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

IMERIR
INSTITUT MÉDITERRANÉEN D'ÉTUDES ET DE RECHERCHE EN INFORMATIQUE ET ROBOTIQUE

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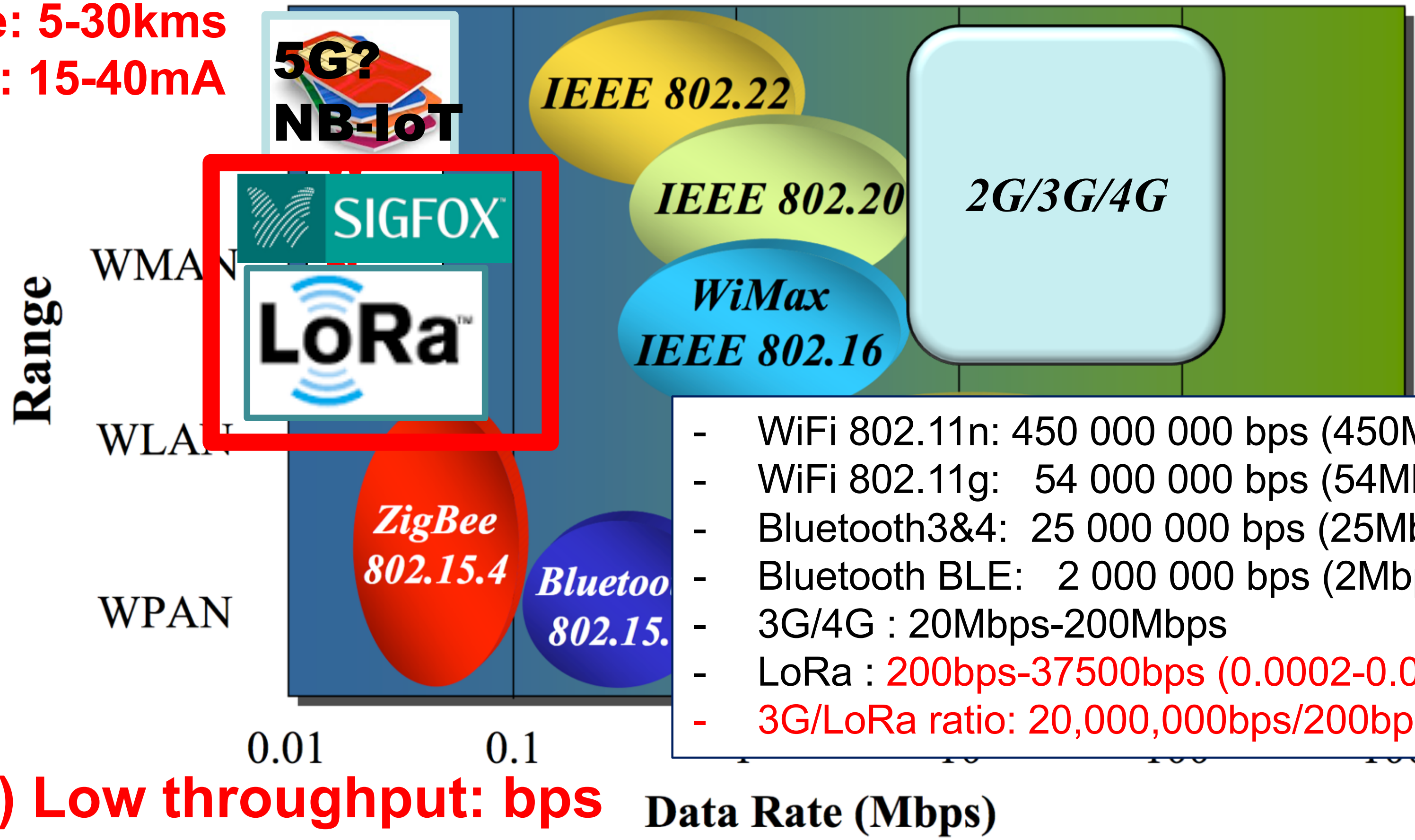
IoT – from idea to reality

Where am I now?

Low-power & long-range radios

Energy-Range dilemma

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



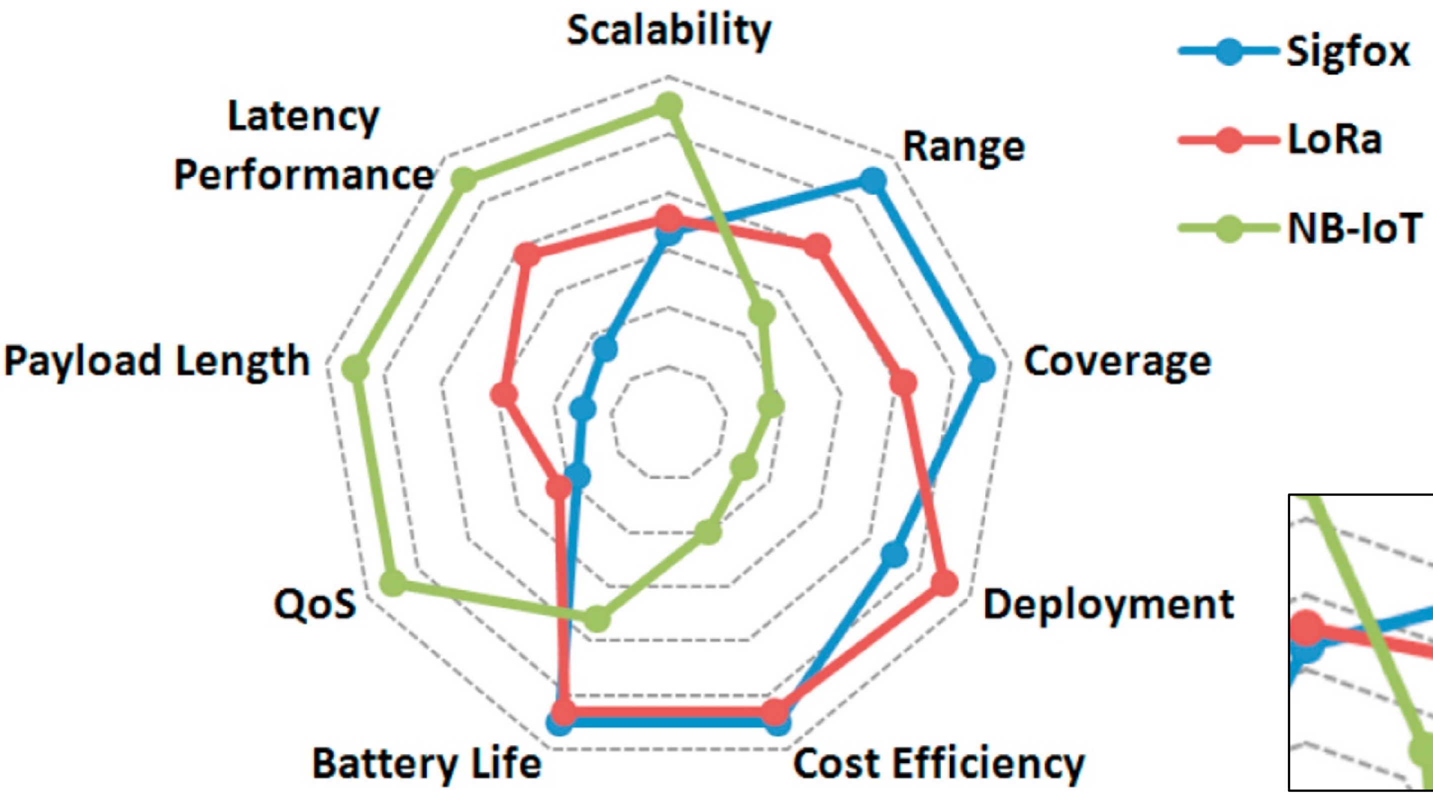
Energy

- 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

Expected range?



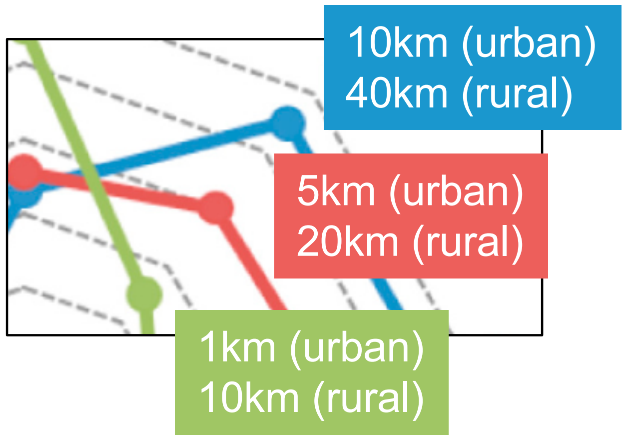


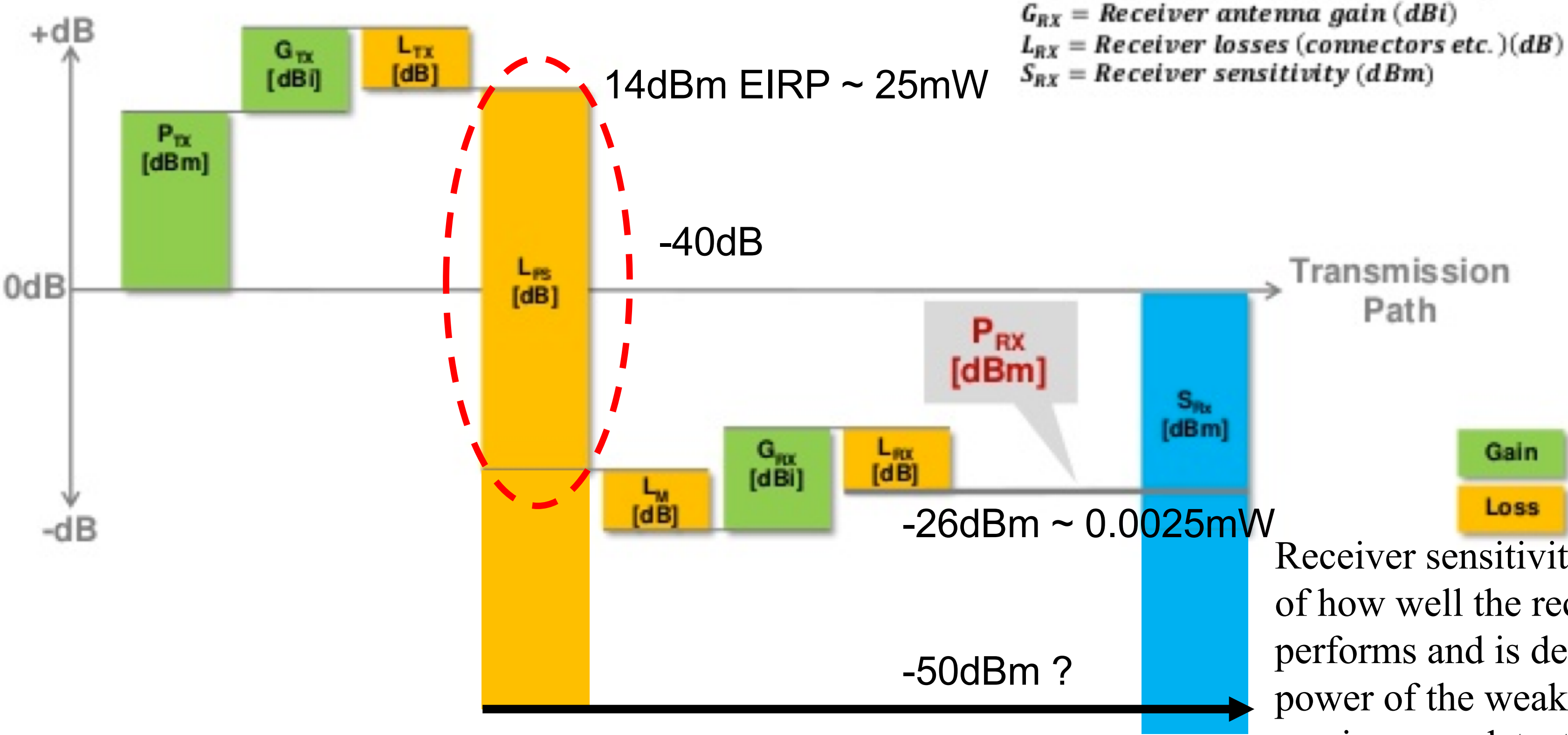
Figure from Kais Mekki, Eddy Bajic, Frederic Chaxel, Fernand Meyer,
A comparative study of LPWAN technologies for large-scale IoT deployment,
ICT Express, Volume 5, Issue 1, 2019.

