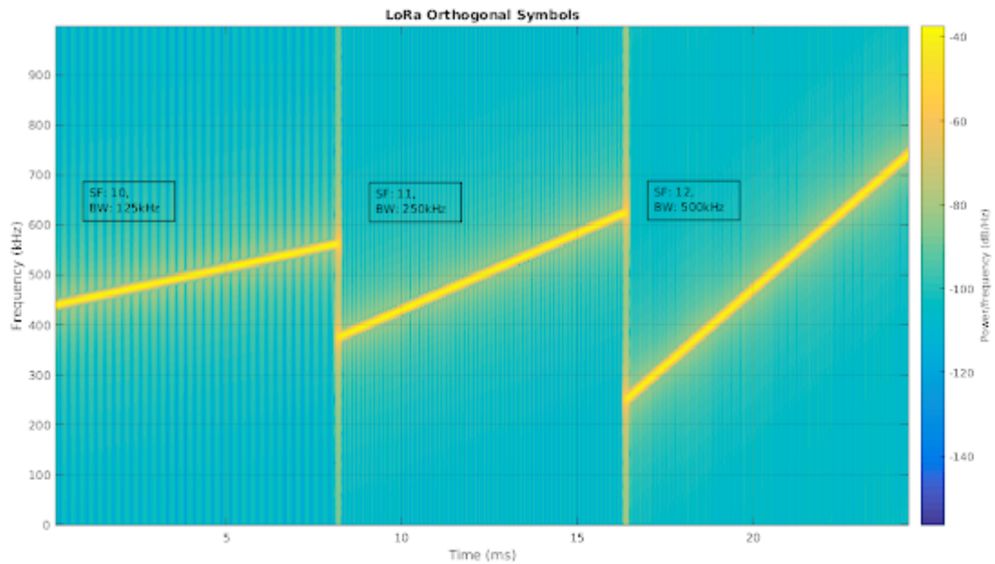
- LoRa currently works in unlicensed (ISM) band
- More devices: more traffic, more interferences & collisions



- 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 6 spreading factors (SF7 - SF12) and 3 different bandwidths (125kHz, 250kHz & 500kHz)



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

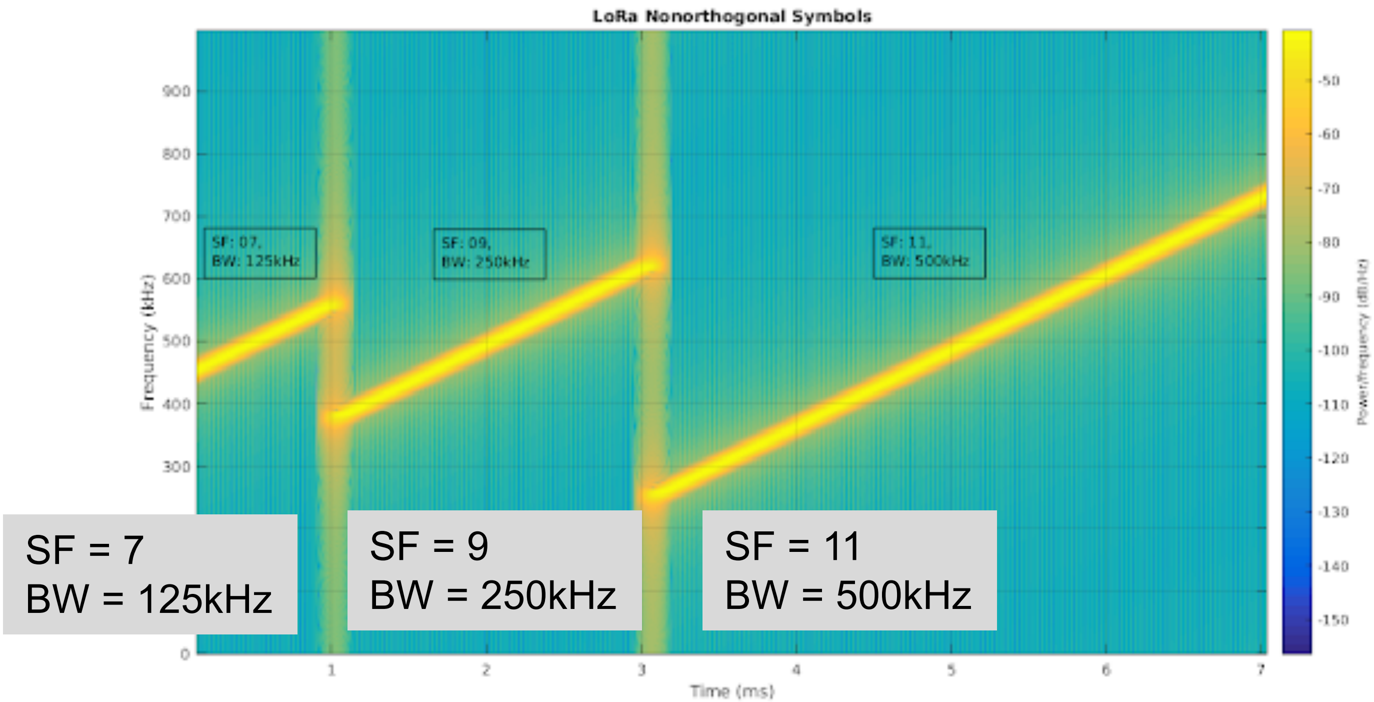


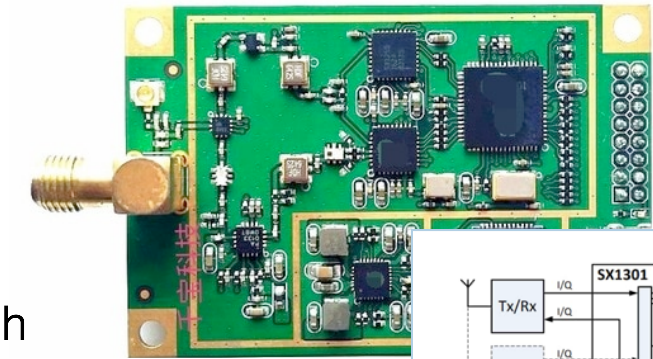
Figure from "All About LoRa and LoRaWAN", https://www.sghoslya.com