Link budget in wireless system

$$P_{RX} = P_{TX} + G_{TX} - L_{TX} - L_{FS} - L_M + G_{RX} - L_{RX}$$

P_{RX} = Received power (dBm)
P_{TX} = Sender output power (dBm)
G_{TX} = Sender antenna gain (dBi)
L_{TX} = Sender losses (connectors etc.)(dB)
L_{FS} = Free space loss (dB)
L_M = Misc. losses (multipath etc.)(dB)
G_{RX} = Receiver antenna gain (dBi)
L_{RX} = Receiver losses (connectors etc.)(dB)
S_{RX} = Receiver sensitivity (dBm)

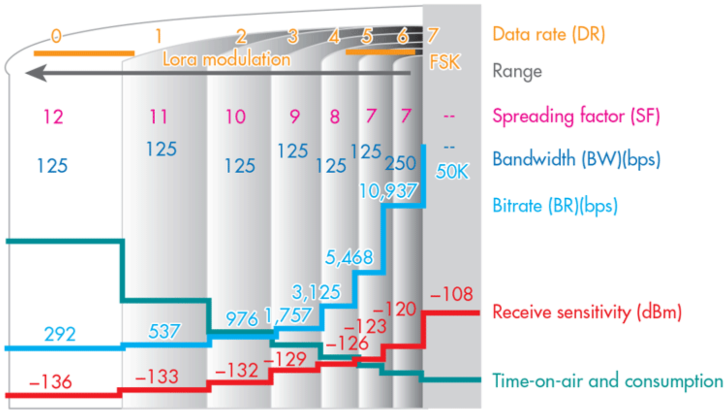
Adapted from Peter R. Egli, INDIGOO.COM



Receiver sensitivity is a measure of how well the receiver performs and is defined as the power of the weakest signal the receiver can detect

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

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Spreading factor in image

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

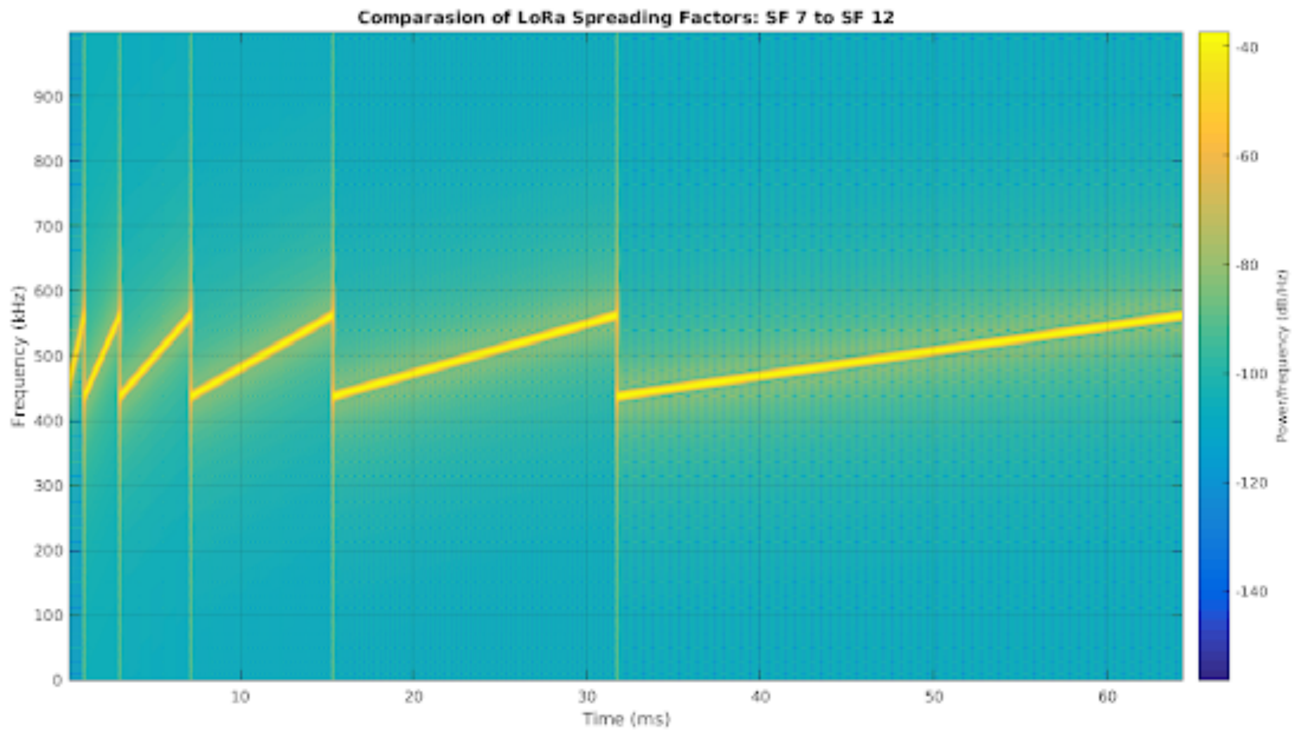
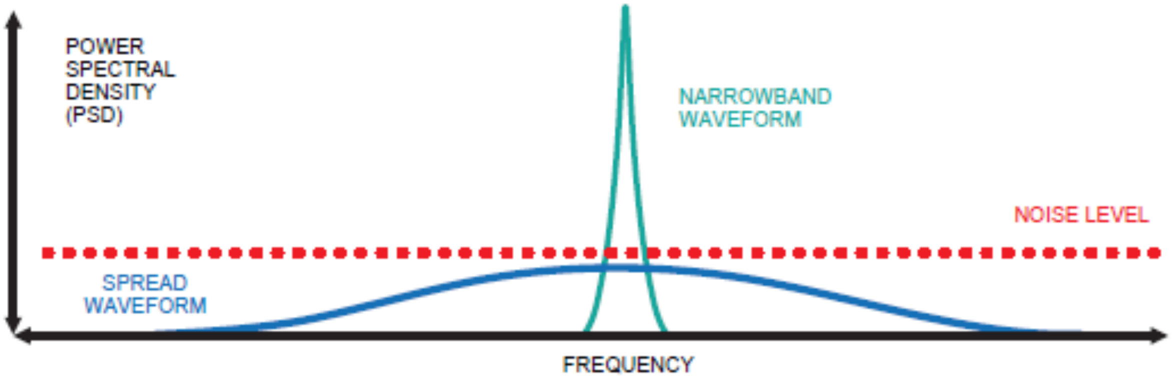
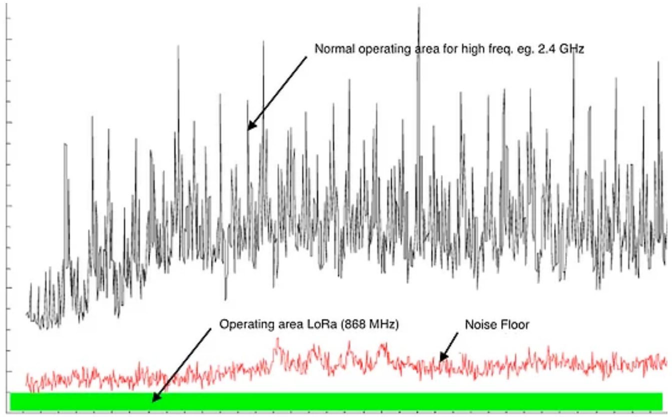


Figure from "All About LoRa and LoRaWAN", https://www.sghoslya.com

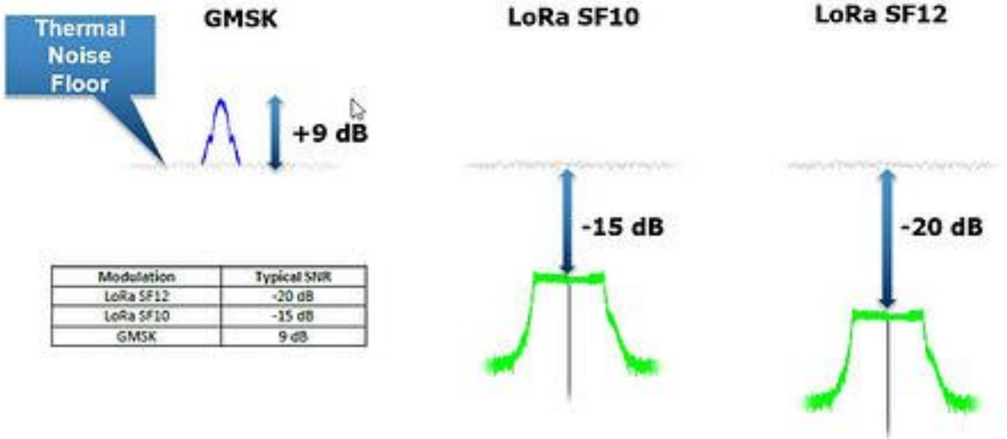
Advantage of Spread Spectrum

- Spread Spectrum techniques are usually more robust to noise





- LoRa signals can be decoded below noise floor

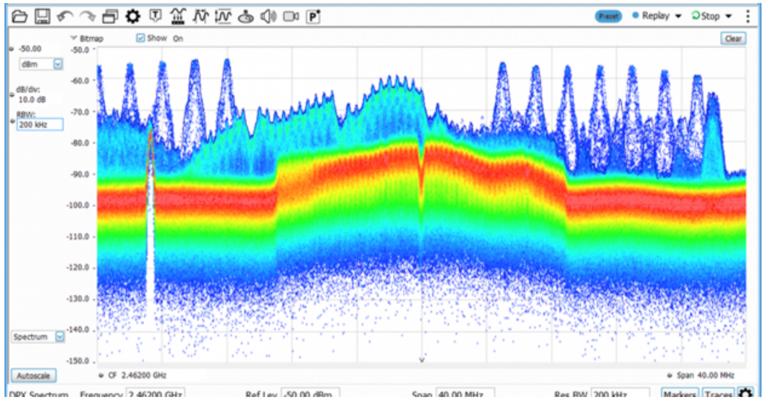


Modulation	Typical SNR
LoRa SF12	-20 dB
LoRa SF10	-15 dB
GMSK	9 dB

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

Large-scale IoT deployment

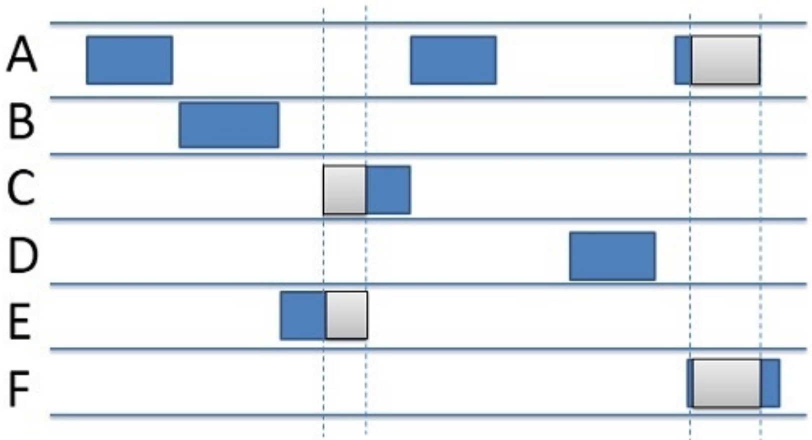
- More devices: more traffic, more interferences & collisions!
- 1 msg/20min = 3 msg/h. For 1000 devices = almost 1 msg/s!

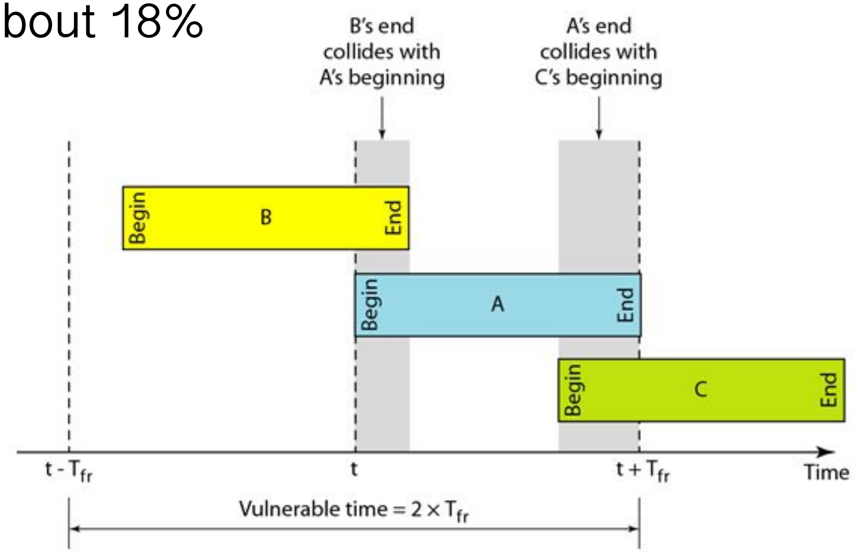


- More gateways increases coverage so can increase SF diversity: transmissions with small SF can reach a gateway

Concurrent channel access

- So-called 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!

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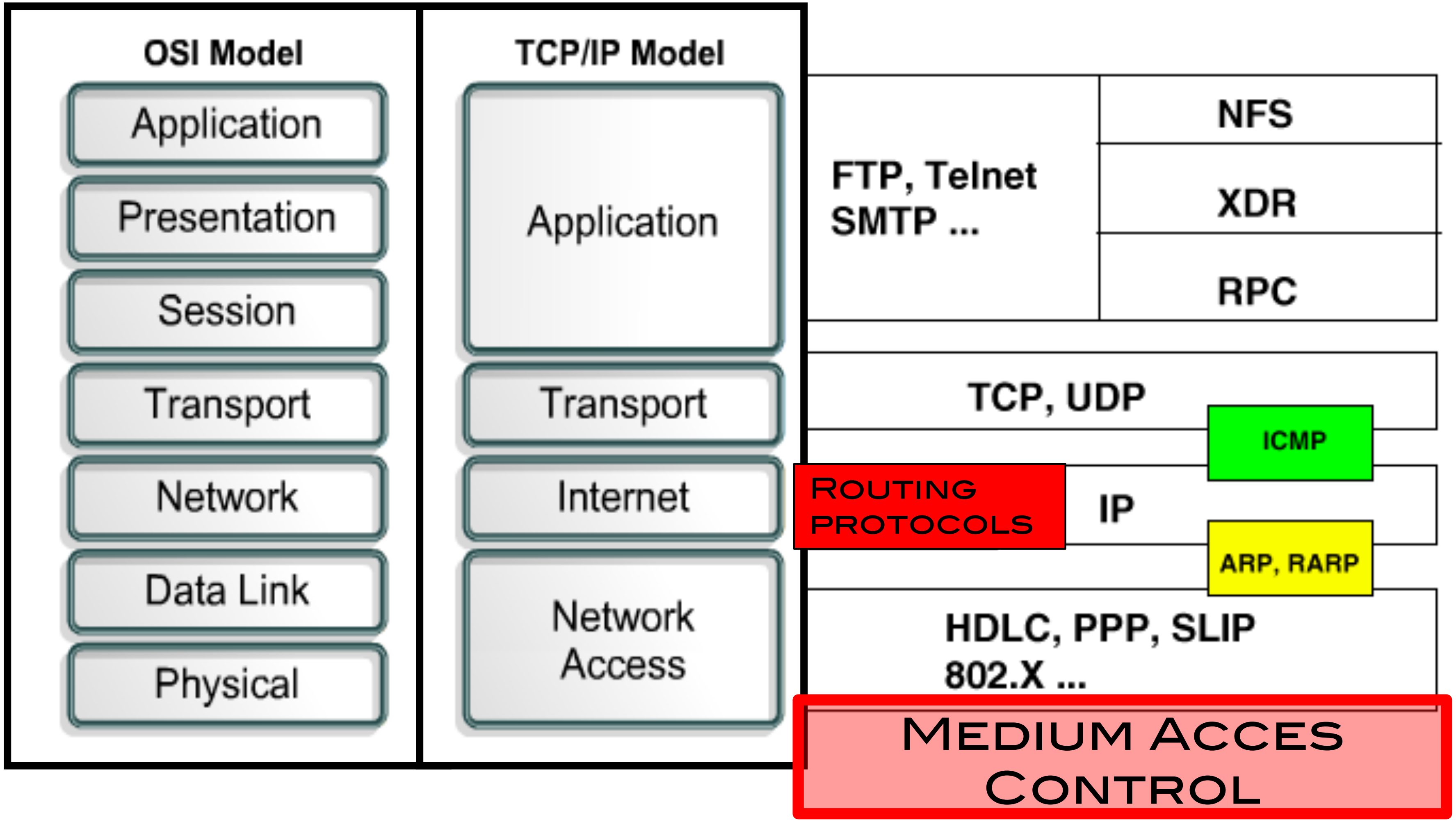
MAC layer



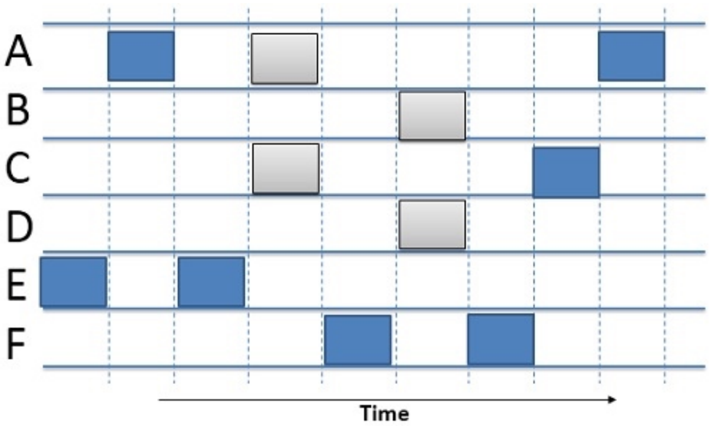
OSI Model
Application
Presentation
Session
Transport
Network
Data Link
Physical
TCP/IP Model
Application
Transport
Internet
Network Access
FTP, Telnet SMTP ...
NFS
XDR
RPC
TCP, UDP
ICMP
Routing protocols
IP
ARP, RARP
HDLC, PPP, SLIP 802.X ...
Medium Acces Control

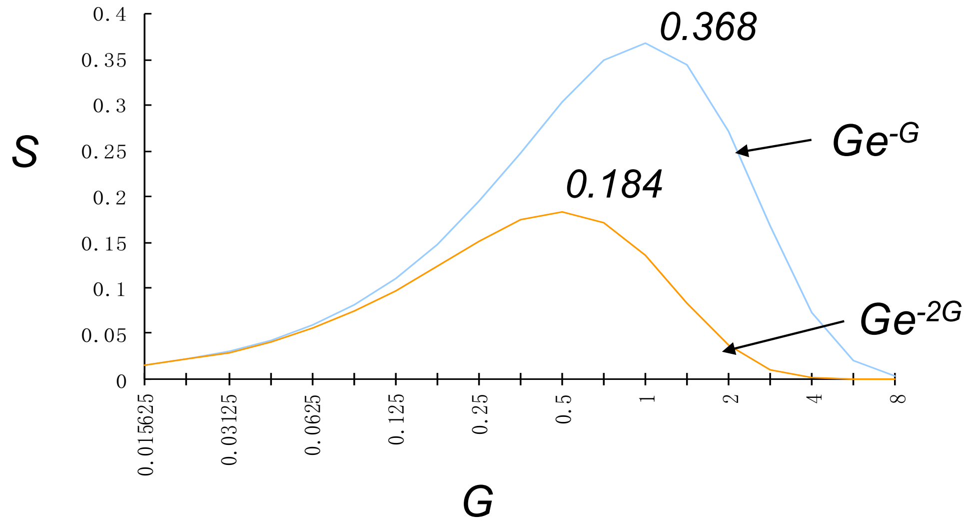
MAC approaches

- Deterministic
  - Cooperation and/or pre-allocation mechanism to assign transmission slots
  - e.g. TDMA (Time Division Multiple Access)
- Competition
  - Allow multiple access
  - But only one node eventually wins to obtain a successful transmission
  - e.g. CSMA (Carrier Sense Multiple Access)
- Hybrid
  - Competition, then Deterministic if needed