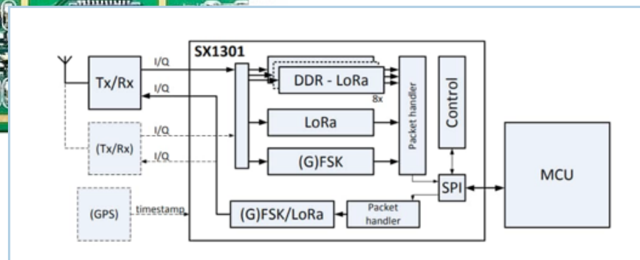
Orthogonal combinations

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

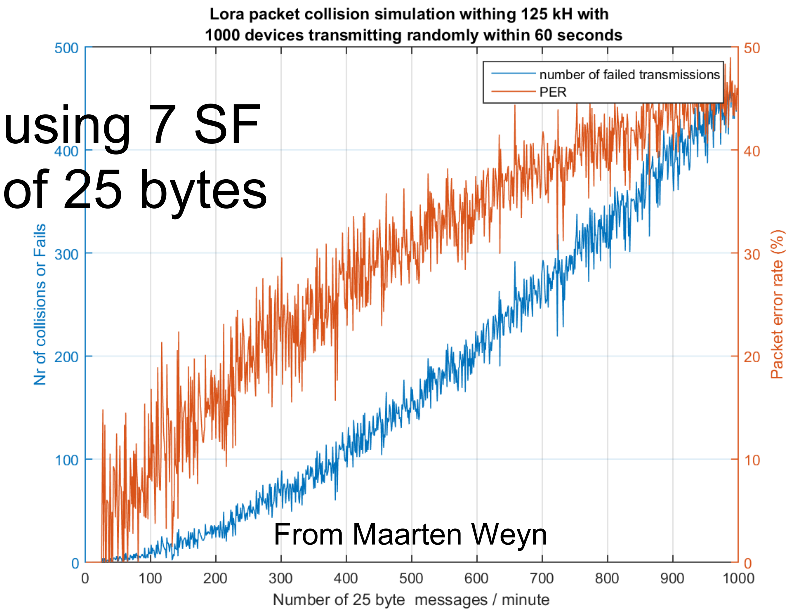
Low-level LoRa interference mitigation techniques

- 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



From Maarten Weyn

"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

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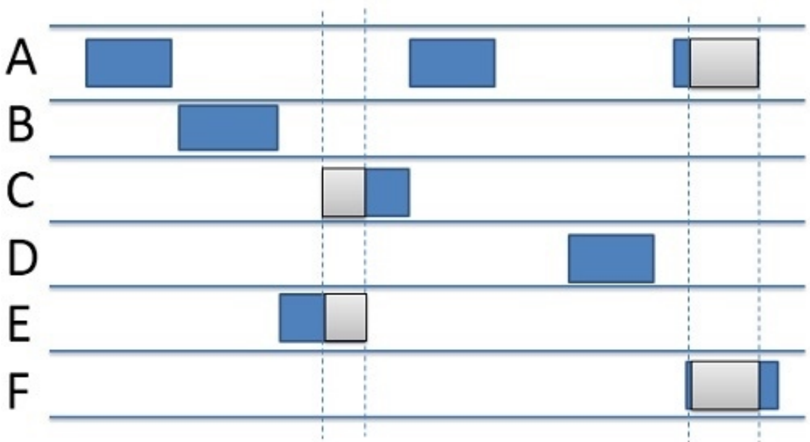
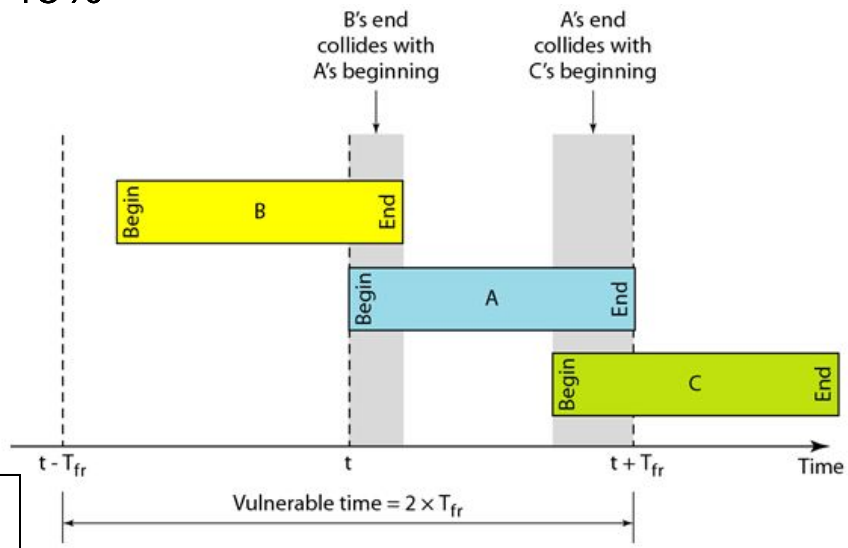
Concurrent channel access issue

- 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.

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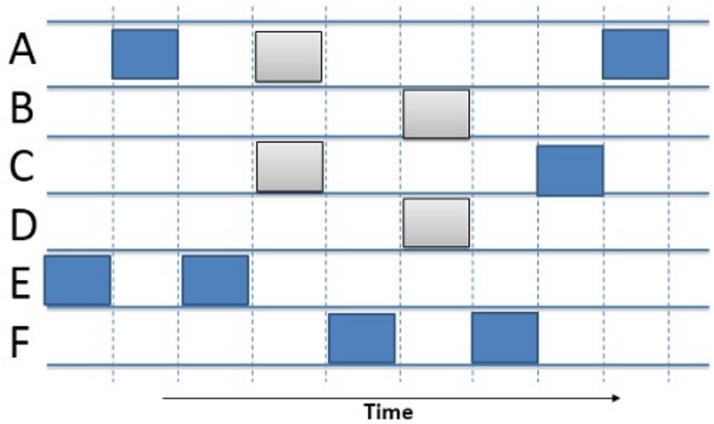
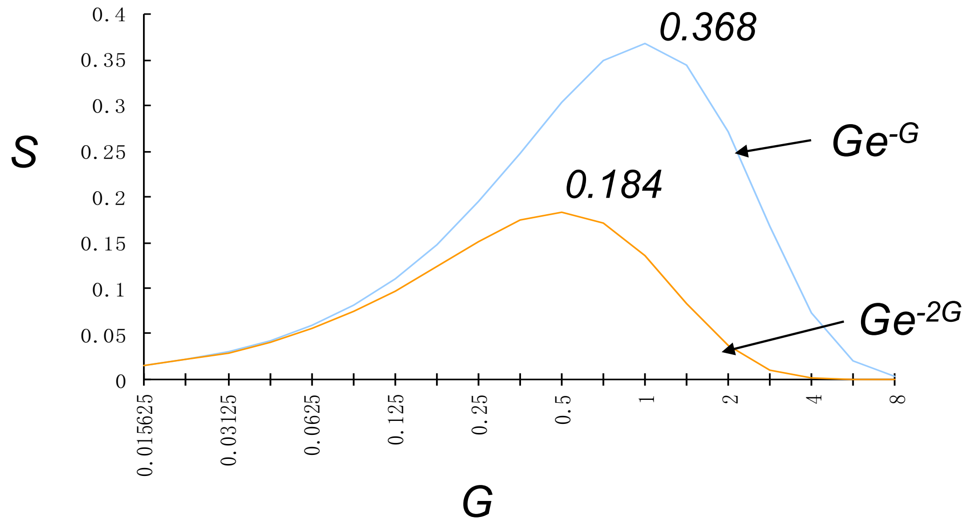
Slotted ALOHA