Slotted ALOHA

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

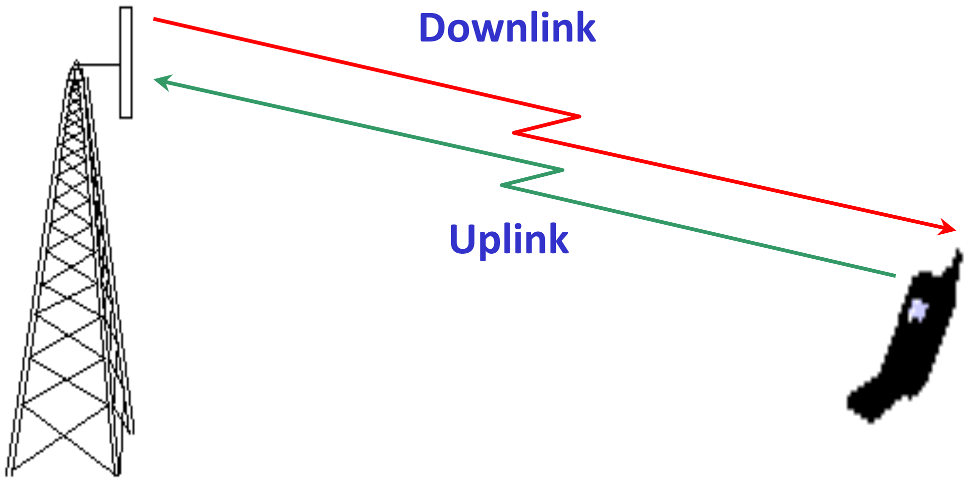


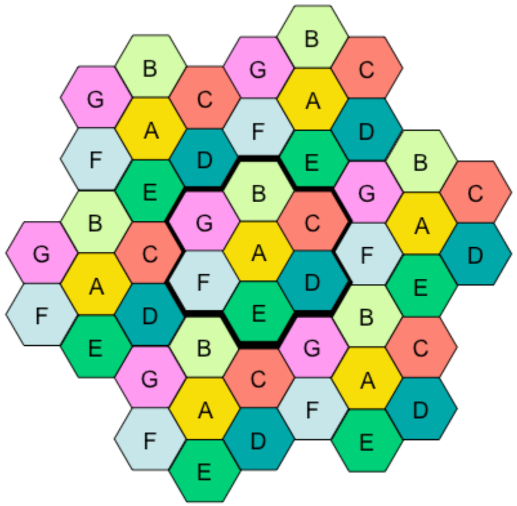


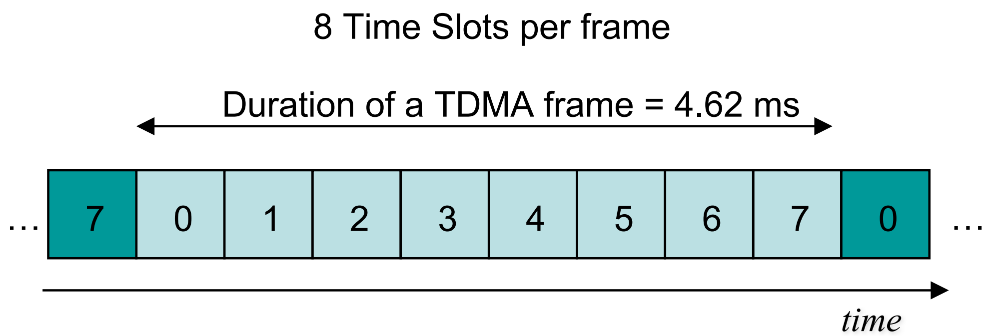
- But slotted mode needs higher level of coordination

TDMA: e.g. GSM (2G)

Channels





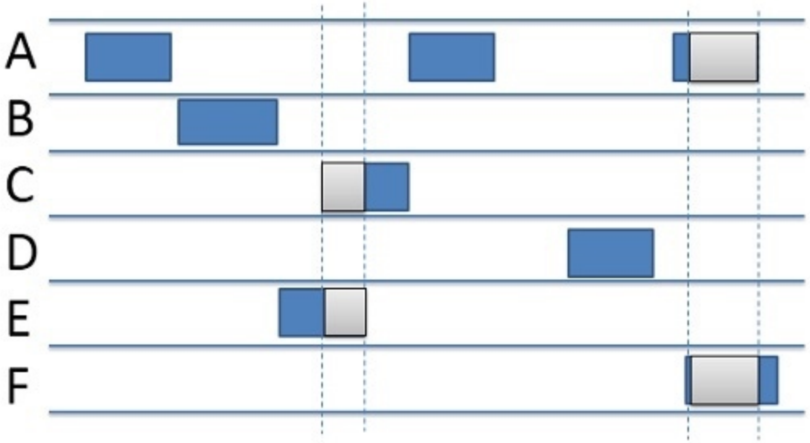


CSMA: e.g. WIFI 802.11

- Uses CSMA/CA, a contention-based access method

What MAC in LoRa networks?

- LoRa networks are basically ALOHA system!



- So, if ALOHA efficiency is low, how can LoRa scalability be improved?

Frequency diversity

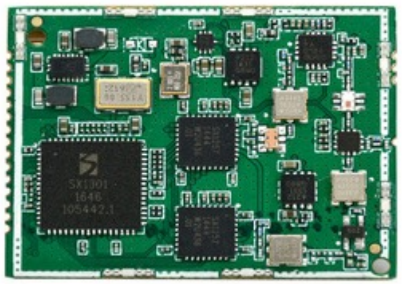
- A full LoRaWAN gateway should be able to listen on multiple channels (x8) and spreading factors (SF7-SF12)

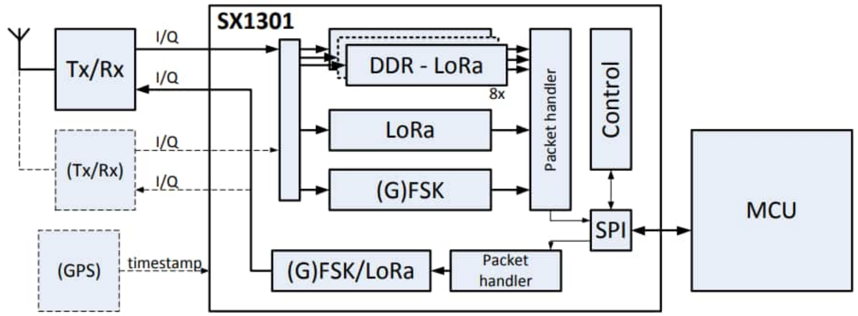
EU863-870

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





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		√		√	√	√

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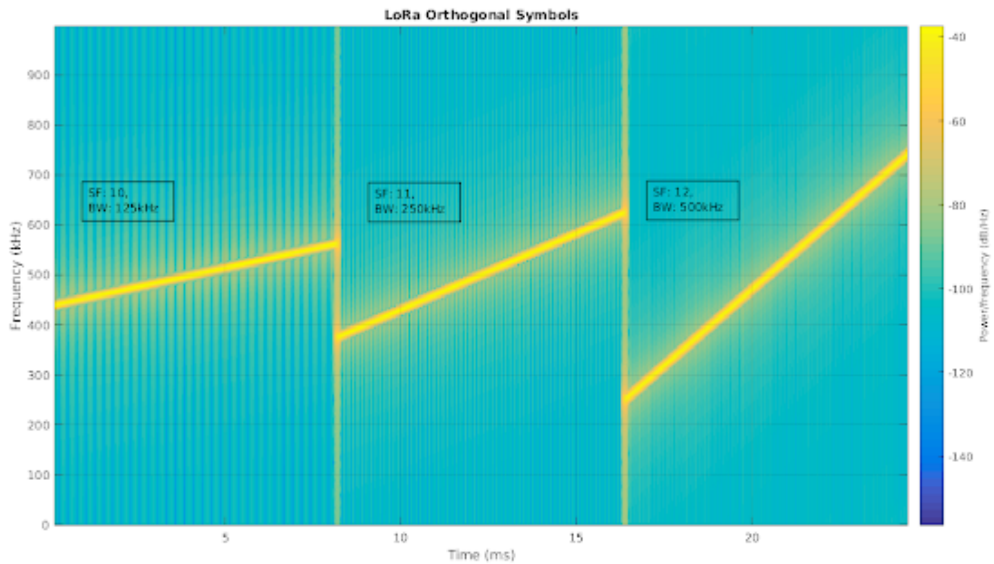
Low-level LoRa interference mitigation techniques

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

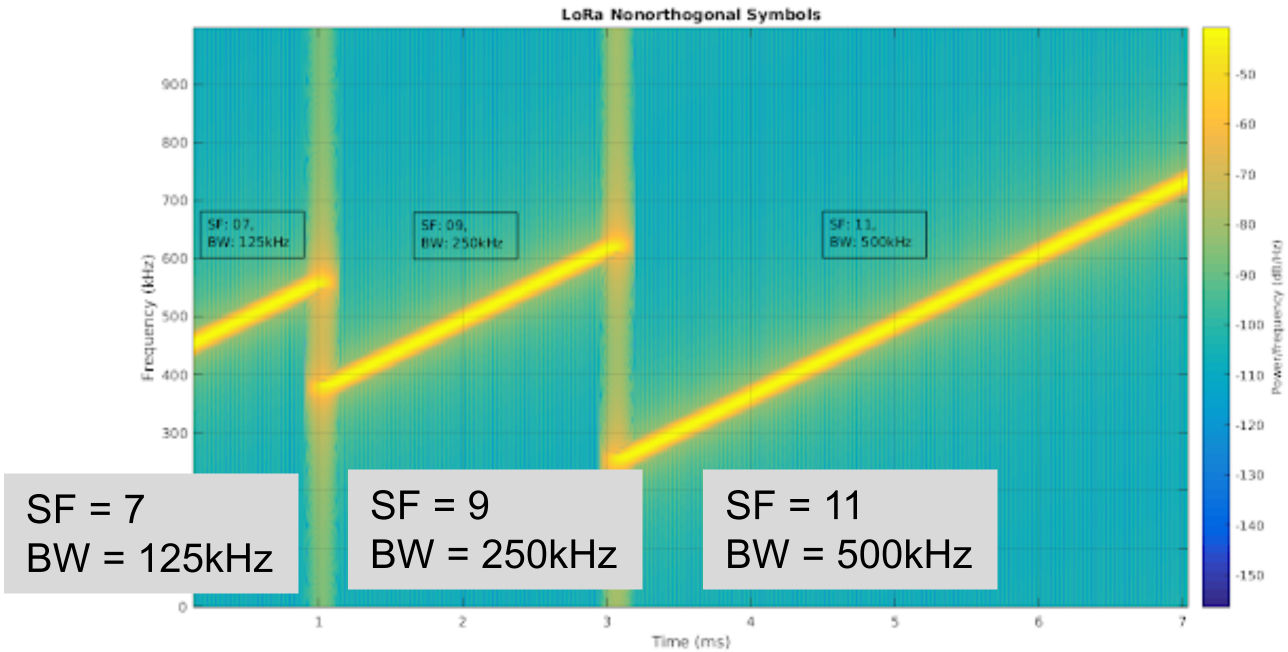


Figure from "All About LoRa and LoRaWAN", https://www.sghoslya.com

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	
12	500		x								x								x

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
  - Limit duty-cycle (<1%, i.e. 36s/h),
  - Limit transmit power (i.e. 14dBm),
- 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**

Side effect of frequency plans

EU863-870

THE THINGS NETWORK

Uplink:

1. 868.1 - SF7BW125 to SF12BW125
2. 868.3 - SF7BW125 to SF12BW125
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4. 867.1 - SF7BW125 to SF12BW125
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6. 867.5 - SF7BW125 to SF12BW125
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

- At some point, there will be be so many nodes that even with frequency and SF diversity, there will still be hundreds of nodes in the same frequency/SF combination!

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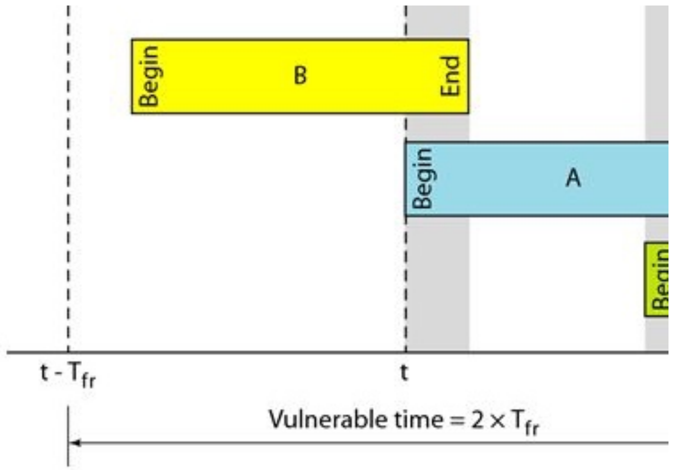
LoRa = ALOHA?

- 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



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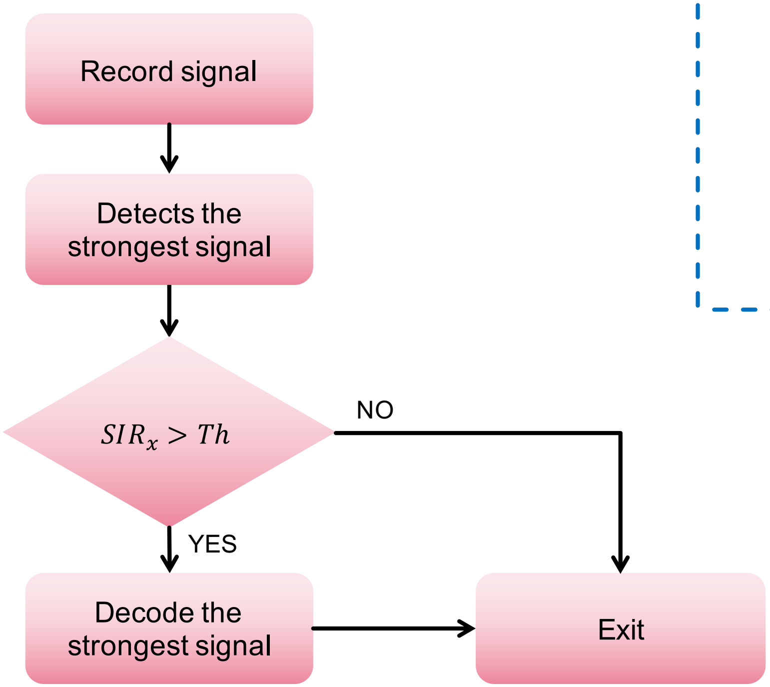
Capture effect in LoRa



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

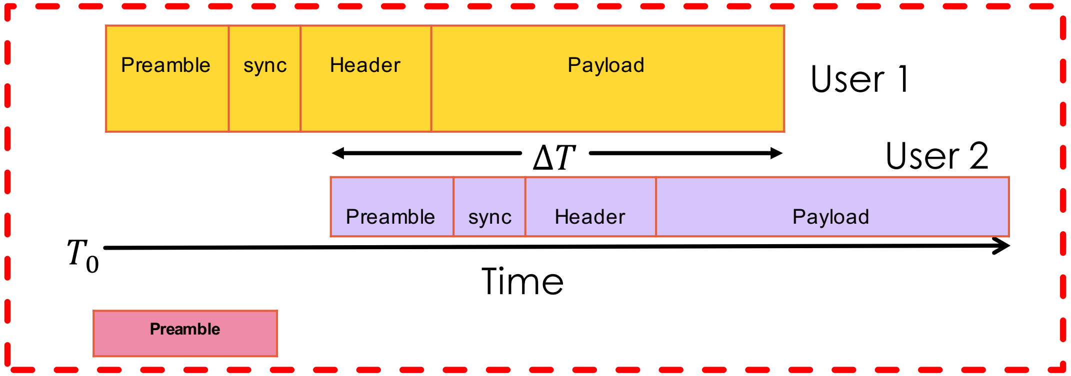
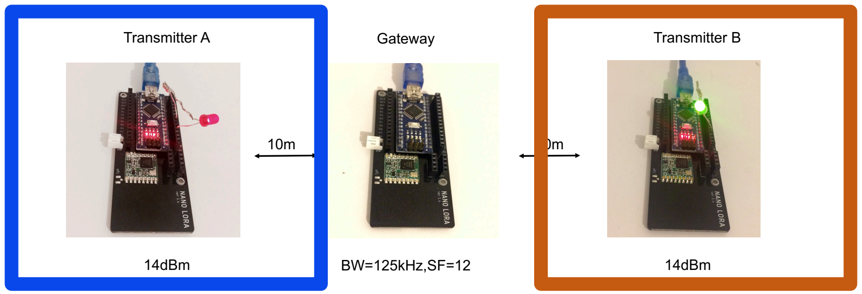


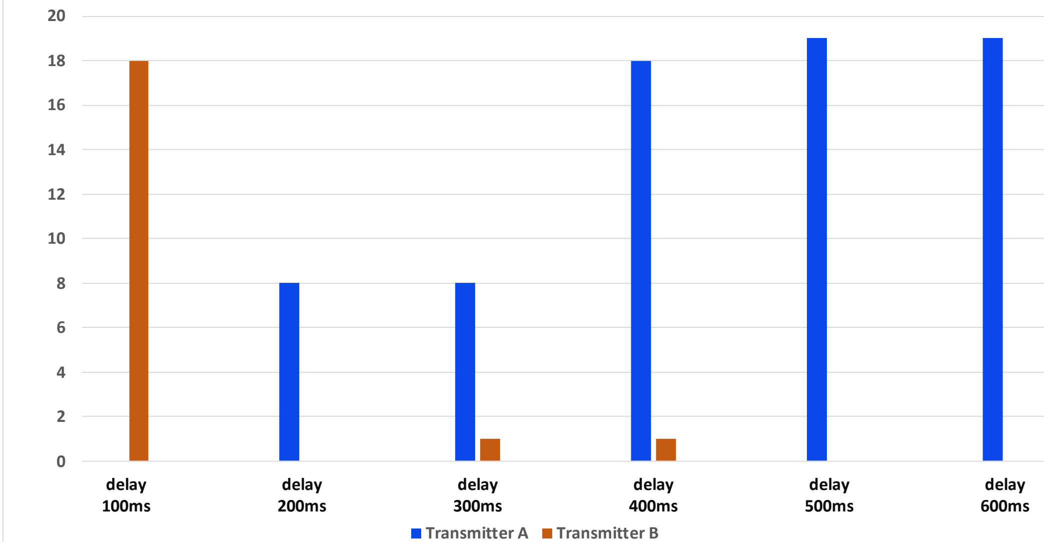
Figure from Umber Noreen, Ahcène Bounceur and Laurent Clavier. LoRa-like CSS-based PHY layer, Capture Effect and Serial Interference Cancellation (24th European Wireless 2018, Catania Italy).

In 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

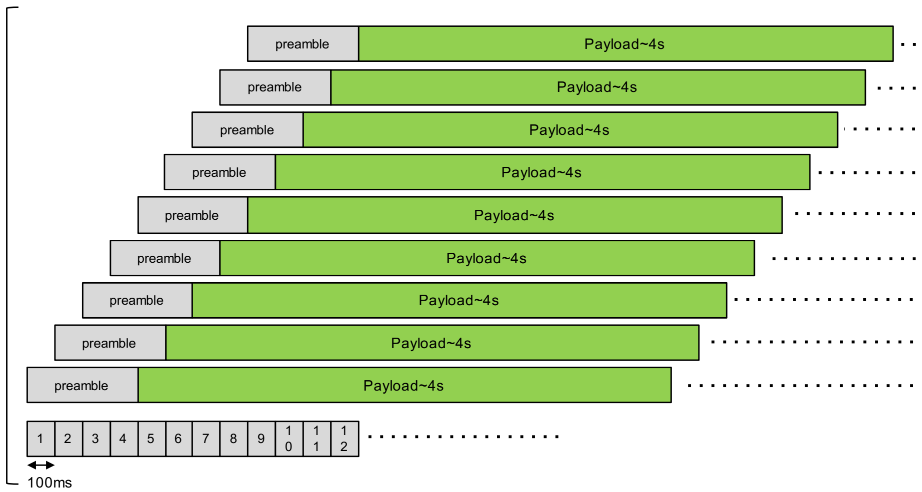
Concurrent transmission during preamble should be avoided
Concurrent transmission after preamble is inefficient but not that harmful

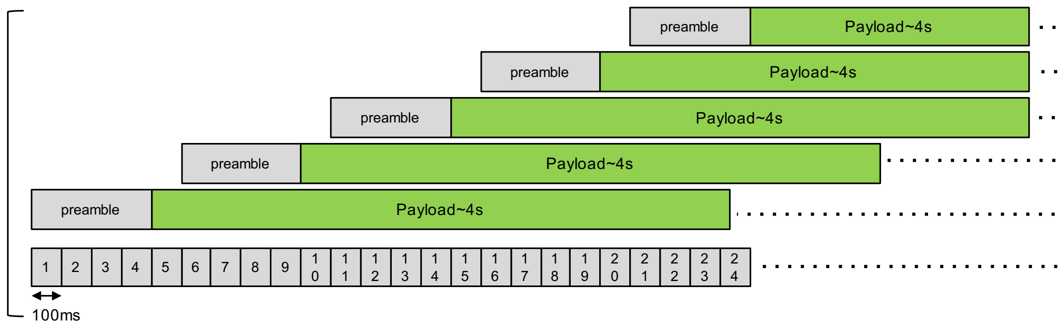




In practice: with high traffic load

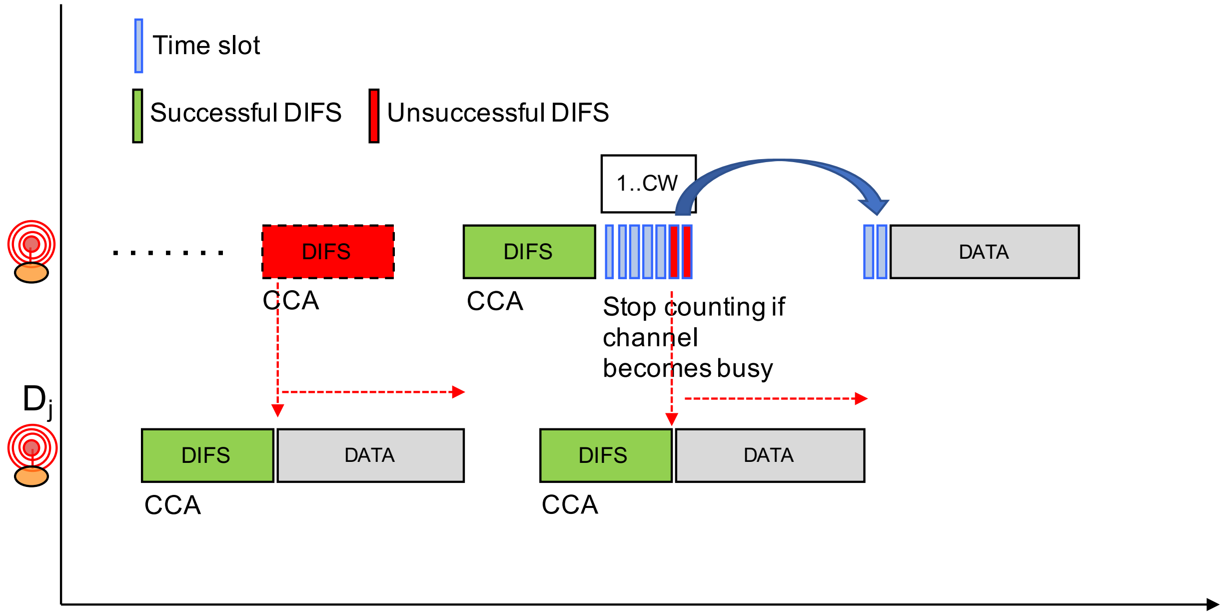
- When there are many overlapping transmissions, Capture Effect is not able to help ☹
- Most of packets are corrupted!
- Neither first nor last packet seems to have higher reception probability!