- 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

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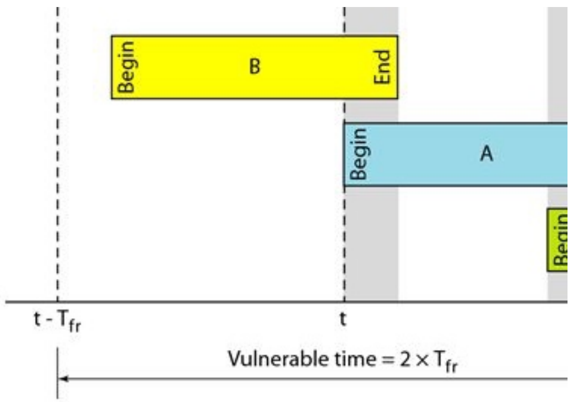
Do we really have LoRa = ALOHA?

- 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

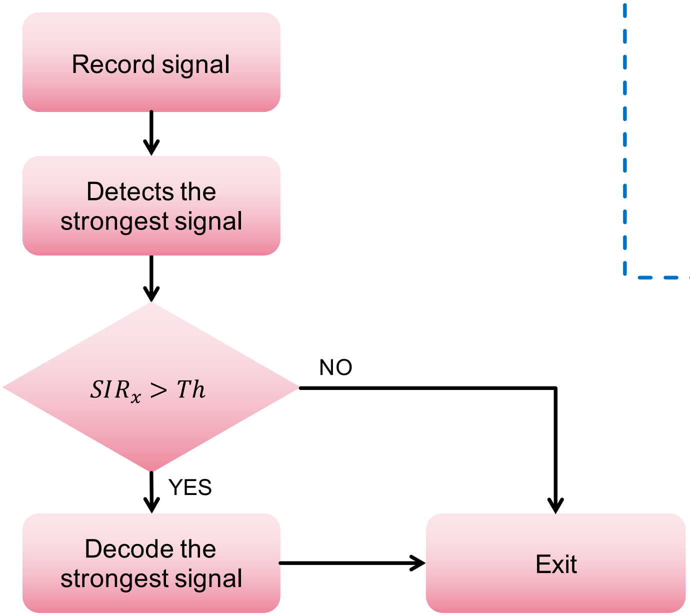


Capture effect in LoRa

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



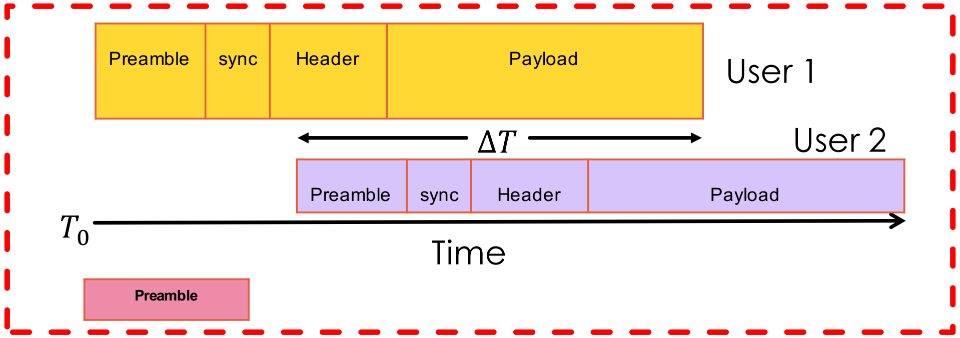
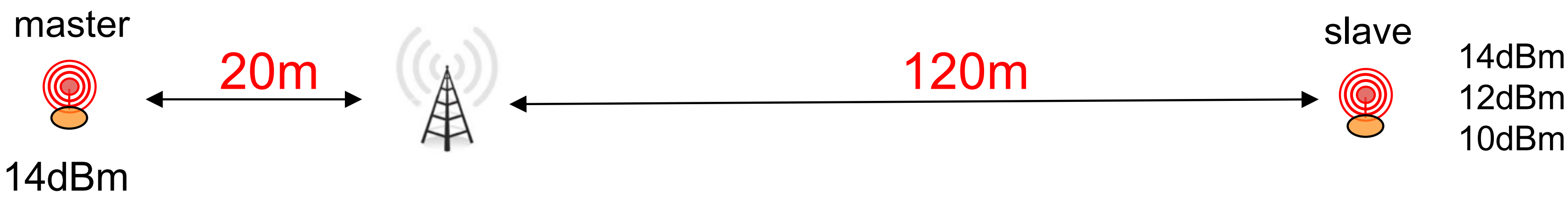