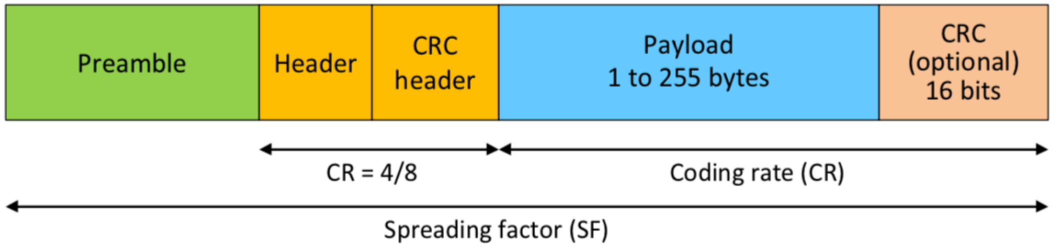
What about Carrier Sense approach?

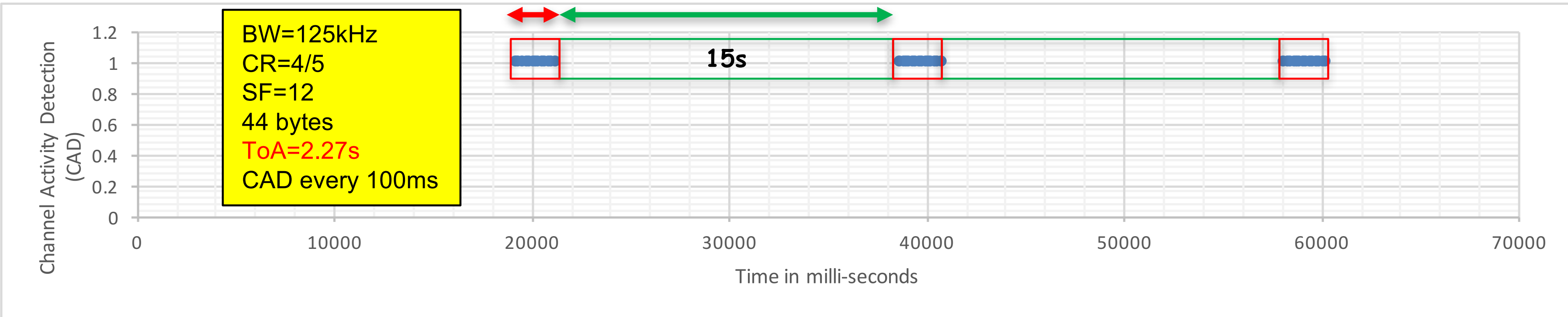
- Can we implement Listen-Before-Talk or Carrier Sense?
- Ex: Carrier Sense Multiple Access/Collision Avoidance in WiFi
  - CSMA/CA in DCF mode with DIFS, SIFS
  - Clear Channel Assessment: is radio channel free?
  - Random backoff [0..W[

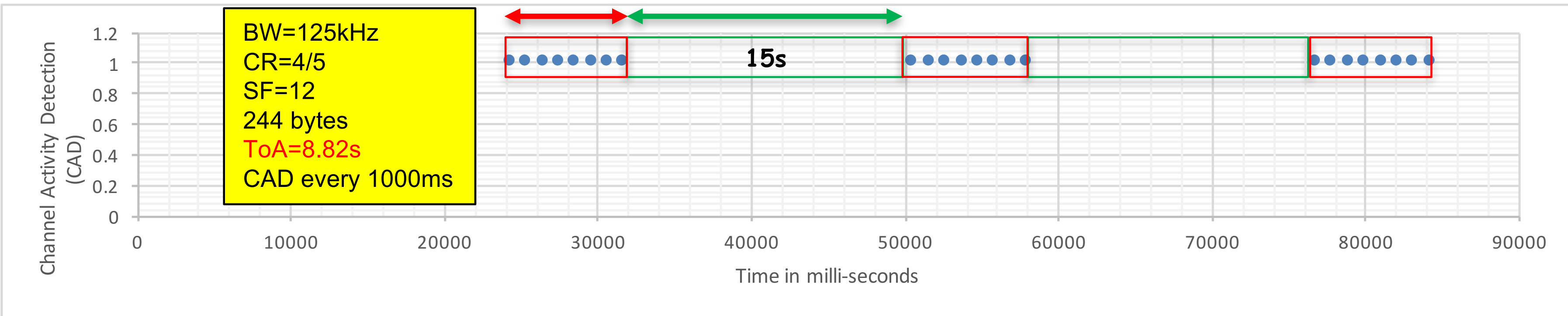


CCA with LoRa

- LoRa's Channel Activity Detection (CAD)

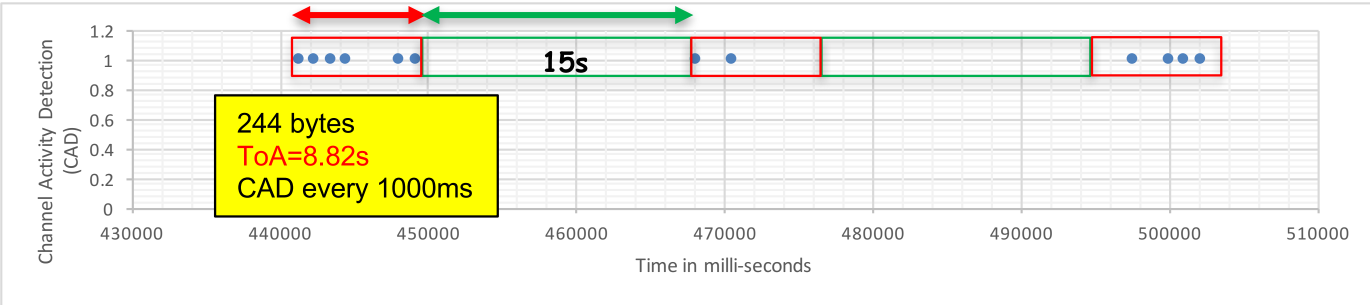




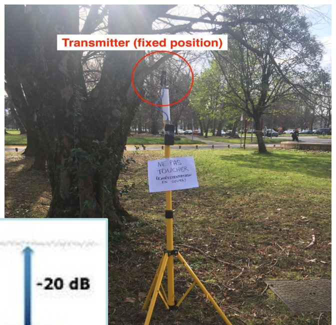


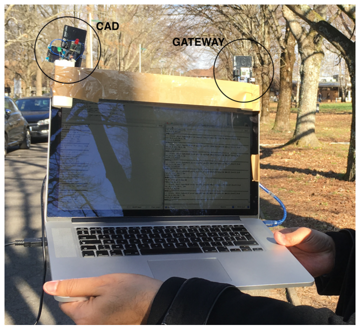
CAD reliability?

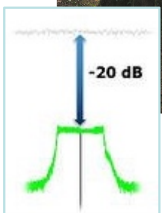
- CAD reliability decreases as distance increases
  - A CAD returning false does not mean that there is no activity!
  - Similar to hidden terminal issue

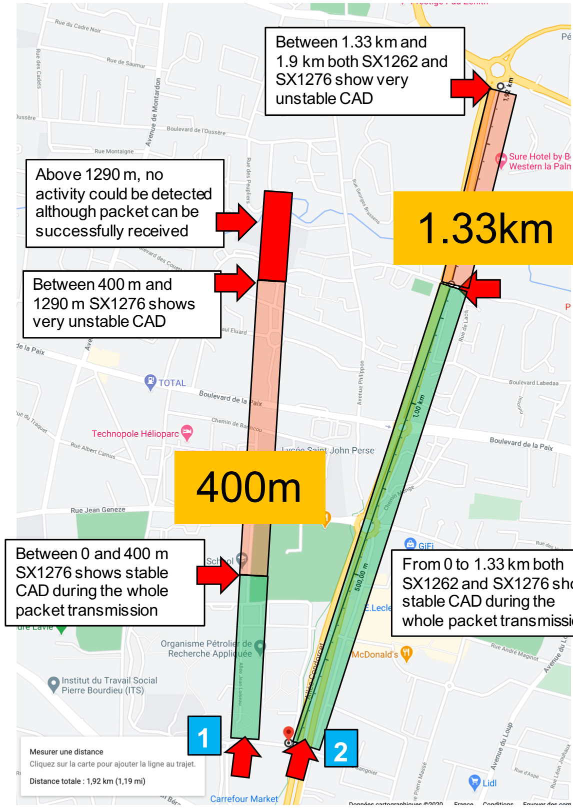


- CAD sensitivity not as good as full reception sensitivity
- CAD returns "no activity" but packet can be received!
- Because LoRa can receive below noise flow!

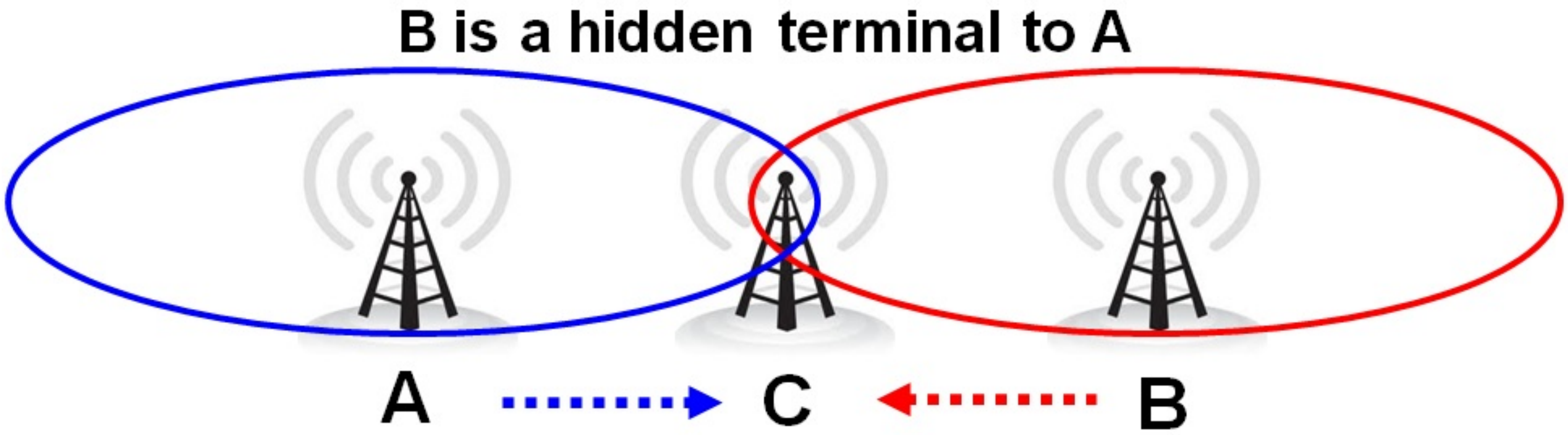






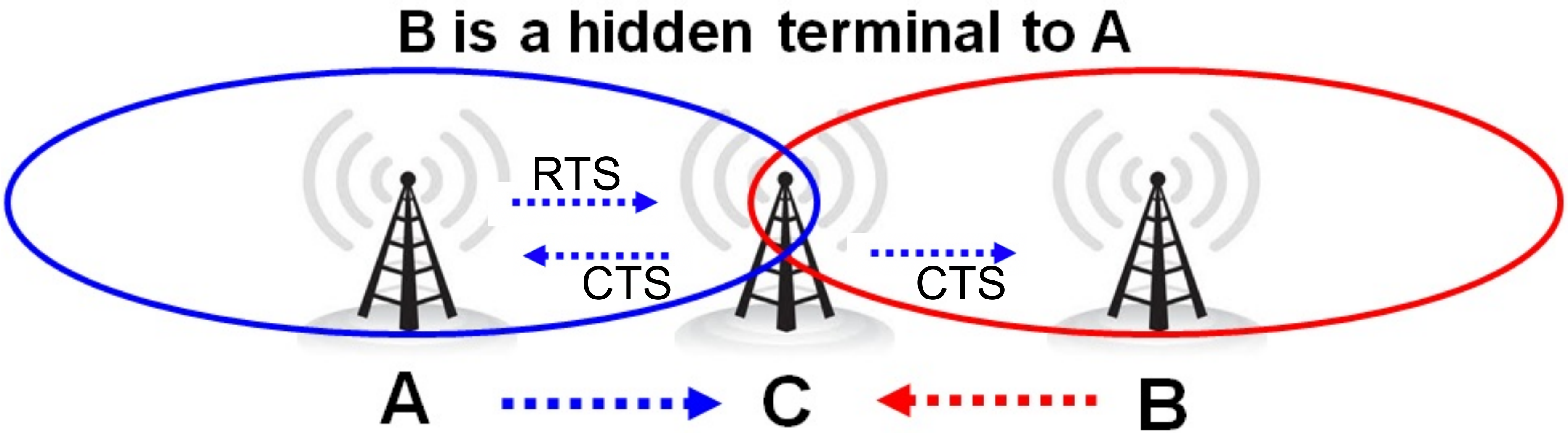


Hidden terminal



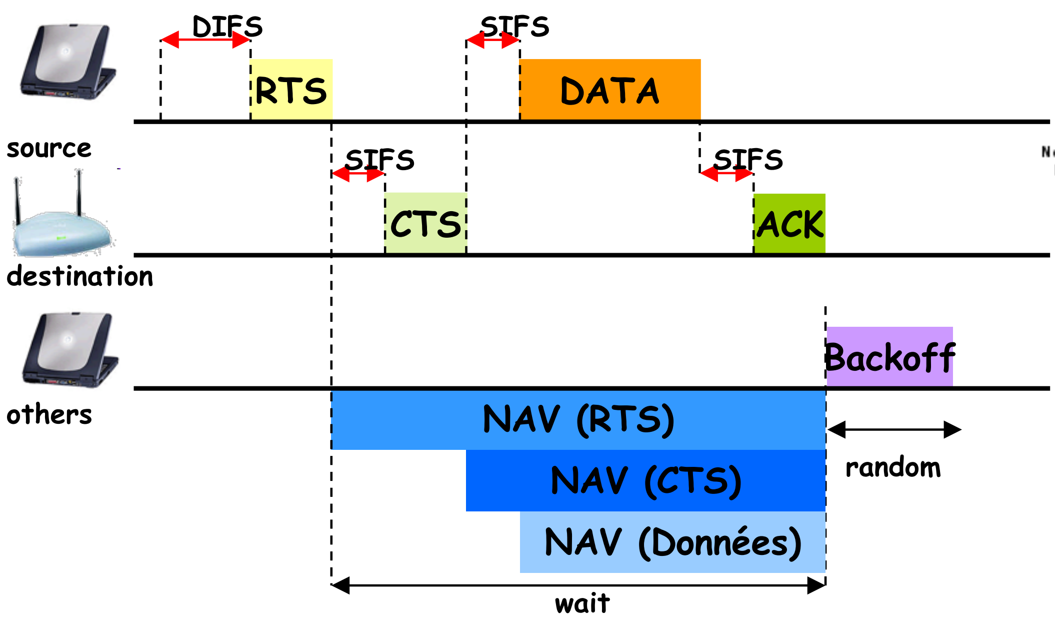
How can we solve hidden terminal?

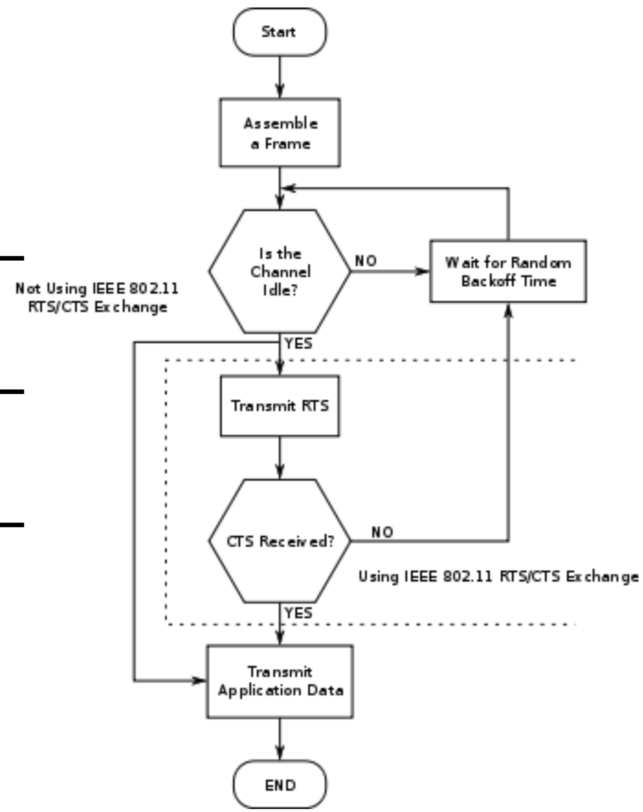
- Use RTS/CTS
  - RTS: Request to Send
  - CTS: Clear to Send



CSMA/CA with RTS/CTS in WIFI

- Collision Avoidance with RTS/CTS to limit the hidden terminal problem
- DCF (Distributed Coordination Function)

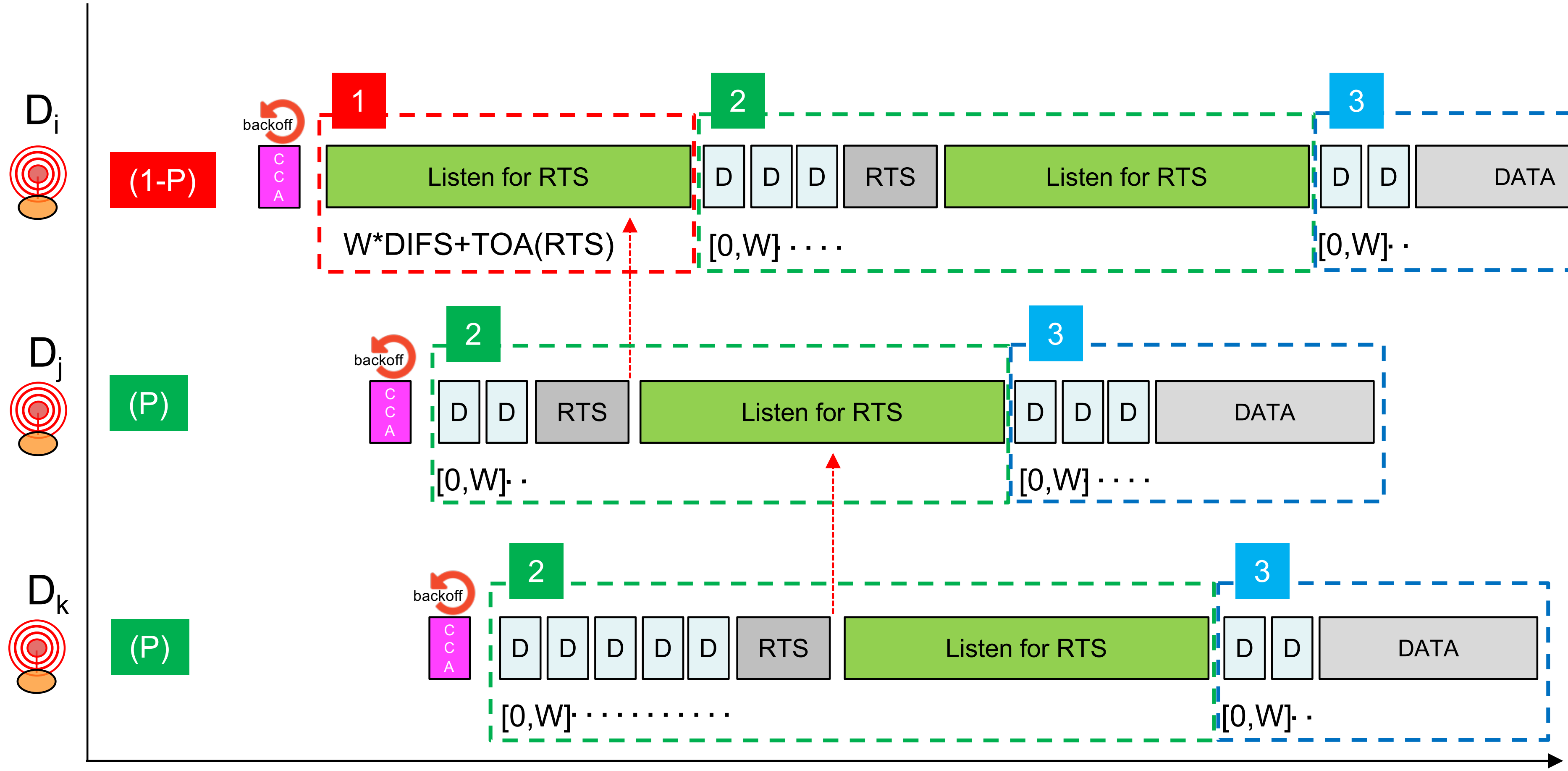




RTS/CTS for LoRa?