Figure from Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

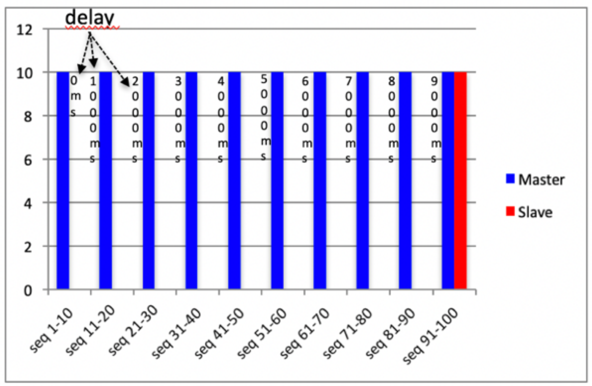
Capture effect in practice



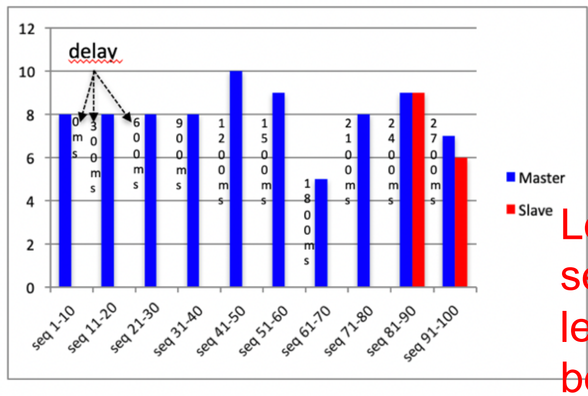
BW=125kHz,SF=12

BW=125kHz,SF=10

Slave at 14dbm

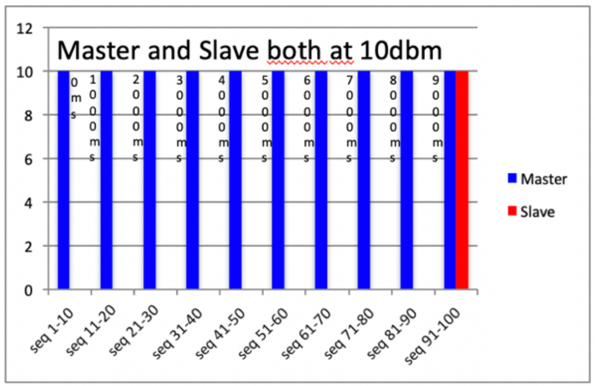


Slave at 14dbm



Lower SFs seem to show less CE benefit

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

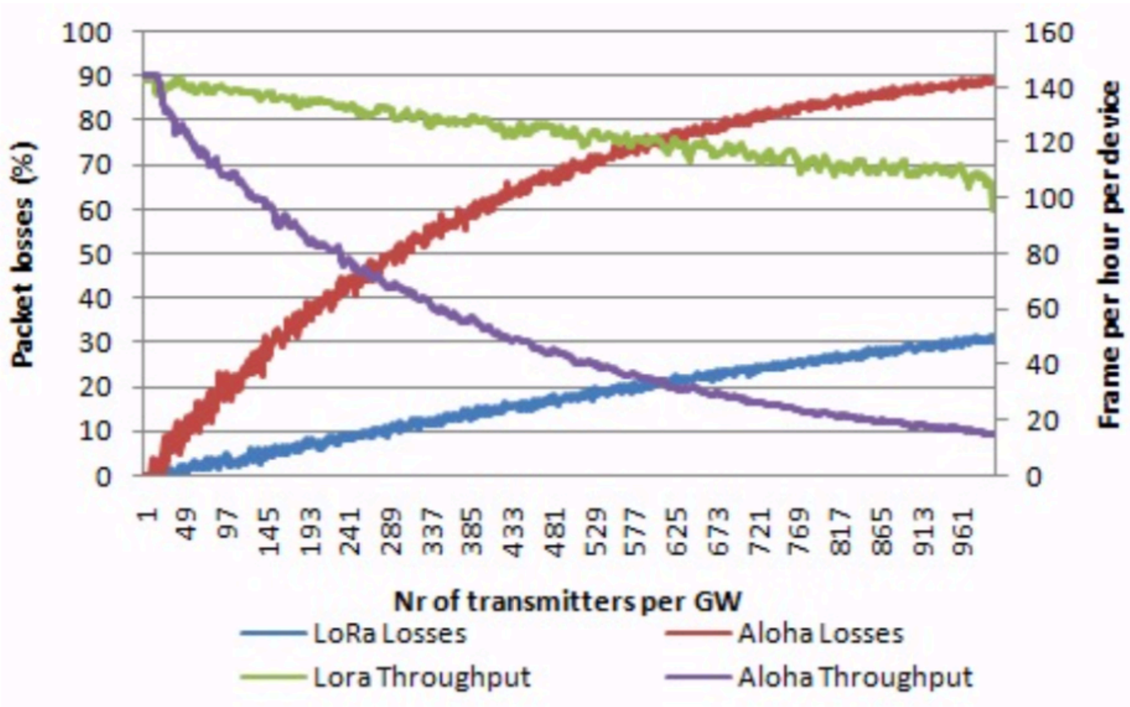


Small distance difference is enough to have SIR enabling CE

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

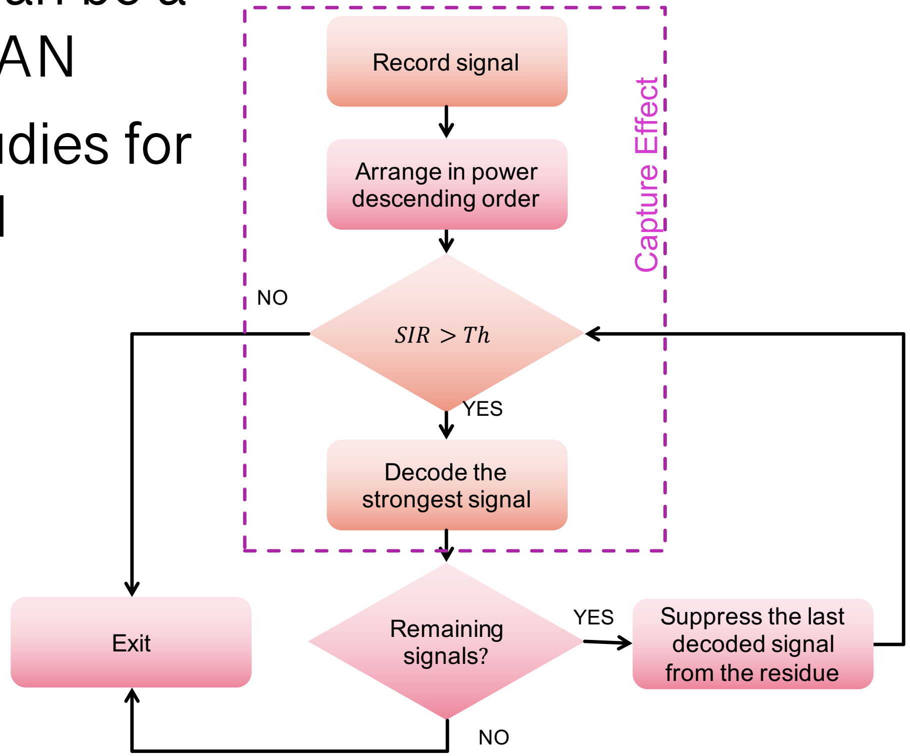


Figure from Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

LoRa with CE and SIC