- 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**

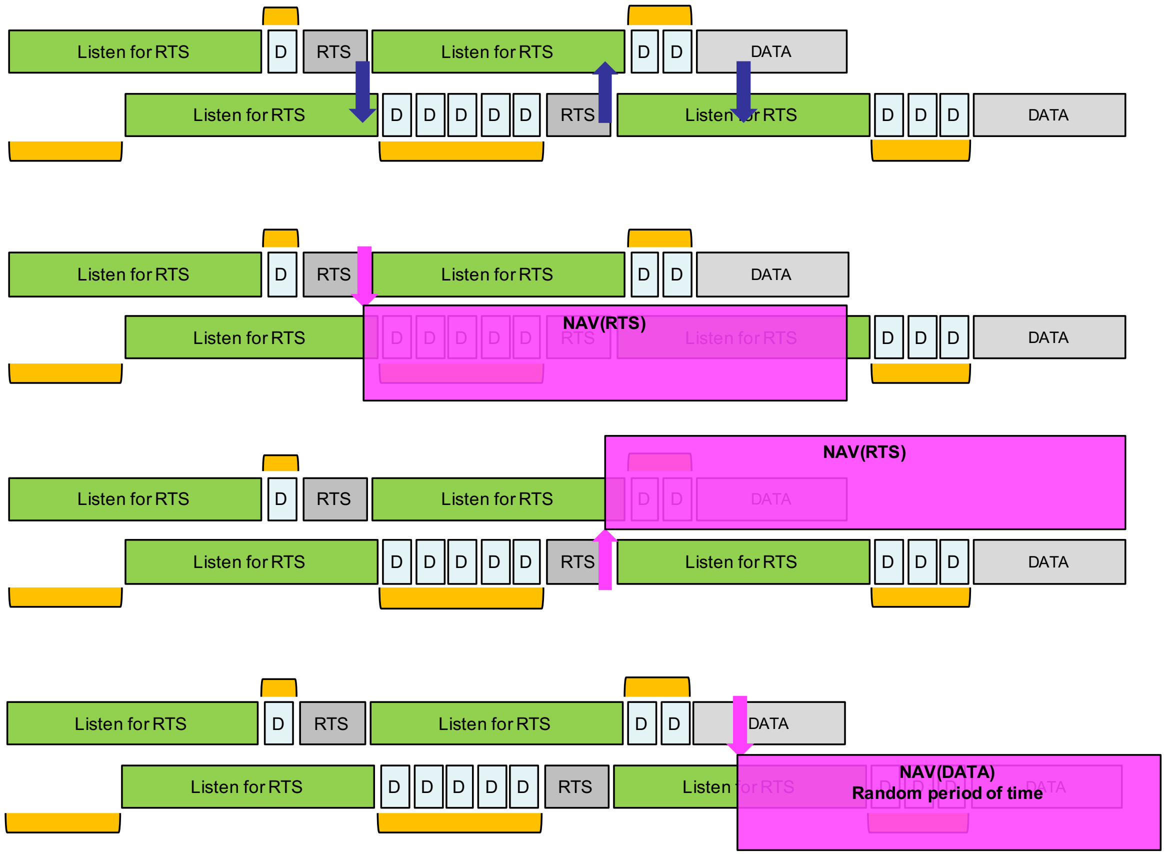
Proposed collision avoidance (CA)



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

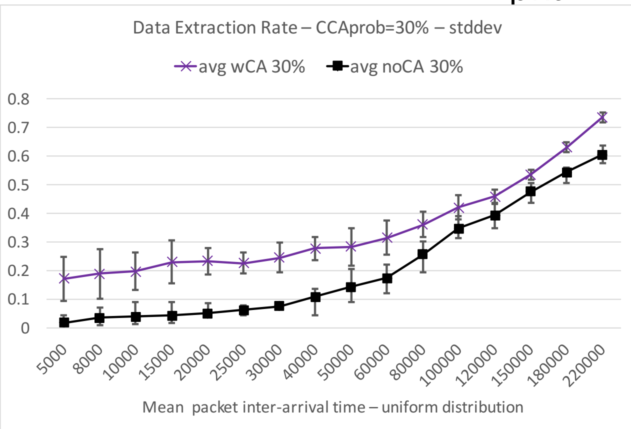
Maximizing transmit/listen overlap

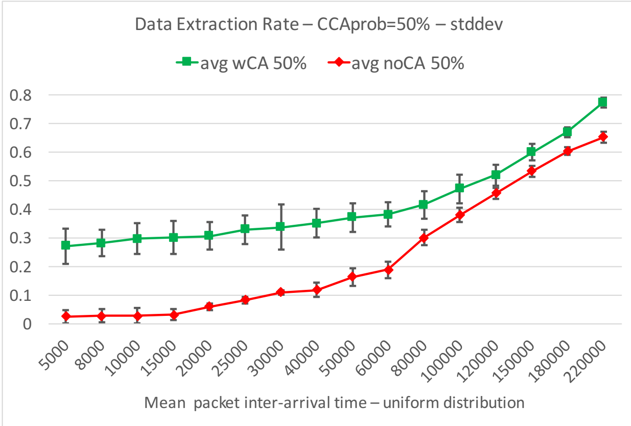
- Random timers (orange blocks) to maximize overlap
- Somehow similar to neighbor discovery or schedule-sharing

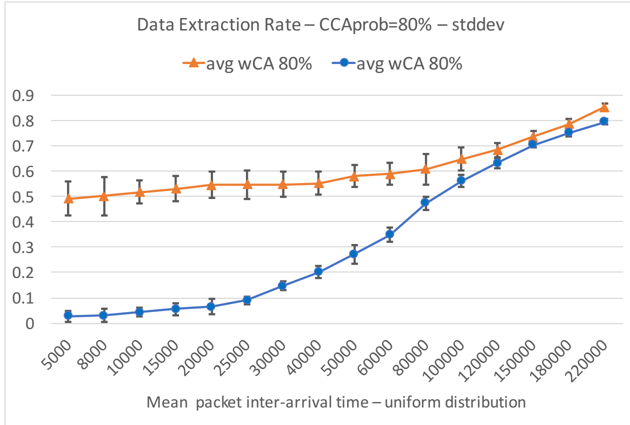


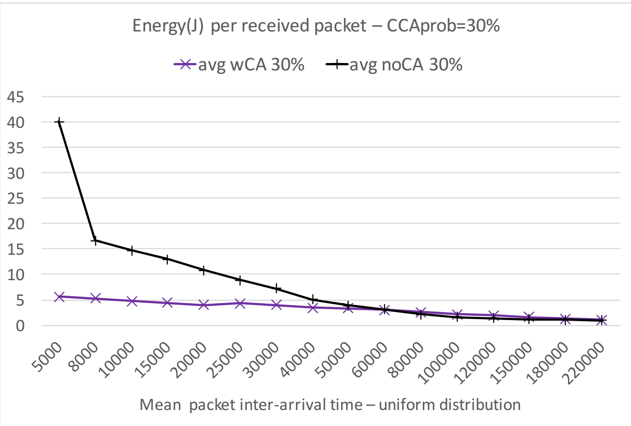
Data Extraction Rate: CA vs CSMA

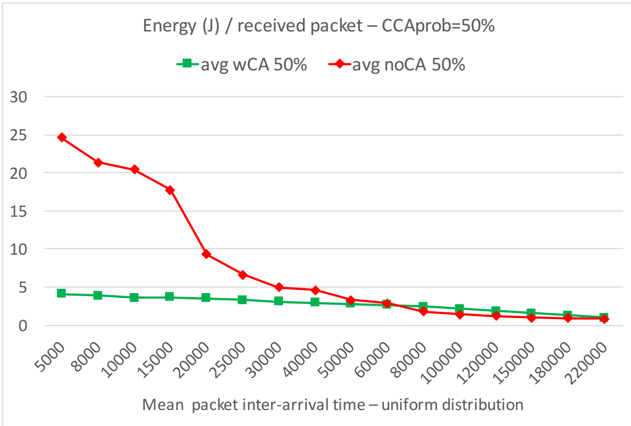
- CCAprob=30%, 50% or 80% (ability to detect radio activity)
- 20 nodes, T_{pkt}=4s, packet inter-arrival time [5s, 220s], DER

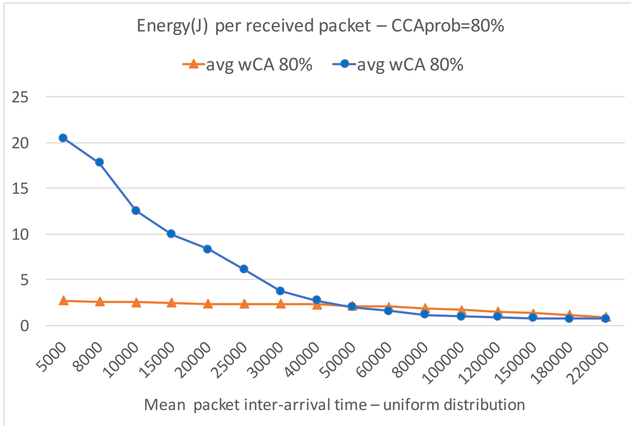






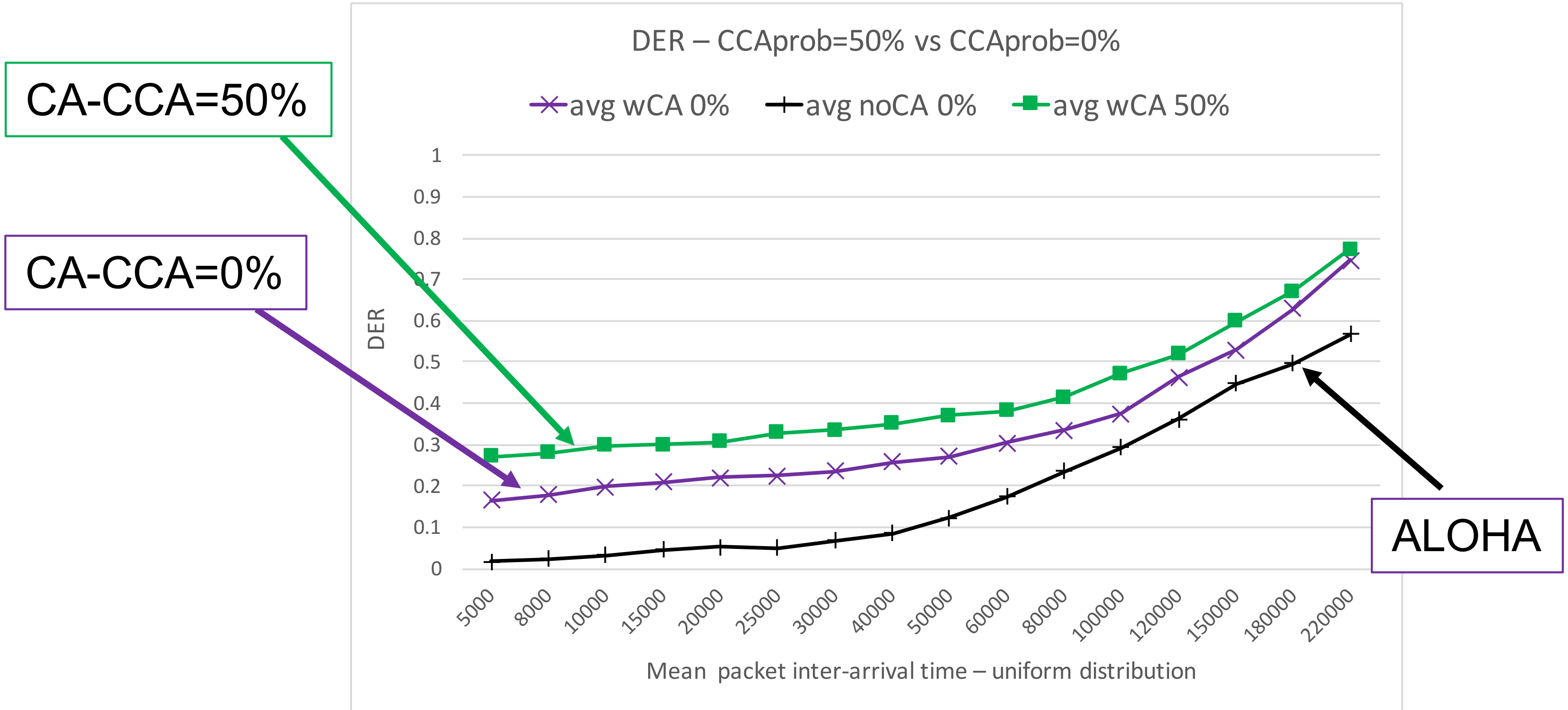






Completely disabling CCA

- 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
  - Novel Collision Avoidance approaches
  - Adapting Neighbor Discovery protocols?

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

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