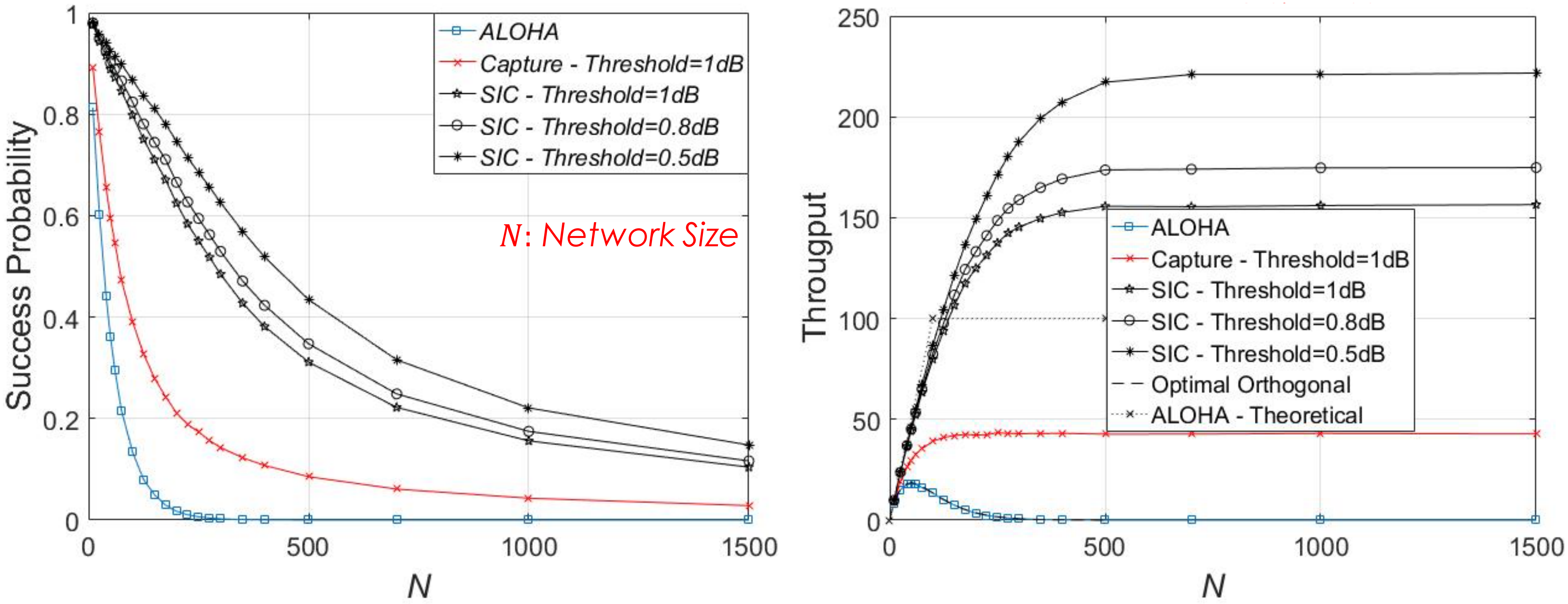


Figure from Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

High-level LoRa interference mitigation techniques

- Policy-based, 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
  - 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

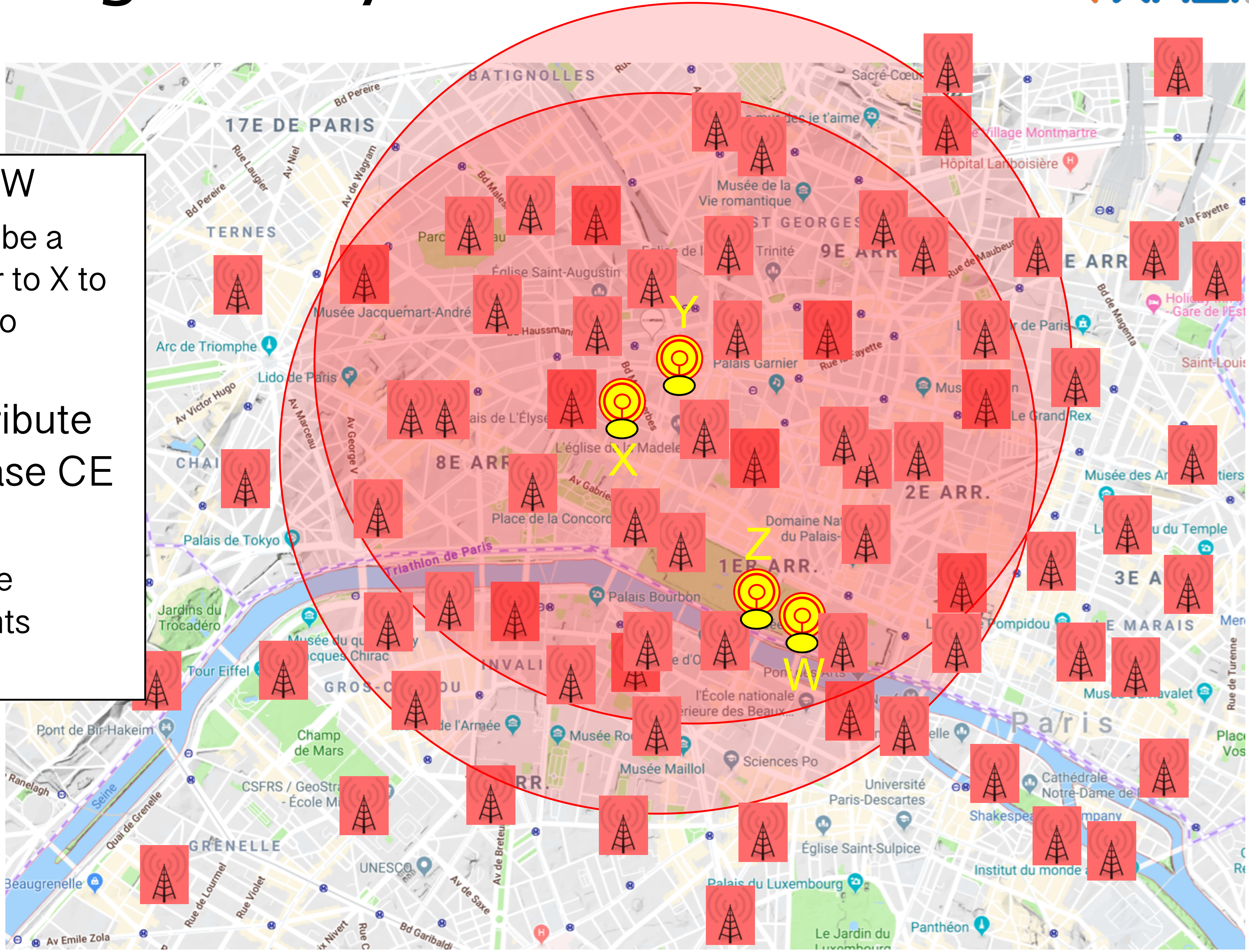
Part Number	8 Channel SX1301	16 channel SX1301	Cat4 Cellular	GPS	WIFI	Battery Backup
RAK7249-0x-14x	√		√	√	√	
RAK7249-1x-14x		√	√	√	√	
RAK7249-2x-14x	√		√	√	√	√
RAK7249-3x-14x		√	√	√	√	√
RAK7249-0x	√			√	√	
RAK7249-1x		√		√	√	
RAK7249-2x	√			√	√	√
RAK7249-3x		√		√	√	√

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
- 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€

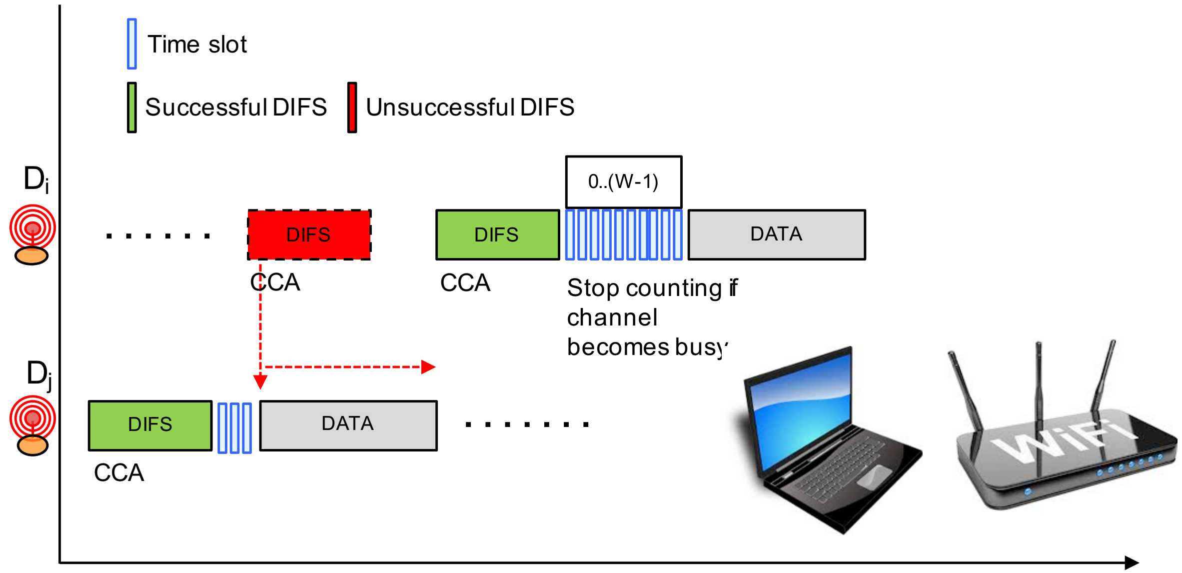
Dense gateway scenario

- 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



Do we have to forget CSMA?

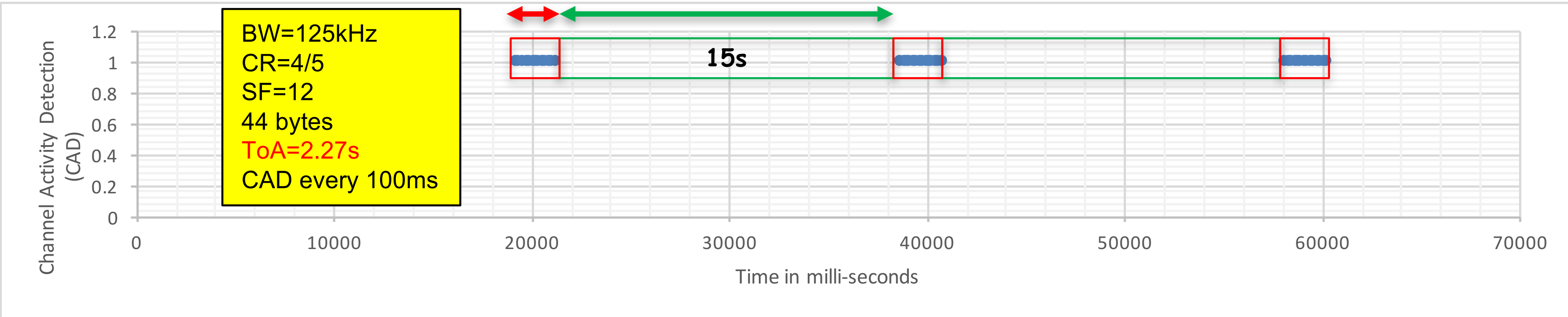
- There will be cases where CE will not happen
  - SIR not sufficient
  - Interferer transmission jams LoRa preamble
- Can we implement Listen-Before-Talk or CSMA?
- Ex: Carrier Sense in WiFi
  - DIFS, SIFS
  - Random backoff [0..W[

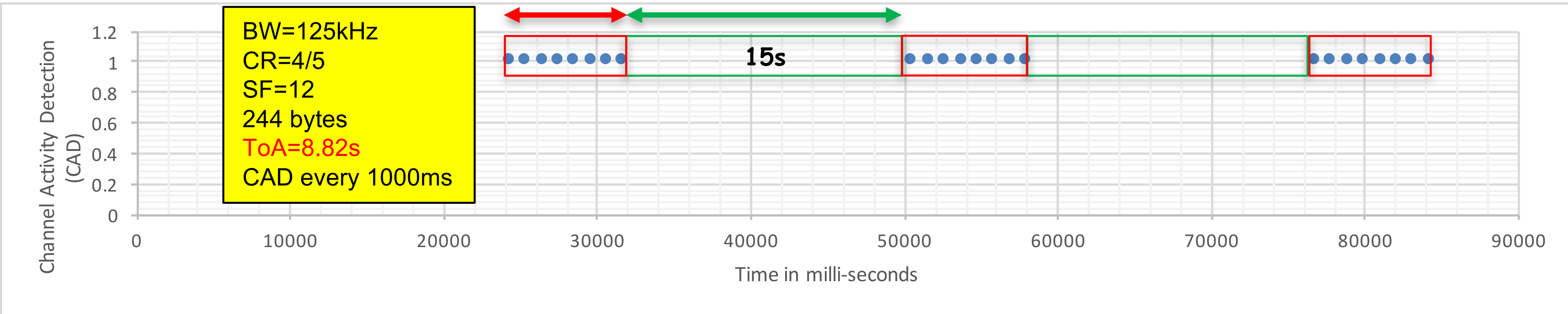


Prof. Congduc Pham
http://www.univ-pau.fr/~cpham

Clear Channel Assessment with LoRa

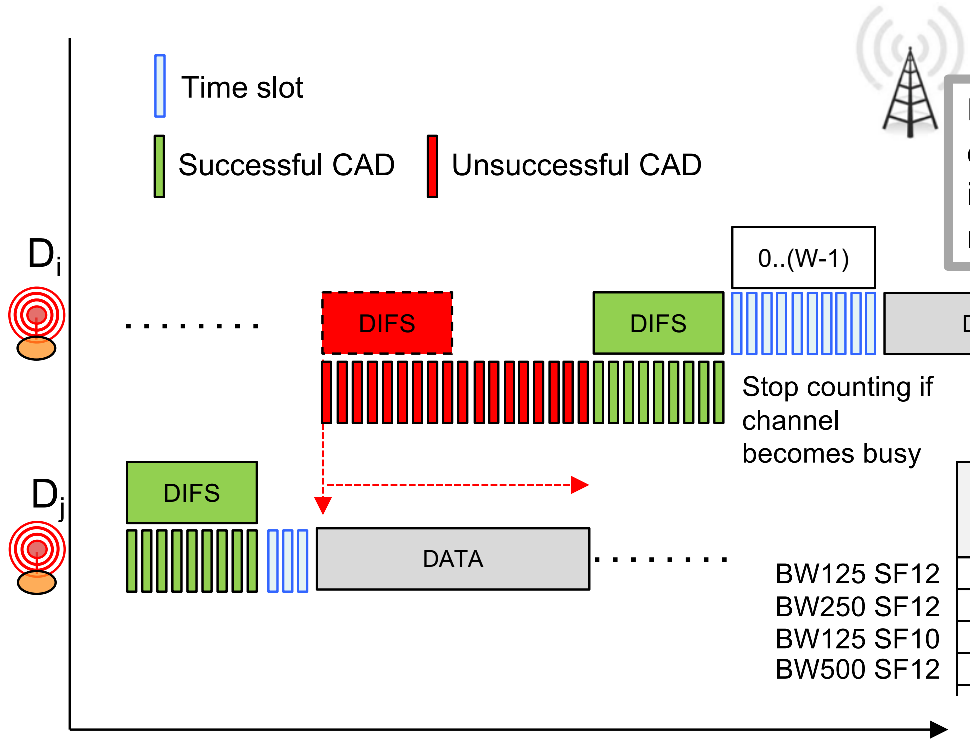
- CCA uses dedicated LoRa's Channel Activity Detection (CAD) as data reception can be done below the noise floor





LoRa CSMA derived from 802.11

- CAD duration is between $1.75T_{sym}$ and $2.25T_{sym}$
- T_{sym} depends on bandwidth & spreading factor
- SIFS & DIFS are mapped to a number of CAD

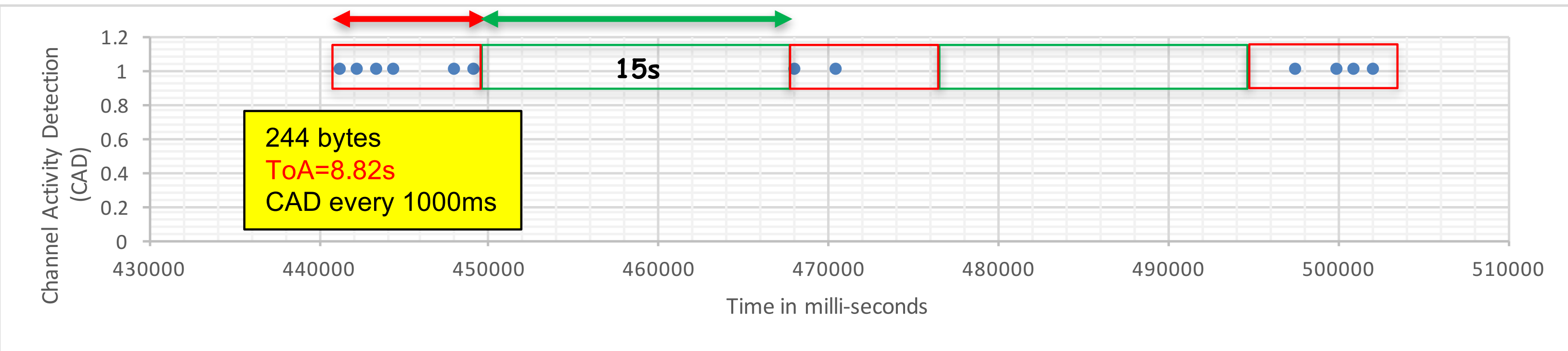


LoRa mainly runs in gateway-centric mode where a gateway is the central point of the network

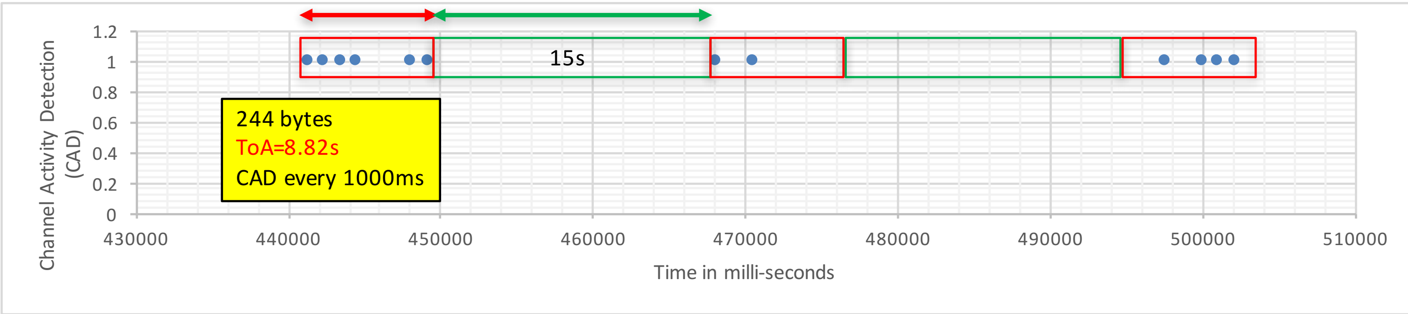
	LoRa mode	Tsym (ms)	CAD duration (Tsym)	CAD duration (ms)	Experimental measures min value	max value
BW125 SF12	1	32.768	1.86	60.948	60	62
BW250 SF12	2	16.384	1.86	30.474	29	31
BW125 SF10	3	8.192	1.77	14.500	14	16
BW500 SF12	4	8.192	1.86	15.237	15	16
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

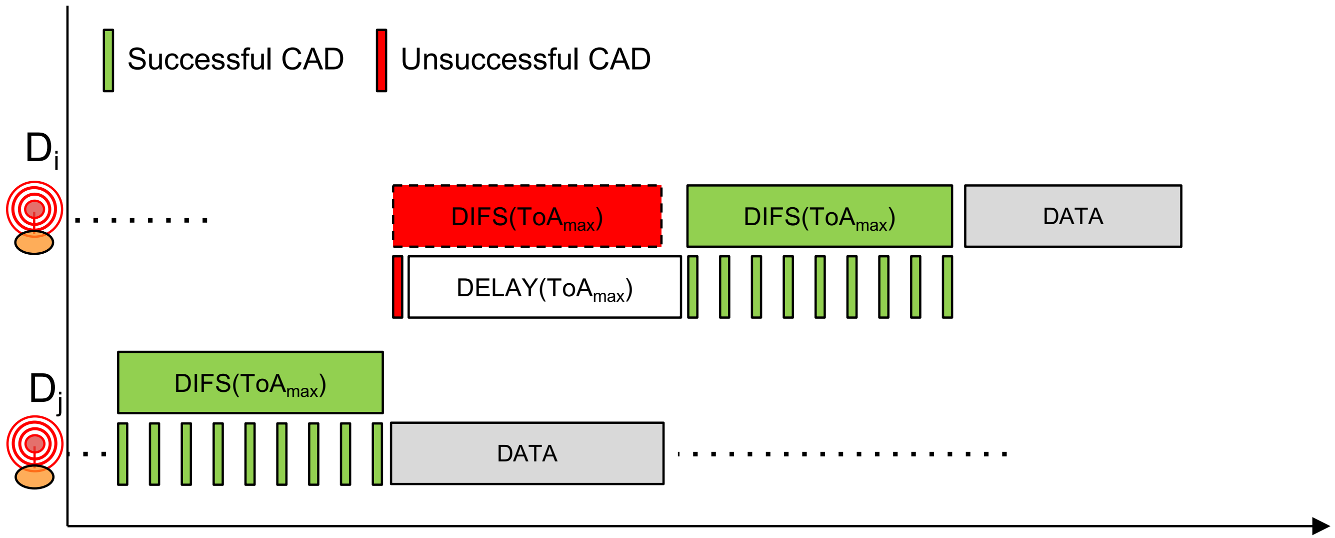
CAD reliability?

- 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
- During a long transmission (i.e. several seconds) there is usually at least one CAD returning true



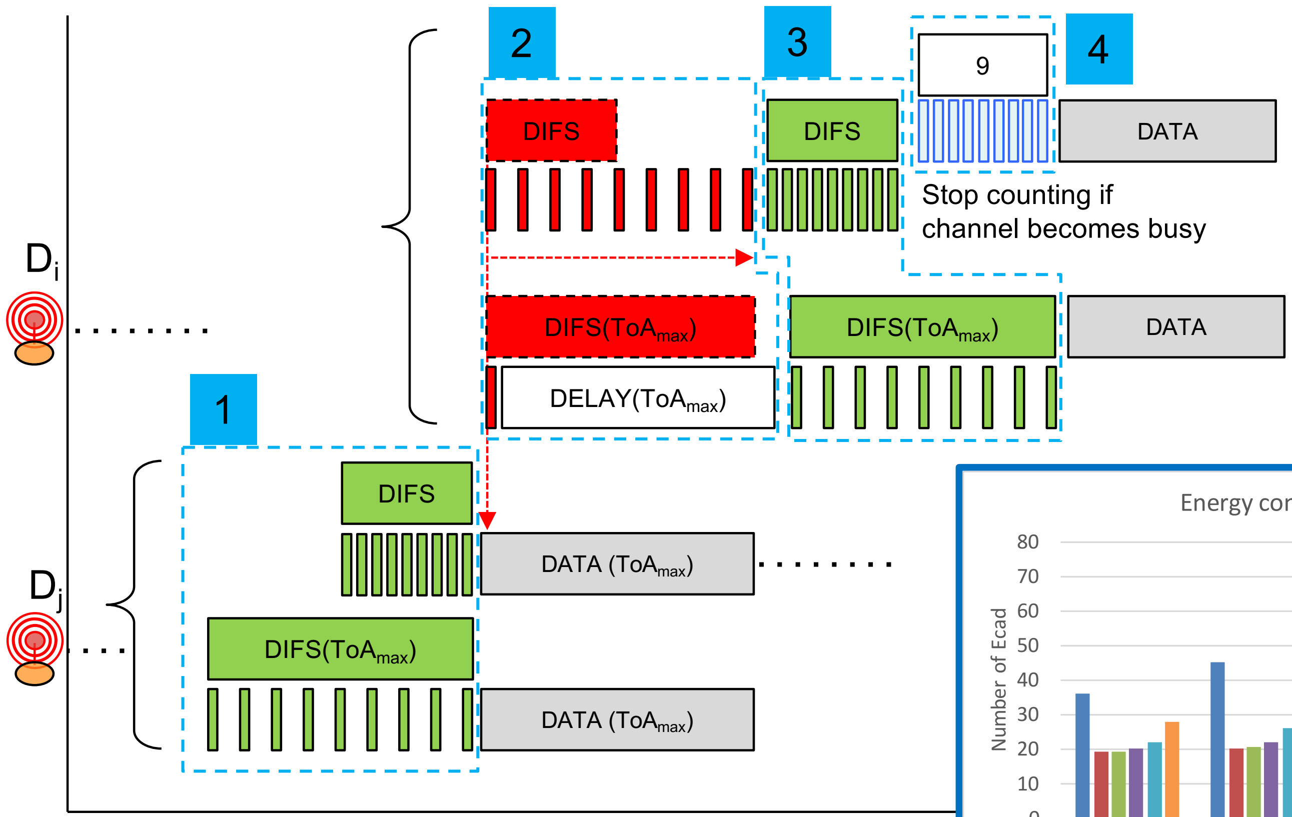
LoRa CSMA to protect longer msg

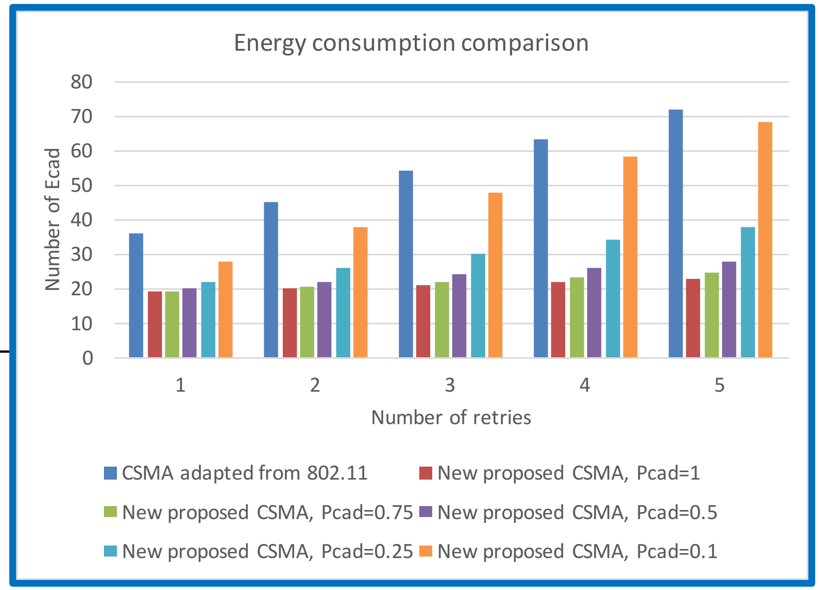




C. Pham, "Investigating and Experimenting CSMA Channel Access Mechanisms for LoRa IoT Networks", Proceedings of the IEEE WCNC conference, Barcelona, Spain, April 15-18, 2018.

CSMA variants & comparison





Conclusions

- LoRa networks are deployed world-wide is unlicensed bands
  - Telco operators, Communities, Private, ad-hoc infrastructures
- 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)

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